Acoustic Control of Wind Farms

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Abstract

Finer acoustic control of wind farms has become essential both to optimise electric production and ensure inhabitant tranquillity regarding the legal acoustic criteria. Current curtailment strategies are based on acoustic measurements done on short periods of time and online control is based on wind parameters only. This leads both to economic losses and acoustic discomfort. For those reasons, we present a new approach to control wind farms with a control model based on real-time source separation. We use a source separation system to provide estimates of the noise level imputed to the wind turbines and the noise level imputed to the other sound sources. Our work focuses on designing a control model. We have proposed a first algorithm that was tested on real data and that will be ground tested soon (2016). The control model is based on a look-up table and on a discrete optimisation algorithm to compute curtailment plans. For the validation part, we experimented our control model on the data provided by three acoustic measurement campaigns. The results show that an electric gain is always possible without any acoustic degradation compared to the current strategies.

Key words - acoustic annoyance, non linear discrete optimisation, branch and bound algorithm, audio source separation.

1 Introduction

For the past few years, preventing people living around wind farms from noise pollution has been one of the main concerns of numerous countries around the world.

All countries that pay attention to acoustic annoyance use either the total ambient noise level or a criterion called acoustical emergence to measure the acoustic annoyance and impose maximal admissible values. However, the current curtailment strategies slightly differ from one country to another. In this article, we compare our system to the current curtailment acoustic strategy in France. It should be noted however that the algorithm can be adapted for any country. The acoustic emergence is fundamentally the acoustic energy gain brought by the wind turbines to the background noise perceived near housings around the farms. The acoustic control is difficult since the ambient noise level and emergence rapidly evolve with weather and noise conditions.

Currently, pre-studies are made to establish the curtailment plan that must be set in the wind farm control system (SCADA). They consist in 2 week measurement campaigns where the wind turbines are periodically turned off. The process however induces high uncertainties which are handled by considering worst case scenarios. This leads to great economic losses since the electric production is highly correlated to the noise emission.

For that reason, a finer, real-time control of the noise pollution is required to optimise the economic gain. To address this, **VENATHEC SAS** (France) have imagined and developed a new control system called **iEAR** based on real-time acoustic measurements and source separation. The design of the algorithm has raised challenges in the fields of audio source separation and control. We have focused our work on the control model and we present in this article a first algorithm and the first experiments on that issue.

The control algorithm is based on the manufacturer's electric and acoustic power curves and on simulated propagation data stored in a look-up table. The instantaneous curtailment plans are computed by solving an optimisation problem every 10 minutes which can be written as a *convex non linear discrete programming problem* [1, 2, 3] or equivalently a *non-linear knapsack problem* [4, 5]. We developed our own adapted *branch and bound* algorithm [6, 7] to solve this problem. *Branch and bound algorithms* are indeed commonly used to solve that type of problems along with *outer-approximation* [8], *generalized benders decomposition* [9], *extended cutting plane* [10], *LP/NLP based Branch-and-Bound* [11] and hybrid algorithms.

The general control problem is described in Section 2. The proposed model is then presented in Section 3 and the experiments in Section 4. Finally, the conclusion and the perspectives are given in Section 5.

2 Control problem

2.1 Acoustic criteria

The goal is to optimise the electric production while ensuring that the acoustic constraints are respected for each housing around the farm.

Based on the graphical representation of the acoustic power levels in Figure 1, the acoustic constraints can be formulated as follows:

$$\forall j \in \{1, .., J\},\ e_j < S_{e,o} \text{ or } b_j < S_{s,o} \qquad (1)$$

where $S_{e,o}$ is the emergence threshold, and $S_{s,o}$ is the ambient noise threshold. Here J denotes the number of measurement points considered and j one of these measurement points. b_j stands for the total ambient noise in decibels. e_j denotes the emergence which is the acoustic power gain in decibels brought by the wind turbines on the environment. It is defined as follows:

$$e_j = b_j - r_j \qquad (2)$$

where r_j is the background level (also called residual noise level).

2.2 Operating modes

The tool provided to reduce the wind turbines' noise emission is a discrete set of smart operating modes that allows the wind farms owner to lower the acoustic emission at the expense of some economic loss. The instantaneous electric production and the acoustic production of a given wind turbine depend both on the wind speed and on the chosen operating modes. In the following, $\mathcal{C} = \{1, 2, ..., C\}$ denotes the set of integers that represents the C operating modes available for the wind turbines on a farm. The operating mode of each wind turbine can be chosen independently. We also use f_v to denote the concave function that gives the electric power from the acoustic power expressed on a linear scale ($\mathrm{W/m^2}$) for a given wind speed v. This notation is used in the description of the optimisation problem in Section 3.1.

2.3 Scientific challenge and current strategy

The inherent difficulty about acoustic control of wind farms is that the acoustic emergence and the ambient noise depend both on the residual noise level (i.e, the acoustic noise power due to other sources than wind turbines) and on the particular noise level (i.e, the noise power due to the wind turbines). This double dependency makes the acoustic control challenging:

- The residual noise around a residential area strongly varies over time, even within a single day. Yet, it is not possible to measure the residual noise directly and

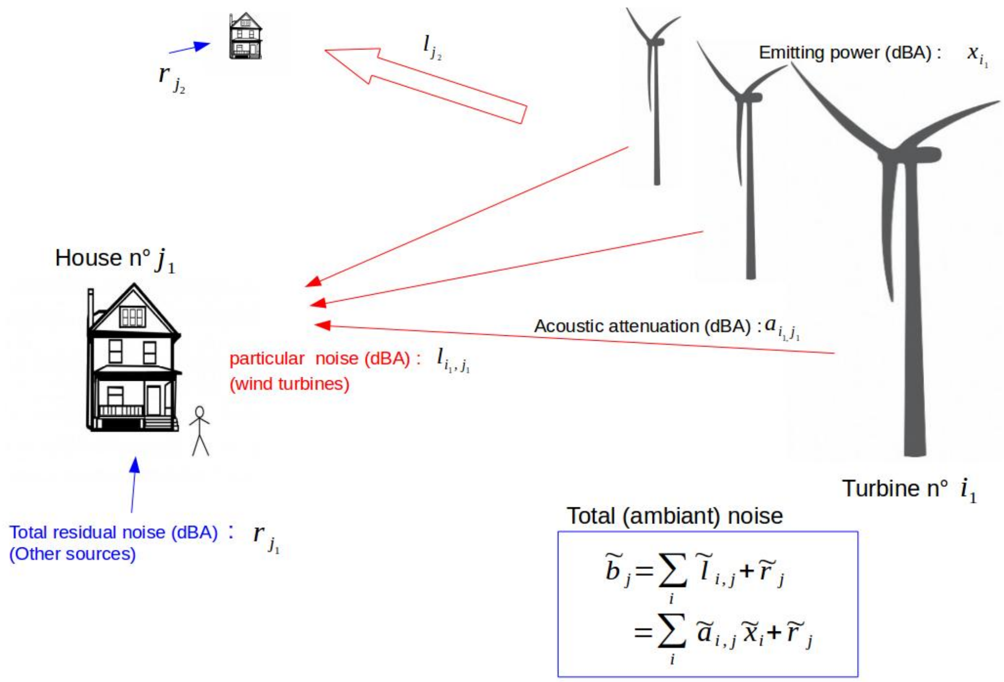

Figure 1: *Graphical representation of the acoustic power levels*

it is impossible to explain these variations with a physical model.

- The particular noise depends on the current acoustic emission and on the energy loss due to the acoustic propagation which strongly varies with the weather conditions. Theoretically, they can be both computed easily:
  - The current emission can be computed from the current operating modes and measured wind speed given the manufacturer's power curves.
  - The propagation energy loss can be simulated using a physical model with ray tracing but changes quickly with the weather conditions.

In France, two weeks measurement campaigns are performed to design the curtailment plans. The wind turbines are periodically stopped and the difference between the measured ambient levels (with the turbines on) and the measured residual noise levels (with the turbines off) gives an estimate of the acoustical emergence and allows acoustic engineers to design curtailment plans. In order to cope with the variability of the ambient level and of the acoustic emergence, the measurements are indeed classified by weather conditions and noise conditions (wind speed, wind direction, period of the day, *etc.*). The emergence and the ambient level are considered constant in each class. Yet, as great variability still exist on the system parameters, worst case scenarios are considered in current acoustic studies. Figure 2 gives an example of 32 homogeneous classes based on wind speed, angular sectors of wind directions, and period of the day.

Because of this process, the legal criterion in France was slightly modified and the acoustic constraints are then written as follows:

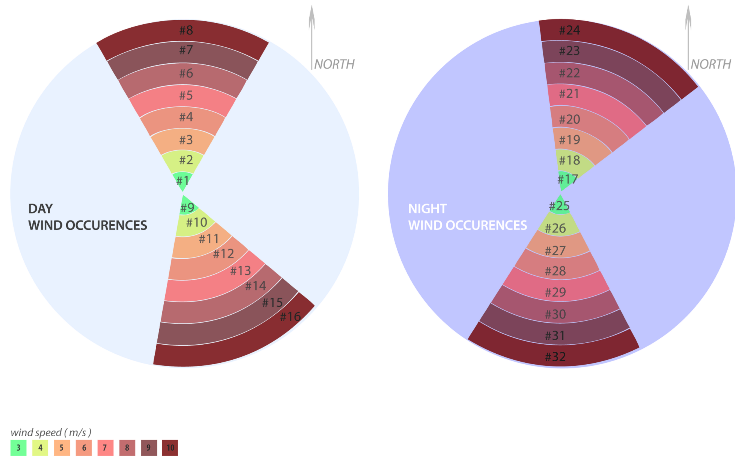

Figure 2: *Example of partition of the state parameters into 32 homogeneous classes.*

$$
\begin{aligned}
&\forall o \in \mathcal{O}, \forall j \in \{1, ..., J\}, \\
&\text{median}_o(b_j) - \text{median}_o(r_j) < S_{e,o} \\
&\text{or median}_o(b_j) < S_{s,o}
\end{aligned} \tag{3}
$$

where $\mathcal{O}$ denotes the set of homogeneous classes and o is one homogeneous class. This criterion uses the median of the measurements in each homogeneous class to take the remaining variability into account. This approximation was also developed as it is impossible to measure the emergence directly and curtailment plans are computed with that criterion.
However, the current process is too coarse:

- The measurement campaign is representative of the noise environment for a short period of time. In practice, the noise environment evolves over the course of the year. For instance, the residual noise is usually higher in summer than in winter.
- Moreover, even during the measurement campaign, the residual noise level present a high variability.

These last two reasons induce economic losses as worst case scenarios are considered.

3 Proposed model

The control of the particular noise level can be handled by a physical model. We chose to use the manufacturer's power curves and simulated propagation data stored in a look-up table. However, the measurement and the variability of the residual noise level require the design of a new control system. Because of the novelty of this field of research, we decided to design first an **instantaneous and deterministic model** based on the approximation usually made for the problem of allocating acoustic operating modes.
The first control algorithm we designed is based on the following hypotheses:

- We considered no lack of reactivity of the wind turbines.
- We considered no uncertainties on the simulation data.
- For the calculations, we developed the algorithm to optimise the electric power under any maximal value of instantaneous particular noise. This allows us to fulfil the instantaneous emergence (equation 1) or even the median criteria used in France (equation 3) with a specific control method.

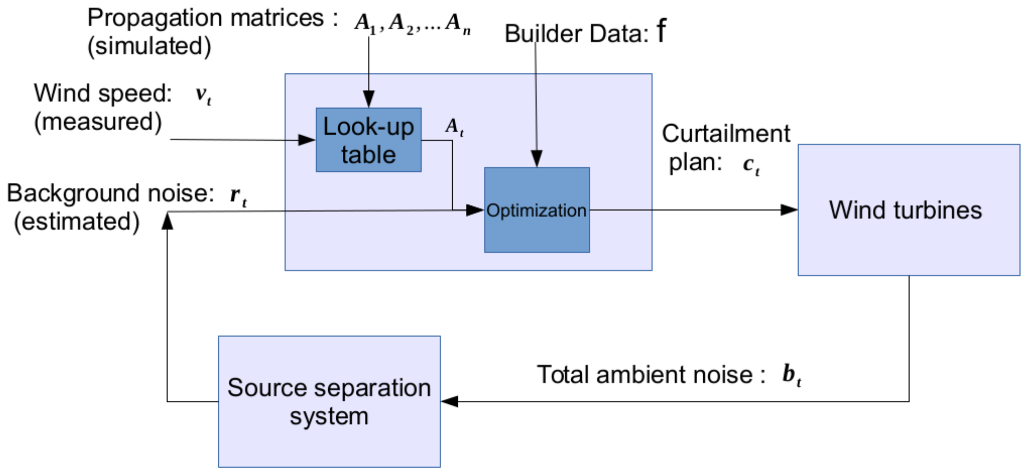

Figure 3: *General operation scheme of the instantaneous and deterministic system*

Figure 3 gives the general operation scheme of the first model.

The wind speed and the wind direction measured at the turbine hub and the residual power estimated by the source separation system are the input data. From the wind data, the corresponding acoustic power attenuation matrix is retrieved and the optimisation is then computed with the power curves to build the curtailment strategy to be applied for the next 10 minutes.

3.1 Optimisation problem

We have shown that the deterministic and instantaneous assumptions allow us to write the problem as a *non linear convex discrete programming problem* or equivalently as a *nonlinear knapsack problem* [12, 4]:

$$\begin{cases} \max_{\tilde{\mathbf{x}} \in (\tilde{\mathfrak{x}}(\mathcal{C})^I} \sum_{i=1}^{I} \mathfrak{f}_v(\tilde{x}_i) \\ \\ \tilde{\mathbf{A}}^T \tilde{\mathbf{x}} \leq \mathbf{q} \end{cases} \tag{4}$$

where I is the number of wind turbines, $\tilde{\mathbf{x}}$ is the $I \times 1$ vector of emission power of the wind turbines of the farms and whose values are chosen in the discrete set of acoustic emission power denoted by $\tilde{\mathfrak{x}}(\mathcal{C})^I$. $\mathfrak{f}_v$ is the function that gives the instantaneous electric production and $\tilde{\mathbf{A}}^T$ is the matrix of acoustic power attenuation due to propagation. $\mathbf{q}$ is the $J \times 1$ vector that specifies maximal admissible values of particular noise at each measurement point j.

Note that this formulation is very general and our algorithm can optimise the instantaneous electric production under any maximal admissible values of particular noise.

We solved the problem with an adapted *branch and bound algorithm*. *Branch and bound* algorithms are optimisation methods based on a tree structure to represent the admissible[1] solutions and on a browse them efficiently using the "divide an conquer principle". Each node is labelled with an upper bound of the objective function. A each iteration, a new solution is found thanks to the value of the former solution. To illustrate the principle, Figure 4 gives an intuitive example of one iteration of the de-

[1] values that fulfil the constraints

veloped algorithm:

- We suppose that we already have a solution achieving a power of 2000 kW at the beginning of the iteration.
- Usually a step is done simply by taking the following node.
- When a node with a lower bound is browsed, the current branch is erased and the algorithm backtracks as it is pointless to browse it. Indeed, we are sure that it is not possible to find a better solution than the one we already have among the leaves it leads to.
- When a new leaf of the tree is reached, we obtain a new solution with a better objective value (2100 kW here). The algorithm finishes when all the branches have been either browsed or erased.

Note that the bound of each node is obtained by solving a continuous relaxation problem solved with an adapted gradient algorithm.
We also initialise our algorithm with the solution obtained from a greedy heuristic inspired by an algorithm used in the field of acoustics to accelerate convergence to the optimal solution.

3.2 Handling the median criterion

The proposed algorithm can optimise under any maximal admissible values (see Section 3.1), and one could choose to limit the instantaneous acoustic criterion at each time. However, in the studied cases, the curtailment plans were computed from medians of the particular and residual noise over time. For that reason, it appears that fulfilling the instantaneous criterion (equation 1) may induce economic gain loss in some cases (see 4). To remedy this, we had to adapt the instantaneous algorithm in order to fulfil the median emergence criteria used in France by comparing the obtained result with the static strategy, *i.e* the curtailment plans currently used on the wind farm. Figure 5 illustrates the algorithm used eventually. This adaptation allows the criterion employed in France to be fulfilled with a consistent economic gain compared to the static strategy (see Section 4).

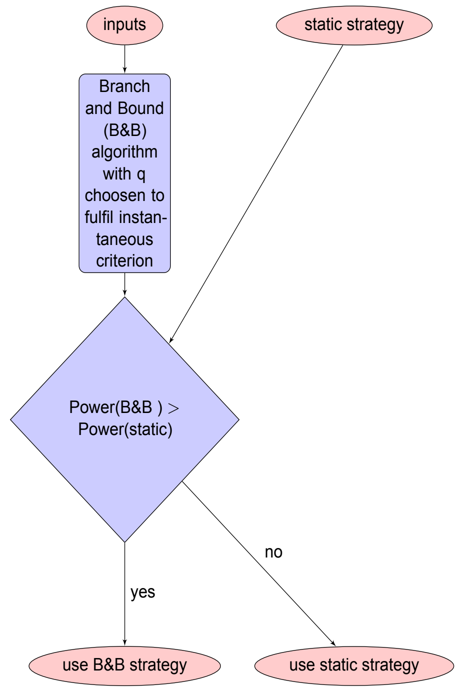

Figure 5: *General scheme of the optimisation unit handling the median criterion (equation 3.*

4 Experiments and results

We tested our algorithm on real data from 3 different wind farms using field measurements for the residual acoustic levels, acoustic simulations for the propagation data, and the manufacturer's curves. The algorithm is to be field tested before the end of next year (2016).

We experimentally verified that the branch and bound algorithm yields most of the time the optimal result (98,5% of the 1210 test cases). Then, we simulated the acoustical control with the acoustical data coming from 3 wind farms. The detailed results are given in Figures 6 and 7.

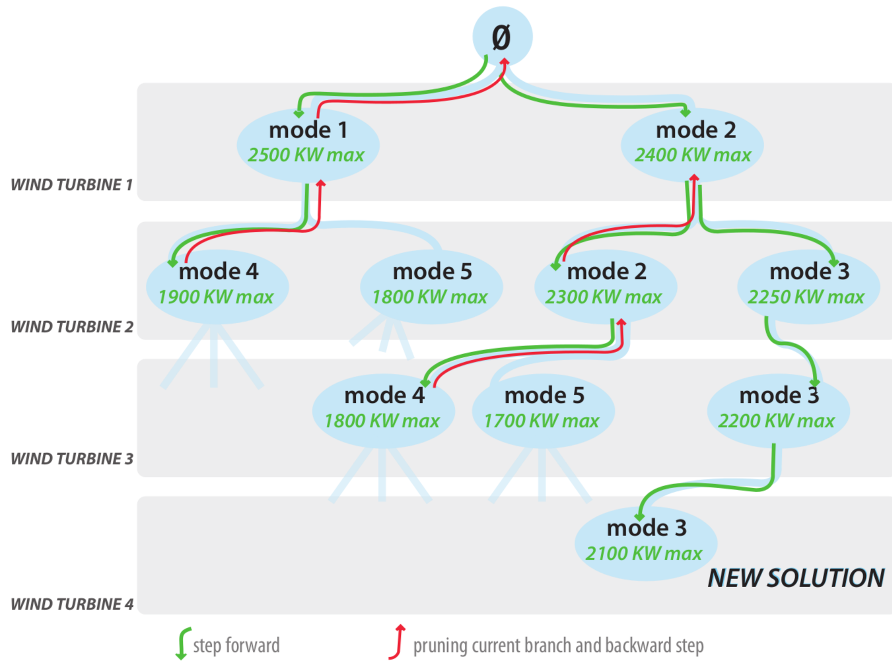

Figure 4: *Example of iteration for the branch and bound algorithm for a starting solution of 2000 kW.*

Production loss (%) compared to full-power	wind farm 1		wind farm 2		wind farm 3	
	day	night	day	night	day	night
Full-power Strategy	0	0	0	0	0	0
Static strategy	2.2	42.4	0	63.6	0	0
Instantaneous criterion control	9.2	34.4	3.8	56.3	0	1.2
Median criterion control	1.4	30.7	0	53.6	0	0

Figure 6: *Production losses compared to full-power operation*

Acoustic excesses (% of time)	wind farm 1		wind farm 2		wind farm 3	
	day	night	day	night	day	night
Full-power strategy	39	91	1	100	0	1
Static strategy	30	33	1	31	0	1
Instantaneous criterion control	0	4	0	1	0	0
Median criterion control	30	31	1	31	0	1

Figure 7: *Proportion of acoustic excesses over time (in percent of the full duration)*

5 Conclusions

In this article, we presented a new system for acoustic control based on source separation. Specifically, we have presented a control method that appears both easy to implement and that can be adapted to specific law of each country. The economic gain of such a system depends on the law governing the usual curtailment plan design. in the French case, special precautions must be taken to ensure a systematic economic gain.
In the future we will seek to refine with more general hypothesis:

- Concerning the wind turbine reactivity, our approximation is acceptable since the reactivity related to switching from an operating mode to another is often very small. In particular, this is verified for the wind turbines that will be used for field testing. However, a more general problem can be formulated using short-term wind predictions [13] and dynamic programming [14].
- The particular noise is an acceptable model for the power curves and the propagation models are based on worst case scenarios. However, recalibration of the acoustic power curves/propagation data

and the remaining uncertainties will be considered. Note also that power curve estimation methods may be used instead of manufacturer's power curves to improve accuracy. On that matter, several power curve estimation methods were recently compared by Lydia and *al* [15] and by Schlechtingen and *al* [16].

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References

[1] Claudia D'Ambrosio and Andrea Lodi. Mixed integer nonlinear programming tools: a practical overview. *4OR*, 9(4):329--349, 2011.

[2] Pierre Bonami, Mustafa Kilinç, and Jeff Linderoth. Algorithms and software for convex mixed integer nonlinear programs. In *Mixed integer nonlinear programming*, pages 1--39. Springer, 2012.

[3] Samuel Burer and Adam N. Letchford. Non-convex mixed-integer nonlinear programming: a survey. *Surveys in Operations Research and Management Science*, 17(2):97--106, 2012.

[4] Dorit S. Hochbaum. A nonlinear knapsack problem. *Operations Research Letters*, 17(3):103--110, 1995.

[5] Kamlesh Mathur, Harvey M Salkin, and Susumu Morito. A branch and search algorithm for a class of nonlinear knapsack problems. *Operations Research Letters*, 2(4):155--160, 1983.

[6] Michel Sakarovitch. *Optimisation combinatoire: Programmation discrète*, volume 2. Editions Hermann, 1984.

[7] Jacques Teghem. La recherche opérationnelle tome 1: Les méthodes d'optimisation. 2012.

[8] Marco A Duran and Ignacio E Grossmann. An outer-approximation algorithm for a class of mixed-integer nonlinear programs. *Mathematical programming*, 36(3):307--339, 1986.

[9] Arthur M Geoffrion. Generalized benders decomposition. *Journal of optimization theory and applications*, 10(4):237--260, 1972.

[10] Tapio Westerlund and Frank Pettersson. An extended cutting plane method for solving convex minlp problems. *Computers & Chemical Engineering*, 19:131--136, 1995.

[11] Ignacio Quesada and Ignacio E Grossmann. An lp/nlp based branch and bound algorithm for convex minlp optimization problems. *Computers & chemical engineering*, 16(10):937--947, 1992.

[12] Stephen Boyd and Lieven Vandenberghe. *Convex optimization*. Cambridge university press, 2009.

[13] Gregor Giebel, Richard Brownsword, George Kariniotakis, Michael Denhard, and Caroline Draxl. The state-of-the-art in short-term prediction of wind power: A literature overview. Technical report, ANEMOS. plus, 2011.

[14] Dimitri P. Bertsekas. *Dynamic Programming: Deterministic and Stochastic Models*. Academic Press, 1976.

[15] M. Lydia, Sahoo Subhendu Kumar, G. Edwin Prem Kumar, and A. Immanuel Selvakumar. Advanced algorithms for wind turbine power curve modeling. *Sustainable Energy, IEEE Transactions on*, 4(3):827--835, 2013.

[16] Meik Schlechtingen, Ilmar Ferreira Santos, and Sofiane Achiche. Using data-mining approaches for wind turbine power curve monitoring: a comparative study. *Sustainable Energy, IEEE Transactions on*, 4(3):671--679, 2013.