IEC-NEWS:
Power Performance and Acoustic Noise

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1. Power Performance 61400 –12

The revision of the IEC 61400-12 Power Performance Measurement standard is finished. The Final Draft International Standard FDIS 61400-12-1 Power Performance Measurements of Electricity Producing Wind Turbines is accepted by the national committees and in the near future the standard will be available.

The IEC Power Performance MT 12 is now focusing on the documents

- 61400-12-2 Power Performance Verification
- 61400-12-3 Wind Farm Performance Testing

WTGS	Evaluated wind speed signal	AEP extrapolated	Relative to av. AEP
		[MWh]	[%]
1	met mast top	5377.0	99.9%
1	nacelle	5388.3	100.2%
2	nacelle	5390.2	100.2%
3	nacelle	5356.2	99.6%
4	nacelle	5338.9	99.2%
5	nacelle	5255.6	97.7%
6	nacelle	5544.6	103.1%
7	nacelle	5555.8	103.3%
8	nacelle	5338.1	99.2%
9	nacelle	5252.4	97.6%
	Av nac. based	5380.0	100.0%
	Sigma	108.4	2.0%

Tab. 1: Power Curve measurements on 9 wind turbines. WT 1 is measured according to IEC 61400-12 determining as well the relation between free wind speed and nacelle anemometer wind speed. Using this relation for all 9 wind turbines the nacelle anemometer based power curve was measured and the AEP was determined. The results differed less than 2 % in terms of standard deviation of the AEP.

The new document –12-2 will describe alternative methods for power performance testing of individual wind turbines. The standard will encompass two separate methodologies: power performance measurement, nacelle anemometry and numerical site calibration. The nacelle anemometry method will be published as a standard and numerical site calibration will be published either as part of the standard or as an informative annex to the standard depending on the national comments. Since the wind speed at the nacelle is affected by the rotor (i.e. slowed down), the measured wind speed needs to be corrected for this. Procedures for determining that correction will be included in the methodology. The numerical site calibration method will allow site calibration after the erection of the wind farm, based on numerical modelling. This numerical site calibration will replace the normal site calibration requirements of IEC 61400-12-1. After this replacement, the rest of IEC 61400-12-1 may be applied. The main effort will focus on validating the models and defining criteria for acceptable models based on this validation.

The table 1 shows example results based on DEWI measurements of nacelle anemometry. In the first example a wind farm of nine turbines has been tested for power performance. At the first turbine a IEC 61440-12 compliant power curve measurement has been performed together with the determination of the nacelle anemometer correction function. This function has been transferred to all other turbines of similar type in the farm to test the power performance. In terms of annual energy production (AEP) maximum deviations of -2.7 % to +3.3 %, with a standard deviation of 2 % have been observed. Furthermore the test of the procedure at the turbine that has been assessed following IEC and nacelle anemometry delivered results with a deviation of 0.3 % in AEP.

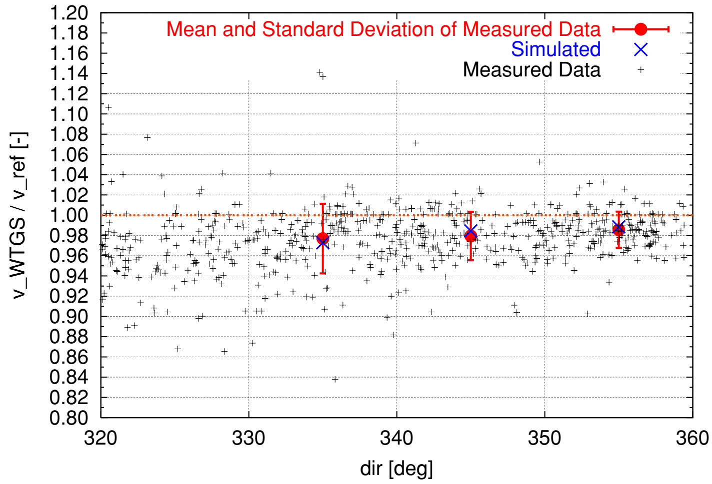
With respect to numerical site calibration, DEWI performed some exemplary case studies regarding the uncertainty of site calibration calculations and comparisons with results from site calibration measurement and nacelle anemometry. These results show that a high accuracy can be achieved (Tab. 2 and Fig. 1). The Round Robin Test „Numerical Flow Modelling in Wind Energy“, which is currently being performed by DEWI, is assumed to deliver further valuable information to the expected uncertainties of these methods.

In the document –12-3 the wind farm will be treated as a single power plant and a method is proposed for testing the performance of a complete wind farm in relation to a reference point (location of a met mast). DEWI has calculated the wind farm performance matrix for a wind farm in Spain which was used as an example for the draft standard which will be circulated in the near future as a CD (committee draft).

2. Acoustic Noise 61400-11 and TS 61400-14

The revised standard 61400-11 ed. 2 was issued end of 2002. The revision allows for the determination of the sound power level and an objective reproducible tonal assessment in the wind speed range 6 to 10 m/s at 10 m height. Right now an amendment to this document is circulated for voting as an FDIS (Final draft international standard). This amendment to 61400-11 ed. 2 addresses special cases where 95 % of rated power is reached below 10 m/s at 10 m height and for sites where wind speeds of 10 m/s at 10 m height are very rare. Furthermore a clarification on regression analysis and frequency weighting is included.

Wind direction	Site calibration factor		
Sector [°]	simulated	meas mean	meas sigma
330 to 340	0.9728	0.9769	0.0344
340 to 350	0.9845	0.9795	0.0239
350 to 360	0.9885	0.9856	0.0179



Tab. 2 and Fig. 1: Comparison of measured and numerical site calibration showing good agreement even in complex terrain.

A proposal for a second revision is circulated for national comments at the moment. The primary focus areas in the revision 61400-11 ed. 3 are expected to be:

- Reference height for wind speed.
- Averaging periods during the measurement should be reviewed
- A more detailed description of the regression analysis is needed.
- Customers and authorities demand standardized data in the wind speed range from 3 to 14 m/s. The methods in the standard should be usable at a broader range of wind speeds (In principle all wind speeds)
- Demands on reduced wind speed ranges for verification purposes should be introduced.
- Improvements in the procedure for 1/3 octave data are desirable. This could be a consequence of altered averaging periods.
- Improvements in the procedure for tonality analysis are desirable.
- Improvements in the uncertainty analysis should be introduced.
- Improvements in the demands for the documentation of measurement results should be made. (mode of operation of the turbine e.g. low noise operation).
- Clarification of the use of power curves in the analysis of measurement results should be included.(air density corrections etc.)
- Small wind turbines.
- Off-shore wind turbines.
- Considerations on the use of the nacelle anemometer for background noise measurements.

- Other aspects of noise are being investigated these years (low frequency noise, infra sound etc.)
- Wind farm noise verification. (number of turbines to be documented)

The Technical Specification TS 61400-14 was issued in March 2005. The intention of this TS is to determine declared noise emission values from a sample of turbines of the same type. The declaration will increase the reliability of wind farm planning and shall facilitate the comparison of sound power levels and tonality values of different types of wind turbines.

A Review of Wind Turbine Noise

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1. Introduction

In many countries the noise radiation is still the major limitation in the tremendous development of wind energy over the last years. New designs resulted in considerable noise reductions of both aerodynamic noise from the blades and machinery noise. The sound power levels of variable speed machines can be adjusted even after they have been put into operation and after the sound pressure levels at the nearest dwellings have been verified.

Some national codes work with absolute noise limits, while in some other countries the limits are based on the ambient noise. The nature of the wind turbine noise and the wind induced background noise are very important for defining masking criteria. The national codes for noise regulations have to be consistent with the international standards of measuring the wind turbine noise including the assessment of tonality and the standards for noise propagation.

The IEC standard 61400-11 Wind Turbines – Part 11 ‚Acoustic Noise Measurement Techniques‘ was revised recently in order to present a procedure expected to provide accurate results that can be replicated by others. Immission measurements are not within the scope of this IEC standard. The different measurement procedures of noise immission from wind turbines at noise receptor locations are described in an IEA Recommendation.

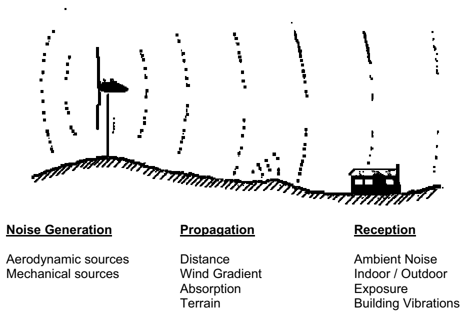


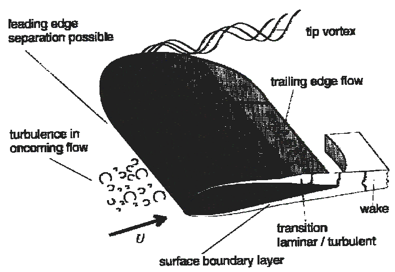
Fig. 1: Wind turbine noise assessment factors
Source: Sheperd, K. P.; Grosveld, F. W.; Stephens, D. G.: Evaluation of Human Exposure to the Noise from; Large Wind Turbines Generators. Noise Control Engineering Journal, Vol. 21, No. 1 pp. 30-37, July-August 1983

In this general review the history and the state of the art of wind turbine noise is given with special emphasis on:

- Noise sources
- Propagation effects
- Standards and Recommendations
- Noise reduction
- Measurement procedures at high wind speeds
- Noise characteristics (e.g. tonality)
- Declaration and verification of sound levels

2. Noise Sources

In order to assess the noise at the receptor locations (nearest dwellings) we have to distinguish between noise generation (noise sources) noise propagation (propagation conditions, prediction standards) and sound pressure levels at the receptor location. The noise sources can be split up into the aero-



Quelle: Blake, W. K.: Mechanics of Flow-Induced Sound and Vibration, Vol II: Complex Flow Structure Interactions. ACADEMIC Press INC., Harcourt Brace Jovanovich, Publishers pp. 426 - 973, 1986

Fig 2: Schematic of the flow around the outer part of the rotor blade dynamic noise sources [1] and the machinery noise. The aerodynamic noise sources are inflow turbulence noise (leading edge of the blade), turbulent boundary layer noise (interaction with the trailing edge of the rotor blade) and tip noise (see. Fig. 2)

Machinery noise (mainly (gearbox noise, generator noise)) has been reduced significantly so that it is mostly not contributing to the overall sound power level. On the other hand there are still some turbines radiating an audible tone which is assessed according to IEC 61400-11 ed.2. In some countries penalties are imposed under the national code depending on the audibility of the tone.

Fig. 3 shows the sound power levels of 49 different types of wind turbines in the range of 80kW to 2500kW (see also [2]). These are published data in a catalogue issued annually by the German Wind Energy Association BWE (Market Survey 1997-2005)

When looking at the wind speed dependency of the sound power level we have to distinguish between stall-regulated turbines and pitch regulated turbines. The power control by the stall-effect causes an increase of sound power level also at high wind speeds, while pitch regulated turbines not only keep the power constant at high wind speed but also the sound power level. Due to the pitching at rated power the sound power level may even decrease at high wind speeds (see Tab. 1).

3. Propagation

Meteorological conditions, mainly wind and temperature profiles in the boundary layer affect outdoor sound propagation [3]. Wind speed and temperature are functions of height. They are interrelated and can be described by the Monin-Obukhov similarity theory. The Monin-Obukhov length L is a stability parameter for the turbulent boundary layer. The steepest sound speed gradients causing the highest sound pressure levels at large distances occur for downwind conditions at night-time. The most pronounced stable atmospheric stratification can be expected during clear nights and low wind speeds. For that reason a lot of national codes require measurements at low wind speeds at night-time (often referred to as ‘downwind condition’). As the wind turbines have the highest sound power levels at high wind speeds these national codes for noise regulations have to be made consistent with the international standards of measuring the wind turbine noise at wind speeds from 6 to 10 m/s at 10 m height.

V[m/s] at 10 m height	6	7	8	9	10
Sound Power Level Stall-regulated turbine 1300 kW	98.6	99.6	100.8	102.4	**104.1**
Sound Power Level Pitch-regulated turbine 850 kW	98.8	100.0	101.1	**101.5**	101.0

Tab. 1: Sound power level vs. wind speed. Examples for a stall and a pitch-regulated turbine

4. Standards and Recommendations

4.1 IEC Standard 61400-11

The IEC standard 61400-11 ed. 2 Wind Turbines – Part 11 ‚Acoustic Noise Measurement Techniques' provides a uniform methodology that will ensure consistency and accuracy in the measurement and analysis of acoustical emissions by wind turbine generator systems (WTGS). The sound power level is determined for wind speeds from 6 to 10 m/s at 10 m height.

A preferred method is described (mandatory for declaration and certification measurements) using the electrical power output of the turbine (in combination with the power curve of the machine) as a measure for the wind speed instead of a measurement at a 10 m met mast. This is the only method to get **reproducible sound power levels** of a wind turbine independent of the instantaneous wind profile during the measurement period (see also chapter 3) which also means independent of the time of the day. In other words: the propagation conditions for large distance propagation change significantly with the boundary layer stabilities (see chapter 3) but **not** the sound power level of the sound source measured by the 61400-11 standard (if the preferred method is used). The sound power levels are determined for **standardised wind speeds at 10 m height**. The wind speed at hub height is determined by the electrical power through the power curve of the turbine. The related wind speed at 10 m is determined by a standardised wind profile given in the IEC –11 standard.

The IEC group on the –11 standard right now works on an amendment in order to define a procedure to measure reproducible sound power levels at high wind speeds as well. If the standardised wind speed corresponding to 95% of rated power is below 10 m/s, one of the following two methods shall be used to determine the wind speed for data above 95% of rated power:

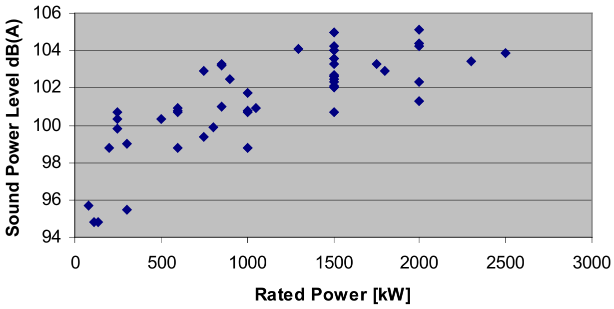


Fig 3: Sound power level of different wind turbines

Nacelle anemometer method:

A linear regression using the nacelle wind speed V_n and corrected hub height wind speed determined from electrical power measurements V_H shall be determined. The corrected wind speed above 95% of rated power shall be determined applying the resulting linear regression to the nacelle wind speed V_n.

κ-factor method

For all data points with power levels below 95% of rated power the ratio of standardised wind speed and measured wind speed, κ, shall be derived. This ratio shall then be applied to the measured wind speed of the data points with power levels above 95% of rated power to estimate the standardised wind speed.

The nacelle anemometer method is the preferred method as the correlation between nacelle wind speed and the electrical power output typically is better than for the wind speed measured below hub height.
The presence of tones in the noise at different wind speeds shall be determined on the basis of a narrow band frequency analysis as follows (see also [4]):

- The sound pressure level L_{pt} of the tone shall be determined
- The sound pressure level of the masking noise L_{pn} in a critical band around the tone shall be determined

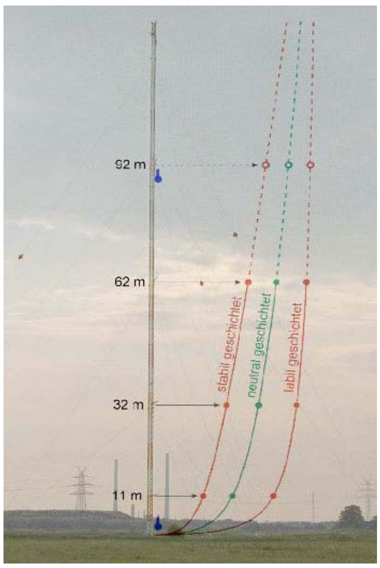


Fig. 4: Wind profiles for stable, neutral and unstable atmospheric conditions. Measured at the DEWI's 130m-mast.

- The tonality ΔL_{tn}, the difference between the sound pressure level of the tone and the masking noise level shall be found

The tonal analysis shall cover the same wind speed range as the sound power level measurement. For each wind speed bin, the two one-minute periods with wind speeds closest to the integer wind speed value shall be analysed.

The narrow band frequency spectrum for the whole two-minute-period shall be determined. Then the two one-minute recordings shall be divided into twelve ten-second periods, from which twelve narrow band frequency spectra are obtained. From these twelve spectra all lines representing tones shall be identified.

Every spectral line is classified as a) 'tone', b) 'masking', or c) 'neither tone nor masking' as illustrated in the figure 5.

Determination of the tone levels $L_{pt,i}$
The sound pressure level of the tone, $L_{pt,i}$ is determined by energy summing all the spectral lines identified as tones from each 12 ten-second spectrum

Determination of the masking noise levels $L_{pn,i}$
The 12 sound pressure levels of the masking noise, $L_{pn,i}$, are defined as follows:

$$L_{pn} = L_{pn,avg} + 10 \lg\left[\frac{\text{critical bandwidth}}{\text{effective noise bandwidth}}\right]$$

Where $L_{pn,avg,i}$ is the energy average of the spectral lines identified as 'masking'.

Determination of the tonality ΔL_{tn}
The tonality $\Delta L_{tn,i}$ is the difference between the sound pressure level $L_{pt,i}$ and the level $L_{pn,i}$. The 12$\Delta L_{tn,i}$ are then energy averaged to one ΔL_{tn}.

4.2 IEC Technical Specification 61400-14: Declaration of Sound Power Level and Tonality Values of Wind Turbines

Information on the sound power level and tonality of wind turbines is needed by planners, manufacturers and authorities. At present wind turbine noise specifications tend to be based on measurement results from a single turbine of a particular make and model and these are then taken to be representative of these turbines as a whole. Clearly this is unlikely to be the case, as there will be individual variation between different turbines. The intention of this document is to determine declared noise emission values from a sample of turbines of the same type. The declaration will increase the reliability of wind farm planning and shall facilitate the comparison of sound power levels and tonality values of different types of wind turbines.

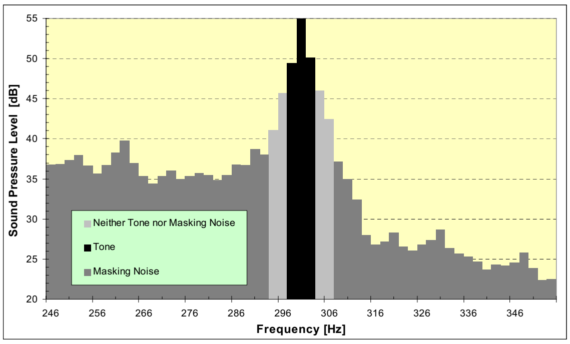


Fig. 5: Illustration of classifying all spectral lines

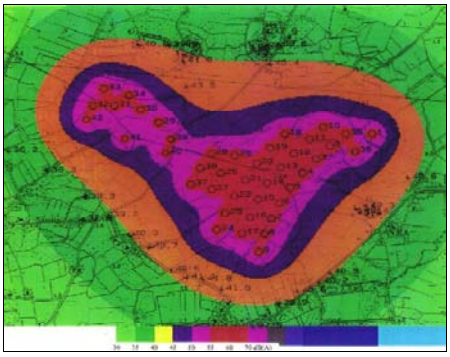


Fig. 6: Sound pressure levels around a wind farm

The document IEC TS61400-14 gives guidelines for declaring the apparent sound power level and tonality of a batch of wind turbines (see also [4]). For the declaration procedure the influence of turbine characteristics on the acoustical performance is of great importance:

- Hub height : The sound power level is correlated to the acoustic reference wind speed and not to the wind speed at hub height. An increase of hub height will increase the sound power level and might have an unpredictable effect on tonality.
- Tip speed: the sound power level is very sensitive to the tip speed (Lw~50....60logVtip). An increase in tip speed will cause an increase in sound power level, and may have an influence on aerodynamic tones.
- Pitch setting: Pitch settings affect the fundamental aero-acoustic processes on the blades, which may significantly change the overall sound power level and the tonality.
- Gear box: A major source of mechanical tones is the gear box. Small changes in the design (like ratio's, tooth shape, casing thickness) can have a significant effect on the frequency and level of the tones
- Blades: Changes to the blade geometry such as trailing edge thickness, tip shape, blade surface finish, internal structure, twist distribution, may all cause significant changes to the acoustical performance.
- In addition to the above mentioned items, there are a number of other items, generator, tower type, yaw motors, cooling fans, hydraulic pumps, etc., which may influence the acoustical performance.

4.3 Measurement of Noise Immission from Wind Turbines at Noise Receptor Locations

The IEA recommendation **Measurement of Noise Immission from Wind Turbines at Noise Receptor Locations** [5] recommends measurement techniques and methods which will enable a characterisation of the noise immission from wind turbines at a noise reception location. In several countries standards or guidelines from industrial sources have been implemented. However, it is not possible to apply these procedures to wind turbine acoustic measurements since they must be carried out in windy conditions outside the scope of the standards dealing with noise from industrial plants.

A major problem when measuring noise immission from wind turbines is the influence of background noise generated by, for instance

- the wind at the microphone
- the wind acting on adjacent trees, shrubs and structures
- traffic on nearby roads and rail tracks
- aircraft and industries
- animal and human activities
- streams or waves on shorelines.

In many measurement situations, the sound level of a wind farm is of the same order of magnitude as the background noise level (see fig. 7). This implies that a very important task is to correct the measured levels for the influence of background noise. For the same wind speed range immission measurements have to be performed for

- turbines operating
- turbines parked.

Measurements at high wind speeds performed only when the turbines are operating are useless in most cases. The IEA recommendation gives guidance how to increase the signal-to-noise-ratio for immission measurements like

- use of a secondary wind screen
- small boards on a building facade
- large free standing vertical boards

Some national codes work with absolute noise limits, while in some other countries the limits are based on the ambient noise. The nature of the wind turbine noise and the wind induced background noise are very important for defining masking criteria. The measurement of the background noise at the nearest dwellings should be performed

- for a defined wind speed range (e.g. 4-8 m/s at 10 m height)
- at night time in order to reduce noise from traffic and human activities
- for relevant wind directions
- with a secondary wind screen
- under noise relevant conditions (for example, no leaves on the trees)

The evaluation of the background noise should include Leq, but also statistical values like L50, L90, and L95 in order to be able to define masking criteria or noise limits.

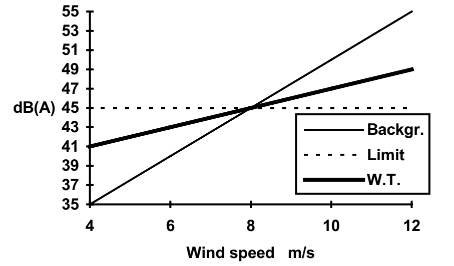


Fig. 7: Example: wind turbine noise and background noise as a function of wind speed at 10 m height.

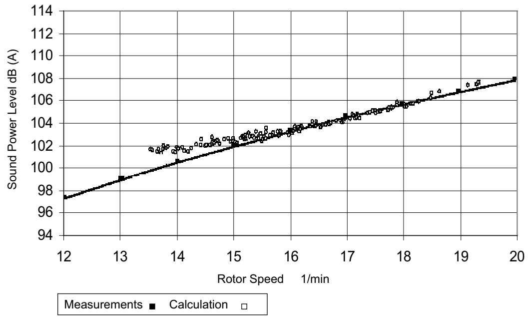


Fig. 8: Sound power level of a 3 MW turbine as a function of rotational speed

5. Infrasound

Wind turbines are radiating sound at extremely low levels in the infrasound range (below 20 Hz).This sound is far below the detection threshold and thus far below levels which can cause any diseases. Measurements at a turbine in the megawatt class at the DEWI Test Site showed levels of 58 dB at a distance of 100 m to the turbine in the one-third octave band level at 10 Hz, which means more than 30 dB below the hearing threshold at this frequency (Source: Measurement Report ITAP: Messung der Infraschall-Abstrahlung einer WEA des Typs Vestas – 1,65 MW; ITAP-Institut für technische und angewandte Physik GmbH, Oldenburg, 26.06.2000).

6. Noise Reduction Procedures

Considerable noise reductions have been reached by modifications of the trailing edge (sharp or serrated trailing edge) and new tip designs (avoiding tip vortex-trailing edge interaction by ´trailing edge cutting´). The tip noise experiments on commercial wind turbines have confirmed the results obtained in the wind tunnel. Tip designs generating strong tip vortices (e.g. extreme curvature at the leading edge) interacting with the TE (trailing edge longer than the leading edge) cause additional noise in the high frequency range (a second maximum in the 2kHz frequency range of the sound power spectra is an indication of tip noise). Reductions of the overall sound power level up to 4 dB(A) have been reached by designs avoiding these effects [6], [7].

The choice of a wind turbine's blade pitch setting and its rotational speed is a compromise between noise radiation and energy production. The advantage of wind turbines with changed operational conditions (rotational speed/pitch setting) in noise-sensitive conditions (e.g. for specific wind directions or at nighttime) are obvious: The acoustically affected area is smaller so that more wind turbines can be erected in a wind farm. The proposed noise-reduction-tool can also be used for subsequent noise reduction in cases of complaints.

As changes in the operating conditions of the wind turbines will influence their power curves, any resulting loss in energy production can be calculated, so that the cost effectiveness of the measures can be evaluated.

Some manufacturers offer the same type of turbine with different sound power levels. They differ due to different control settings (e.g. rotational speed as a function of electrical power). The Technical Guideline TR 1 (Rev. 16) about noise measurement from wind turbines in Germany as well as the MEASNET measurement procedure for that reason require the recording of the rotational speed during the noise measurement as a function of the normalised wind speed (defined in 61400-11) so that the control setting during the noise measurement can be clearly identified. The authorities can also determine from the track record of the turbine's data acquisition system (time series of power and rotational speed) if a noise reduced control version was active for certain periods (e.g. at night time).

The MEASNET procedure requires the following: Relevant wind turbine control parameters such as rotor speed shall be measured and reported. These data may be obtained by online data acquisition of signals from the wind turbine controller. In that case the data have to be verified for example by using optical or acoustical counting of the blade passages during the measurements. These parameters shall be reported as a function of active power and standardised wind speed.

References:

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