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Noise
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3aNSa2. Development of a real time compliance system for wind farms regulated by ambient-relative noise standards

Michael Hankard*

***Corresponding author's address: Hankard Environmental Inc., 100 Park Avenue, Verona, Wisconsin 53593, mhankard@hankardinc.com**

Some noise level regulations in the U.S. require wind turbine farms to not exceed the ambient sound levels at nearby residences by more than a fixed amount. For the project discussed herein, compliance with such a regulation requires curtailment of turbine operations to some degree at times when turbine operations are at or near maximum, atmospheric conditions are conducive to sound propagation, and sound from other sources including vegetation rustle are at a minimum. Based on the analysis of months of time-synchronized sound, meteorological, and operations data, a system was developed to assess compliance on a real-time, ongoing basis. The primary element in the determination of compliance is the shape of the one-third octave band spectrum at the residence, augmented by ground and hub-height meteorological conditions, and wind farm operations information. Without the spectral filter, curtailment would need to take place under a broader array of meteorological conditions to ensure compliance, which would result in loss of power generation revenue. This paper will describe the data collection and analysis methods, the development of the spectral filter, and the results of field testing including both the partial and entire shut down of the wind farm.

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INTRODUCTION

The operation of Industrial Wind Turbines (IWT) produces noise, the levels of which are almost always subject to either state or local regulations in the United States. Presently, these regulations often take the form of a single overall noise level limit in A-weighted decibels (dBA), and/or octave band limits. In some cases, the limit is expressed as a level above "ambient", with ambient being defined to some degree yet always open to interpretation. A partial summary of international and U.S. wind turbine noise regulations was provided in a recent paper (Hessler et al., 2011)[1]. The regulation that the IWT farm that is the subject of this paper must meet requires that the turbines not increase the ambient statistical noise levels, L_{10} or L_{50}, by more than 10 dBA in any one hour. The regulation further states that the wind energy facility may conduct measurements to determine the actual ambient background level. The actual ambient background level is the measured noise level near the point (residence) of concern using generally accepted noise engineering measurement practices. Finally, the measurements should be synchronized with wind speed measurements of hub height conditions at the nearest wind turbine location.

The traditional method of determining the ambient sound level in a given environment is to measure it continuously for a period of a few days to two weeks. In the author's experience of conducting almost 100 ambient noise surveys, the ambient level is most often determined as the average L_{90} (dBA) over a one to two week measurement period in the late spring to early fall time frame. Wind turbine projects require an additional component in that the ambient of concern is not simply the lowest level that is regularly measured, but that which exists over the range of turbine operations, which necessarily involves wind and which in turn can significantly affects ambient sound levels. The traditional method was not possible on this project as an ambient noise survey was not conducted prior to turbine operations. The turbines could have been shut down for a week or two and the ambient determined that way. However, this would result in the measurement of ambient sound levels over only a relatively narrow set of atmospheric conditions, would not account for seasonal fluctuations in both ambient sound levels and wind turbine noise levels, and the resulting levels could dramatically under- or over-predict the times in the future when the turbines would actually be out of compliance with the 10 dBA above ambient rule.

The method chosen instead was to first conduct a nine month long, continuous, robust ambient noise survey. In addition to ambient sound levels, ground wind speed and direction, temperature, and relative humidity were measured near the microphone, and turbine operation parameters such as rotor speed and hub-height wind speed were also monitored. Throughout the survey, the entire turbine farm was shut down for brief periods of time (20 to 30 minutes) to measure the ambient sound level when conditions were considered right for a possible exceedance (high winds aloft with low winds on the ground). Next, all of the measured sound, meteorological, and operations data was time-synchronized and assembled into a spreadsheet for analysis. The data was analyzed to determine (a) the noise levels produced by the turbines under various operational, meteorological, and seasonal conditions, (b) the ambient sound level measured with the turbines off under various conditions, and the ambient sound level under wind conditions just shy of that required for turbine operations, and (c) the conditions under which the 10 dBA above ambient regulation may be exceeded. Based on numerous analyses conducted using this extensive database, a spectral filter was developed that accurately determines the times when turbine noise levels are likely to be more than 10 dBA above the ambient sound level occurring at any given time. The spectral filter is the highlight of this work, and is presently being converted into a real-time compliance system.

MEASUREMENT EQUIPMENT AND METHODS

Noise levels were monitored using equipment conforming to IEC 61672-1 (2002-2005) Class 1 and ANSI S1.4-1983 (R1997) plus ANSI S1.4A-1985 Amendment, Type 1. The microphone was located approximately 1.5 meters above the ground and covered with an 18 centimeter diameter, 80 ppi density windscreen. The system was calibrated before the survey using a handheld acoustic calibrator. The system was also calibrated every one to two months throughout the survey, and the resulting level never drifted more than 0.2 dBA. Wind conditions were measured at one location throughout the survey, at a location approximately 18 meters from the microphone. About half way through the survey two other anemometers were installed. A sonic anemometer (no moving parts, thus quiet) was installed less than one meter from the microphone to test for potential pseudo noise conditions, and another out in front of the residence to better capture regional ground wind speed conditions. All meteorological equipment was calibrated before the survey to standards common for air quality studies, and calibrations were re-checked half way through the survey.

THE SPECTRAL FILTER

The instances when turbine noise has the greatest potential to be 10 dBA or more over the ambient level at any particular time are when the turbines are the dominant noise source in the environment. When noise levels are measured outside at a location (residence) near a turbine farm the measured levels reflect the total noise level resulting from all sources present. In the subject case, the measurements were conducted in a very rural area, such that the only non-turbine noise sources of significance are the wind blowing through vegetation and across the microphone, and birds and insects. There is very little local traffic and almost no distant traffic noise. There are military aircraft overflights, but these are sporadic and adequately filtered by the use of the L_{50} metric.

Therefore, in order to determine turbine-only noise levels it is necessary to separate the contributions from all of these sources. Birds and insects are fairly easy to separate based on spectral shape, with contributions in the 2,500 to 5,000 Hertz range. The effect of wind blowing across the microphone was minimized through the use of a proper windscreen and by placing the microphone in the eddy of the house but still in view of the turbines. The hardest to separate was the effect of wind blowing through nearby vegetation, as (a) its spectral content is similar to that of the turbines, (b) it is almost always present to some degree during turbine operations, and (c) at low ground wind speeds the noise level from vegetation rustle does not always correlate with wind speed. Through the review of hundreds of spectra, listening to audio files, and being on-site during different conditions, the turbine-dominant spectral shape shown in Figure 1 was determined. Also shown in the figure are the effects of vegetation rustle in the 500 to 2,500 Hertz range, and bird/insect sound. Note that the spectrum with the highest vegetation influence does not necessarily have the highest ground wind speed.

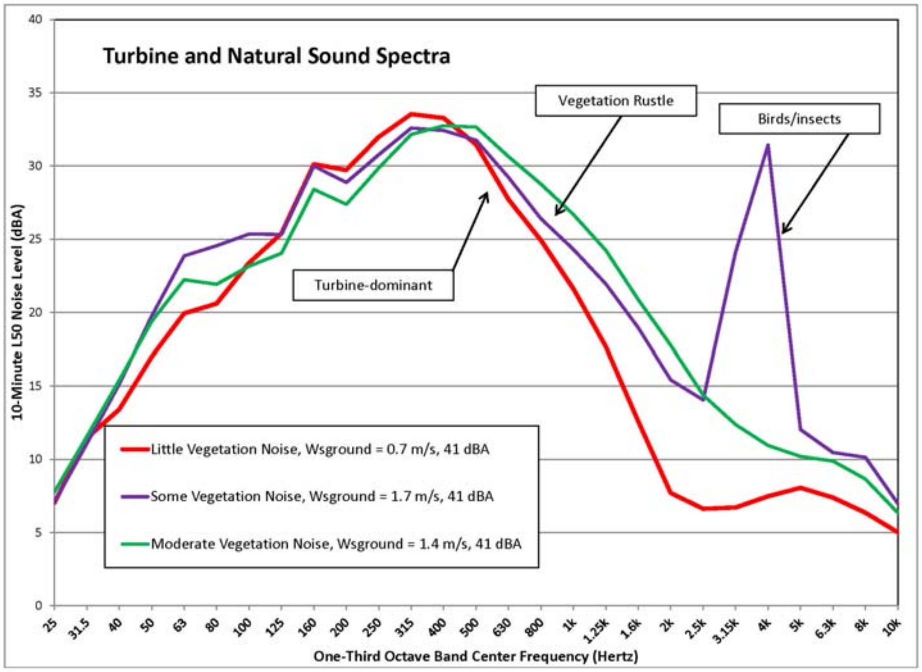

FIGURE 1. Spectral Shape of Turbine, Wind, and Bird/insect Noise One Mile from Nearest Turbines

From the turbine dominant spectra the following formula was developed to calculate the Spectral Filter Number (SFN). The SFN consists of the arithmetic average of the two highest turbine one-third octave bands minus the arithmetic average of the following eight bands. The units are technically dBA, but this is not important.

$$\text{Spectral Filter Number} = \text{Average}(315 \text{ to } 400 \text{ Hertz}) - \text{Average}(500 \text{ to } 4\text{k Hertz}) \quad (1)$$

Figure 2 shows the 100 spectra with the highest Spectral Filter Number. Based on the consistent shape of the resulting spectra it is seen that the filter accurately determines the times when turbine noise is dominant at this particular location. Two other theories for predicting the times when turbines are the dominant noise source in an environment are (1) when wind speeds aloft are high relative to ground winds, and (2) when the turbine rotational speed is high and ground winds are low. For permanent compliance monitoring, these theories have the benefit of not requiring very long term noise monitoring and its associated costs and maintenance requirements. However, as shown in Figures 3 and 4, these theories do not accurately predict the times when turbines are dominant. Figure 3 shows the top 100 spectra from the data set when sorted on the highest hub-height to ground wind speed gradient, and Figure 4 shows the top 100 spectra from a sort on the difference between turbine rotor speed (rpm) and ground wind speed. The latter does a better job, advancing the theory that rotor speed is a more accurate determinant of turbine noise than hub-height wind speed. But in both cases it is clear that many of the spectra are not turbine-dominant, and the turbine farm was unlikely to be out of compliance with the 10 dBA above ambient rule.

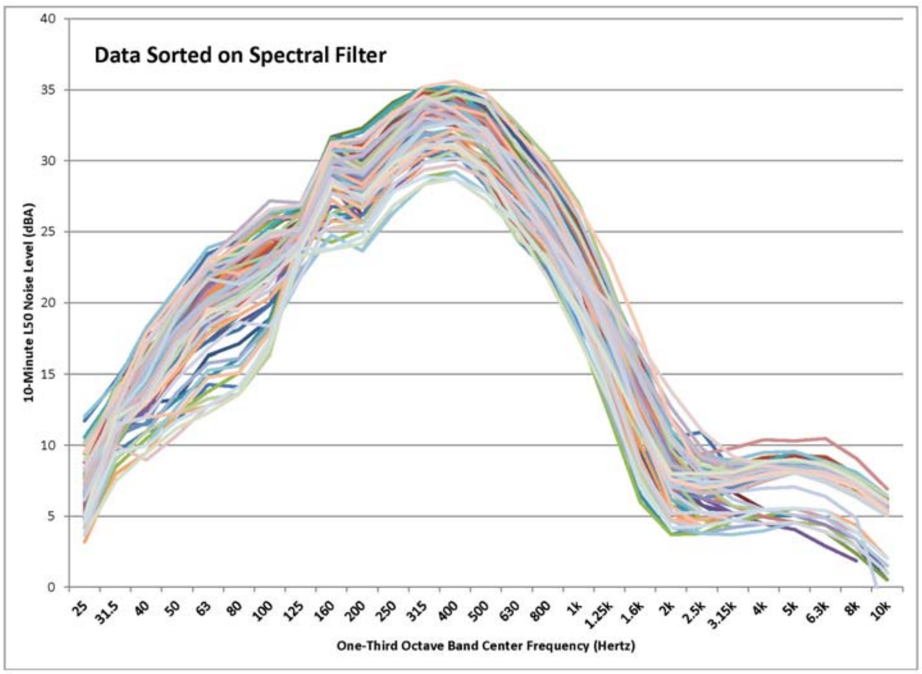

FIGURE 2. Spectral shape of data when sorted on Spectral Filter Number

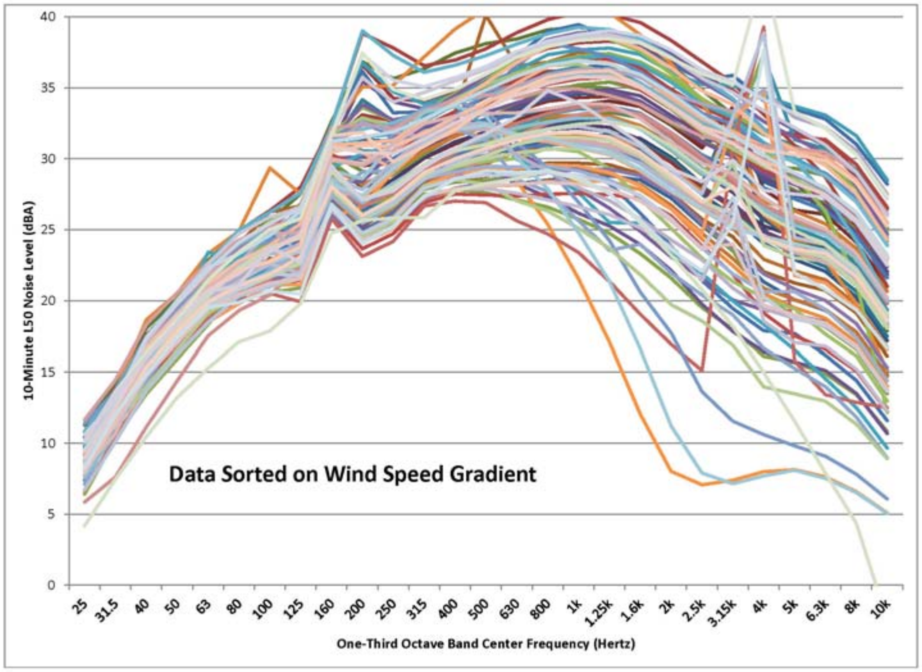

FIGURE 3. Spectral shape of data when sorted on wind speed at hub height minus wind speed at the ground

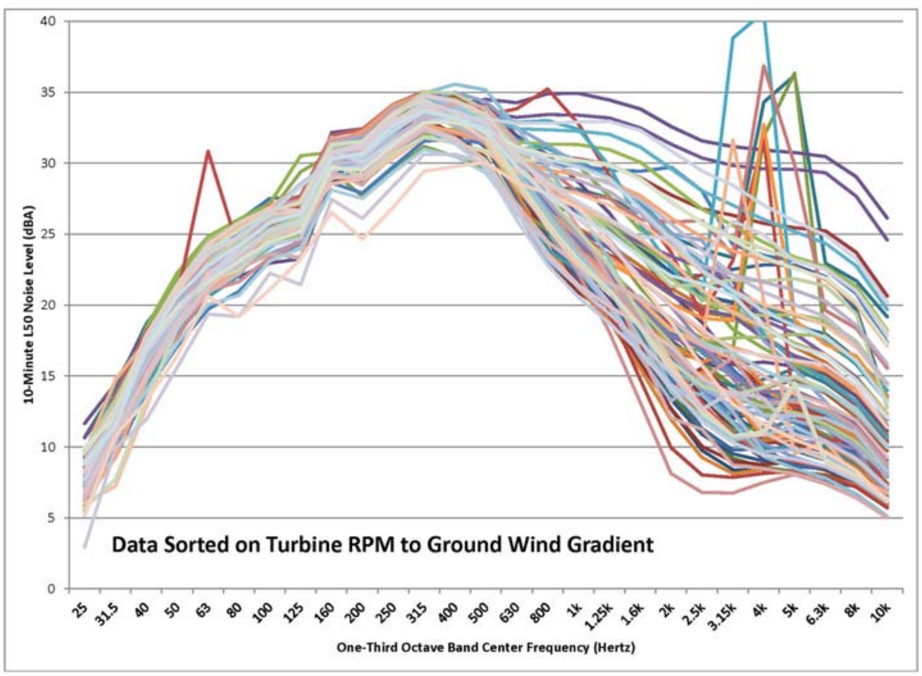

FIGURE 4. Spectral shape of data when sorted on rotor speed minus wind speed at the ground

MAXIMUM TURBINE NOISE LEVELS

The noise measurement survey was conducted over a six month period, from which five full months of valid data were obtained. This data set was reduced to include only the hours between 4:00 p.m. and 10:00 a.m., as it has been found that during the daytime hours there are rarely, if ever, conditions that would allow the turbines to be more than 10 dBA above the ambient. The resulting database is a collection of over 16,000 10-minute evening and nighttime samples. This data was sorted according to the SFN, and the values shown in Table 1 were determined.

Notice that the SFN trends consistently with the average noise level, rotor speed, and hub-height wind speed, and inversely with ground wind speed.

TABLE 1. Noise levels, turbine operations, and wind speeds versus Spectral Filter Number

SFN	Average Noise Level (dBA)	Maximum Noise Level (dBA)	Wind Speed at Ground (m/s)	Wind Speed at Hub-Height (m/s)	Rotor Speed (rpm)
17-16	40	42	1.5	6.7	16
15-14	39	43	1.5	6.7	15
13-12	38	43	1.6	6.1	14
11-10	36	43	1.6	5.8	13
9-8	35	43	1.7	5.3	12

AMBIENT SOUND LEVELS

As mentioned above, the ambient sound level of interest on this project is that which occurs over the range of atmospheric conditions under which the turbines would operate. Thus, simply taking the lowest measured ambient level is not appropriate. One method of achieving this is to look at times when the hub-height wind speed is just below and just above the speed at which the turbines begin to operate, which in this case is 3.5 m/s. A review of the measurements conducted when the hub-height wind speeds were 3.5 m/s ±1.0 m/s shows a range of 10-minute L_{50} levels of 22 to 45 dBA. The lowest level of 22 dBA occurred for only one 10 minute period during the entire six month survey. A minimum level of 26 dBA was more regularly observed. This level should not be compared to maximum turbine-on levels, however, because it occurs only when the turbines would just barely be operating. A more accurate method of determining the ambient sound level over a broader array of atmospheric conditions is to measure the ambient level with the entire turbine farm turned off. This was done on over 50 occasions, for 20 minutes per occasion. The range of ambient sound levels measured during these times was 26 to 40 dBA. During some of the times when the ambient was 26 dBA hub-height winds were strong enough to operate the turbines at near maximum conditions. Thus, there is the potential for a 16 dBA increase in ambient levels due to turbine operations.

COMPLIANCE WITH THE 10 dBA ABOVE AMBIENT LIMIT

Turbine-on noise levels range from the low 30's (dBA) to 42 or 43 dBA. Levels of 42 dBA are consistently produced. The range of turbine-off levels is 26 dBA to over 40 dBA. Thus, there is at least a 16 dBA difference between the loudest turbine levels and the lowest ambient levels that could occur during turbine operations. The shut-down testing referred to above has thus far yielded approximately six instances where the measured difference was greater than 10 dBA, with a maximum difference of 14 dBA. To date, turbines were turned off for testing when the average rotor speed was 16 rpm or greater (moderate to maximum operating conditions), the ground wind speed was 2.5 m/s or less, and the time of day was between 4:00 p.m. and 10:00 a.m. A review of the data has determined that only about one-third of the tests were conducted when there was a potential for exceedance based on the SFN. Often, ground winds would increase after test initiation, thus obscuring the potential for low ambient levels. On other occasions, despite low ground wind speeds, vegetation rustle was still present and little to no increase in the ambient was measured. Thus, using only the rotor speed and ground wind data does not sufficiently determine the times when a potential for exceeding the 10 dBA over ambient rule is occurring.

As part of testing to date, just prior to the full shut-downs the closest 10 turbines to the residence of concern were shut down for 20 minutes. This testing has consistently shown to reduce the 10-minute L_{50} by 3 to 4 dBA. Thus, given that the largest exceedance demonstrated to date is 14 dBA, and the limit is 10 dBA, this action would bring the project into compliance. The challenge is to be able to do this in "real time", and to a reasonable degree of accuracy.

"REAL-TIME" SPECTRAL FILTER COMPLIANCE SYSTEM

At the time of this writing, the project initiated a "real-time" spectral filter system that will direct turbine curtailment and shut down testing to those times when the turbines are the most dominant noise source in the environment, and thus the times when the turbines have the greatest potential to be more than 10 dBA above the ambient at that moment in time. Every ten minutes a data logger at the residence reads from the sound level meter the most recent 10-minute L_{50} one-third octave band spectrum, as well as the most recent 10-minute average of ground wind speed. The turbine farm control system has a radio link to the logger, combines the data with turbine operations information, and updates the Spectral Filter Number at the control center. When the SFN reaches the level at which analysis has shown the potential for non-compliance for a specified length of time, a full shutdown will be initiated as a test followed by the 10-turbine curtailment to ensure compliance.

With this system the difference between turbine-on and ambient levels will be measured at precisely the time when there is the greatest potential for exceeding the standard, and curtailment (turning off of 10 closest turbines) will also be directed at time of greatest potential for exceedance. Analysis of the resulting test data will eventually yield the SFN which forms the threshold for exceedance. Once this is determined, it will be possible to review the data measured to date and determine how often the standard is being exceeded. Given the length of the study, seasonal fluctuations will be evident. To date, seasonal changes have not drastically affected the maximum or minimum noise levels observed. However, it has been determined that, in general, the times of potential exceedance are from sunset to sundown, and in the summer the length of time in any given night that an exceedance might occur is longer than in the fall or winter.

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