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Noise Optimized Wind Park Operation

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Summary

The present paper provides an overview of operating schemes to maximize farm-level annual energy production in noise constrained environments.

First, a general methodology is presented at the single turbine level to design efficient noise reduced operation modes (NRO). In order to satisfy noise constraints with the highest possible energy yield, NRO modes are built using optimization procedures that combine both noise and power response surfaces. NRO's are designed for a single turbine and based on near-field noise data; as a consequence, they do not provide a direct solution to meet far-field noise limits.

Second, strategies are described to best combine these modes in the context of a wind farm. It is usually up to the farm operator to provide a site layout and operation that satisfy the local noise regulations. Typically, a single noise propagation simulation is carried out using the maximum noise emission of all turbines as input. Following this approach, a single NRO mode is attributed to each turbine across the farm. Obviously, this results in conservatism for situations outside this worst case.

More sophisticated wind farm operation schemes are possible, with higher energy yield. These schemes do take into account real-time changes in wind and ambient conditions in order to adapt the operation of each turbine and thus maximize the overall farm energy production. Such continuous adjustment of the farm operation can only be achieved by combining suitable control architecture with real-time inputs.

1. Introduction

Wind turbine noise represents one of the major obstacles to a more widespread use of wind energy today. As wind turbine rotors become larger and wind farms are located closer to residential areas, innovative approaches to sound reduction, low noise operation, and strategic siting methods can all be used together to provide wind farms that mutually satisfy the interests of operators and the communities that they serve. Nowadays manufacturers are able to provide hardware solutions that mitigate noise at the source in an efficient fashion, such as trailing edge serrations and low noise tip designs [Petitjean et al., Kinzie et al.]. In noise sensitive areas, however, these solutions may not be sufficient. A solid understanding of turbine operation and the impact of turbine siting is also necessary to properly control the observed sound at the receptor locations where farm operators are required to meet local regulations. Figure 1 illustrates the key components and opportunities for wind turbine sound generation starting at the turbine source and ending at the receptor.

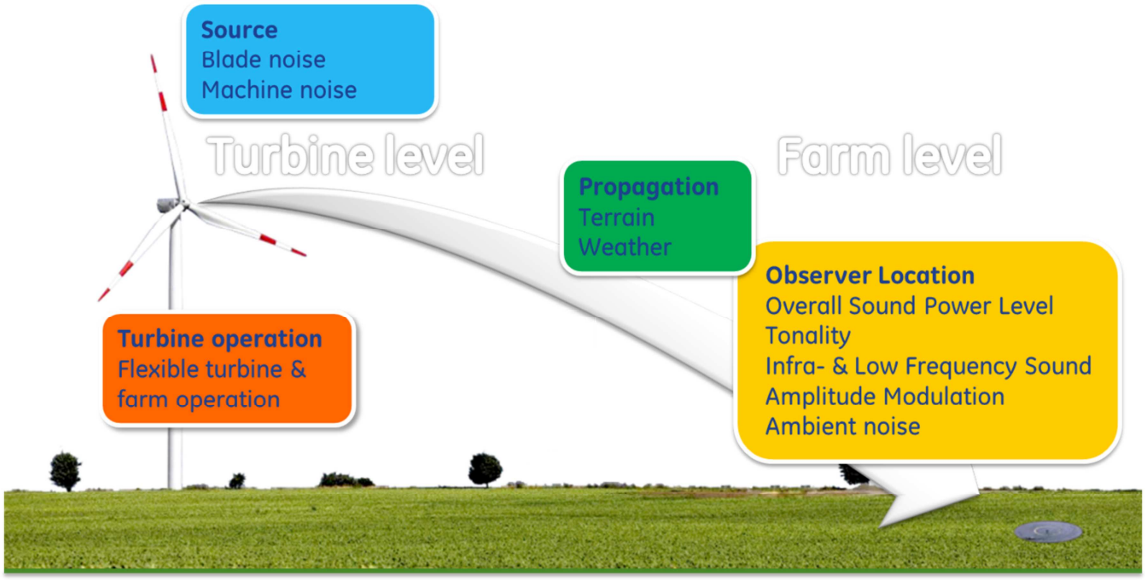

Figure 1. Illustration of key elements of wind turbine farm level sound

In rural, quiet areas (especially in regions where there are ambient based noise limits), it is often necessary to adapt the wind turbine operation as a whole to meet the noise requirements, for example in a certain wind speed range. For this purpose a general methodology is presented at the single turbine level to design efficient noise reduced operation modes (NRO). This approach allows to design turbine-specific modes of operation that provide incremental noise benefits (in steps of 0.5–1.0 dB) compared to normal operation. As a second step these modes must be adequately combined at the farm level in order to satisfy the noise constraints at the critical receptor locations around the farm and optimize energy production. Two strategies to achieve this goal are presented in this paper. Finally, these strategies are applied to an example wind farm to illustrate and compare their respective features and performance.

2. Noise optimized wind turbine operation

At the turbine level, it is generally true that during normal operation most operating parameters that drive towards higher power also drive towards higher noise. The challenge for the wind turbine manufacturer is thus to determine how to operate the turbine in a way that noise constraints are met with the highest possible power output. The response to this challenge is provided in the form of so-called Noise Reduced Operation (or NRO) modes; these modes are designed for a single turbine, based on noise measurements or predictions performed at the location prescribed by IEC standard 61400-11 [see Ref. 3] – i.e. typically 100-150m downwind of the turbine. As a consequence, NRO modes do not provide a direct solution to satisfy far-field noise limits at the various critical receptor locations identified around a wind farm, but it is their adequate combination that will help to meet this goal.

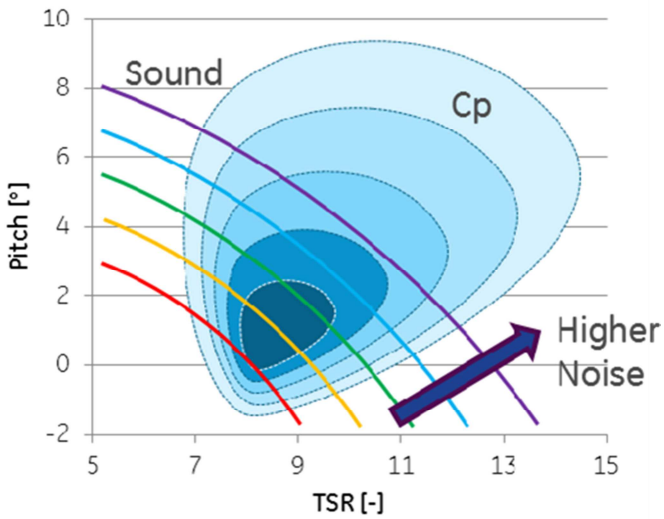

Figure 2. Conceptual response surfaces for turbine power coefficient (Cp) superimposed over sound contours.

For any given blade design, noise reduced operation can be achieved via an optimization procedure that combines a noise response surface (i.e. noise vs. turbine operation parameters) with the corresponding power performance response. Conceptual diagrams of these response surfaces are shown in Figure 2. The colored curved lines show lines of constant noise as a function of blade pitch and tip speed ratio (TSR) for a given rotational speed. In general, lower pitch values (i.e. higher blade angle-of-attack) and higher TSR (i.e. rotational speed) drive towards higher levels of noise. The blue contours indicate blade power coefficient (Cp) where darker shades indicate higher Cp values. While it is clear that the Cp contours show a maximum level at only one combination of pitch and TSR, it is also seen that for lower values of Cp there are multiple combinations of pitch and TSR that provide the same Cp level, but the noise is different at each value of pitch and TSR. Therefore, it is possible to find an optimum value of pitch and TSR where the turbine can operate at a given noise level while maximizing Cp.

In practice, such a procedure can be repeated multiple times to build a series of NRO modes. Each NRO mode is referred to by the noise reduction benefit it provides compared to the peak noise level in normal operation. For example, the peak noise level of the 'NRO -1' mode is 1 dB below the maximum noise emitted by the turbine in normal operation. These modes represent the critical building- blocks employed for noise optimized wind farm operation, as described in the following section.

3. Noise optimized wind farm operation

Once the turbine sound characteristics have been designed by the manufacturer, it is up to the farm operator to provide a site layout and operation that meets the local noise regulations. In practice, this works best as a partnership between the manufacturer, operator and acoustic consultants to maximize the output of the farm while meeting noise constraints. By judiciously selecting the right turbine configuration and operating modes, it is possible to optimize sound and power output without incurring unnecessary operating losses.

Typically, turbine configuration and operating modes are selected based on the worst situation, i.e. highest possible noise emission. A single noise propagation simulation is carried out using the maximum noise emission of all turbines within a farm as inputs; the noise levels at observer / residential locations are then derived as the sum of all individual contributions and are usually required to stay below a given limit. Following this approach, a single (fixed) NRO mode is attributed to each turbine across the farm. The approach will thus be referred to as 'single NRO control' in the remainder of the paper. Note that the NRO modes can vary from turbine to turbine, but they are independent from any time-varying parameters influencing the overall farm noise emission, such as wind speed, wind direction, air density or turbine shut down times for maintenance. Obviously, this results in conservatism for situations outside this worst case.

More sophisticated wind farm operation schemes are therefore possible, with higher energy yield. Repeated optimization runs performed with a large variety of inputs representative of the different conditions experienced within a farm (and not only worst-case conditions) can be used to determine the most appropriate distribution of NRO modes across the farm, which will both satisfy all noise constraints and maximize AEP. Combining appropriate control architecture with real-time inputs allows to continuously adjust the farm operation in a manner that accounts for conditions that influence the sound received at key receptor locations while meeting all noise constraints. This second approach will be referred to as 'optimized noise control' in the remainder of the paper.

4. Case study

4.1 Wind farm layout

For illustration purposes, both the 'single NRO control' and the 'optimized noise control' methods will now be applied to an imaginary wind park composed of 8 turbines with 82.5m rotor diameter, 1.5MW rated power and 106 dBA peak noise level. As far-field noise requirement, a single absolute limit of 43 dB LAeq has been

selected. This limit must be satisfied at 4 separate noise critical receptors, referred to as R1–4. The wind farm layout and the critical noise receptors are shown in Figure 3. The wind climate for the site is shown in Figure 4 in the form of a radar plot with Weibull shape, scale parameters and frequency as a function of wind direction. The frequency is an indication of the probability over a year (expressed as %) that the wind blows in a particular direction.

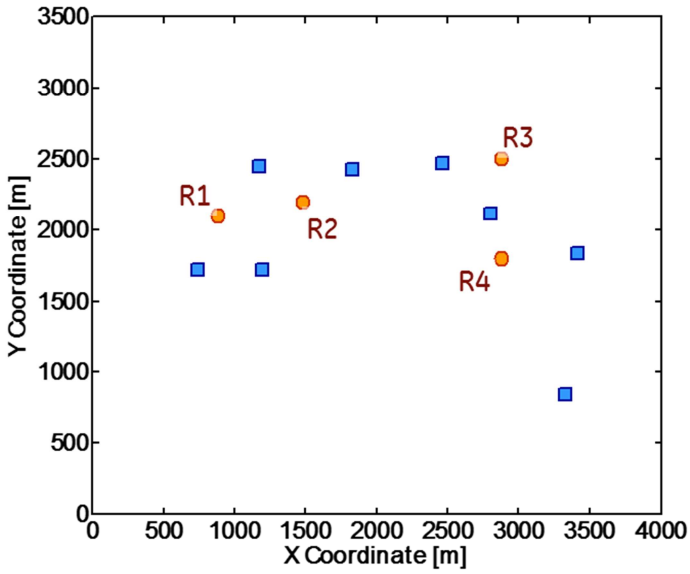

Figure 3. Wind farm layout and critical noise receptor points used in case study

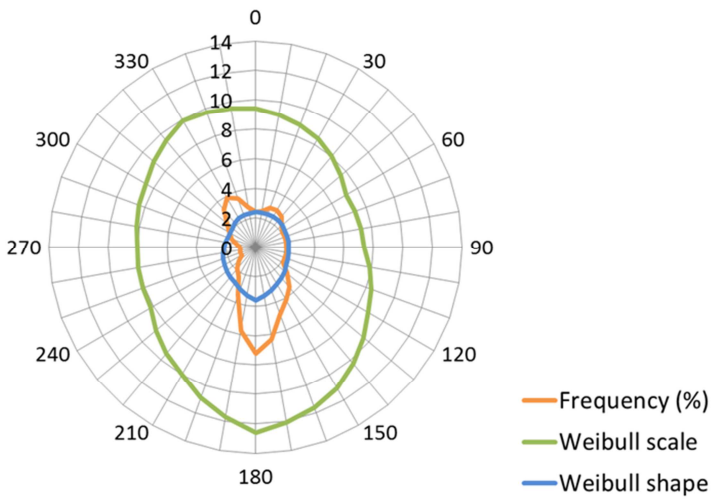

Figure 4. Wind climate data for the park layout shown in Figure 3.

As a first step, far-field noise calculations are carried out using the ISO 9613-2 noise model [see Ref. 4] and assuming maximum noise emission from all wind turbines to determine the peak noise levels at each critical noise receptor point. These levels are shown in Table 1. It appears that the 43 dB noise limit is exceeded

for all receptors, with violations between 3–5 dB. Therefore an appropriate noise curtailment scheme must be designed for this park. The park-level AEP in this baseline configuration is also calculated and will be used as reference (i.e. 100%) to assess the % losses incurred with the curtailment schemes in place.

Table 1. Peak noise levels and violations assuming maximum noise emission.

Receptor	**Predicted Max. LAeq** [dBA]	**Constraint** [dBA]	**Noise Violation**
R1	47.8	43.0	4.8
R2	48.1	43.0	5.1
R3	46.2	43.0	3.2
R4	46.5	43.0	3.5

4.2 Single NRO control

As a second step the single NRO control method is applied, which consists in identifying the best distribution of NRO modes that provides mitigation for the worst-case noise emission scenario. The identified solution is shown in Figure 5: the 8 turbines are attributed NRO modes that vary from -3.5 to -5.5 (i.e. peak noise level emissions reduced to 102.5 dB and 100.5 dB). With this curtailment scheme the 43 dB noise limit is now met at each receptor point (as can be seen from the location of the 43 dB noise contour line in Fig. 5). As an example, the power curves for normal (baseline) operation and NRO mode -5.5 are shown in Figure 6. These power curves are used to calculate the penalty in energy production, which turns out to be rather significant; the energy yield drops to 82.0% compared to the baseline configuration, which represents a loss of AEP of 18%.

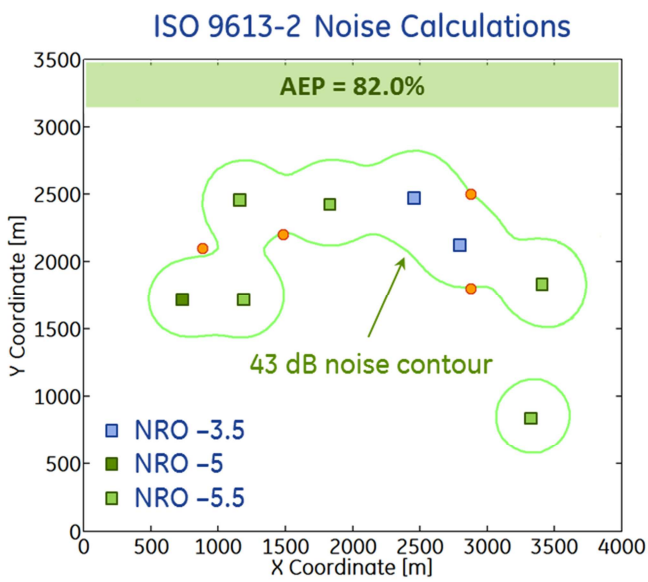

Figure 5. 43 dB noise contour line with single NRO control

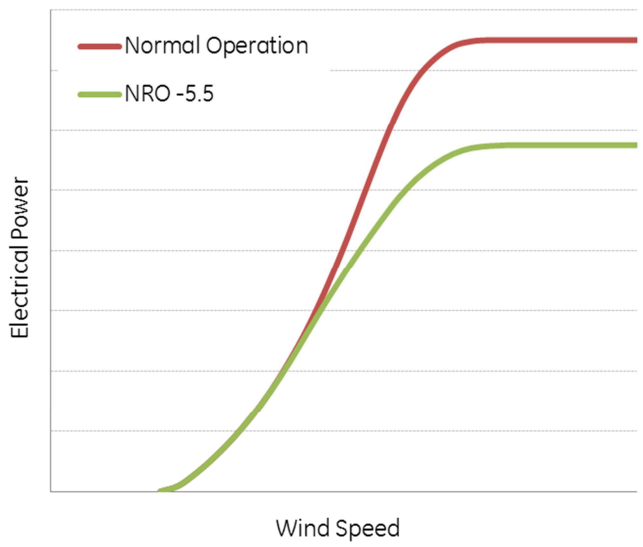

Figure 6. Representative power curves for normal operation and NRO mode -5.5

4.3 Optimized noise control

Finally, the optimized noise control method is applied, which consists in repeated optimization runs in order to identify the best possible distribution of NRO modes as a function of wind speed and wind direction. In this case, the individual power curves become a function of both wind speed and wind direction, as shown in Figure 7 for only one of the 8 turbines in the park selected for the case study. It is particularly interesting to observe that for 240° wind direction the optimized solution falls very close to the worst-case solution (NRO -5.5). Nevertheless, for other wind directions a less strict noise curtailment is possible, which will lead to higher energy yield.

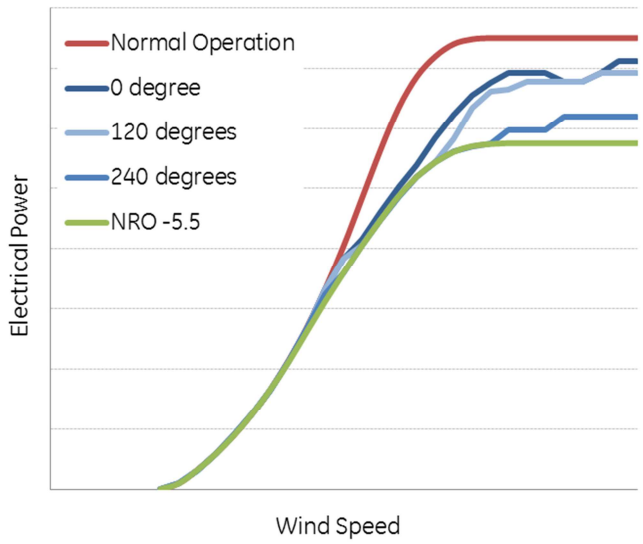

Figure 7. Representative power curves for normal operation, NRO mode -5.5, and optimized noise control (wind direction-dependent power curves)

It is important to note that when considering the impact of wind direction, it becomes possible to specifically account for such phenomena as wind turbine noise directivity, i.e. the fact that a turbine does not radiate noise evenly in all directions. This directivity effect was accounted for in the present study using the function proposed by [Oerlemans et al.]. It would also be possible to include more complex noise propagation models than ISO 9613-2, which can differentiate between upwind / downwind noise propagation – e.g. Concawe, Harmonoise, or NORD2000. This, however, was not done in the present study.

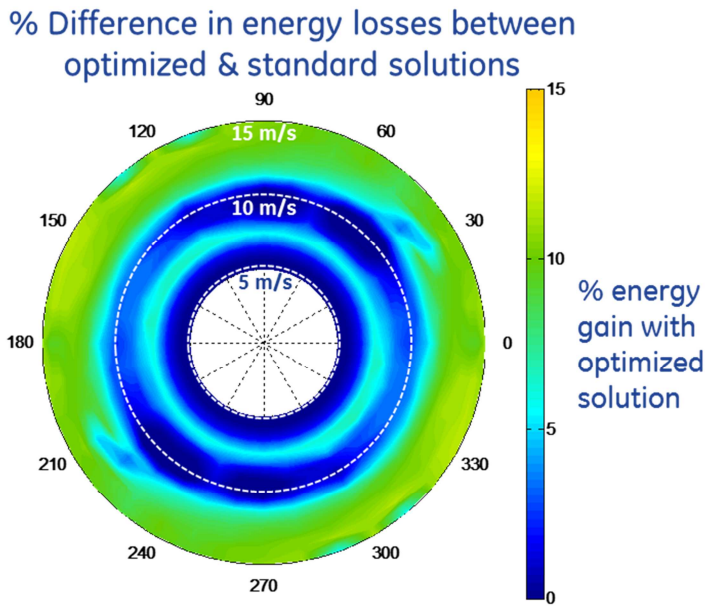

Figure 8. % difference in energy losses between the optimized and single NRO control strategies, plotted as a function of wind speed (radial direction) and wind direction (azimuthal direction).

As a last step the energy yield is calculated for the optimized noise control scheme. This computation is somewhat intricate, as it imposes to use different combinations of the standard NRO power curves as a function of wind speed and wind direction, following the results of the optimization routine. But the energy gain is rather important, as the overall AEP jumps to 88.1%, which represents roughly a 12% loss compared to the baseline configuration, and a 6% increase compared to the single NRO control. To illustrate the specific range of wind speeds and directions that allow a less strict curtailment and consequently an increase in energy capture, the difference between the optimized and single NRO control strategies is plotted in Figure 8. Obviously the increase in energy capture strongly varies with wind speed and direction, and is directly influenced by the wind turbine noise signature, the applied directivity function, and the geographical location of the receptor points.

5. Conclusions

An optimized noise control strategy that provides the flexibility to continuously adjust the farm operation depending on wind speed and wind direction offers clear AEP benefits in noise constraint environments compared to standard noise reduced operations.

The system can make use of the fact that wind turbines have a specific acoustic directivity, which is usually not leveraged when fixed NRO modes are attributed to each turbine across the farm. Within even more sophisticated solutions, the system could take noise propagation effects into account, which would lead to differences in noise levels for upwind and downwind directions in certain wind shear conditions.

Finally, for sites with specific, ambient-based noise limits the optimized noise control strategy is flexible enough to allow customized farm operation that is perfectly adapted to the local conditions.

References

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