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Executive Summary of the Thesis

Combining yaw redirection and static axial induction in a ultimate-load-constrained wind farm control

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

Author: Federico Isella

Advisor: Prof. Alessandro Croce

Co-advisor: Prof. Stefano Cacciola

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1. Introduction

The wind energy industry is moving toward larger and more densely populated wind farms to minimize the cost of installation and infrastructure. The issue with pursuing this strategy is that numerous turbines close to each other can interact in a decremental way in terms of power production. In fact, as the wind direction shifts, it is inevitable that at some point, two or more turbines will be one in the wake of another. This phenomenon is known and unavoidable and can lead to losses of up to 23% of the total power produced [1]. This sensible loss of efficiency makes the research of strategy to mitigate this effect a very active field of sturdy. The strategies employed to improve the efficiency of a wind farm are called wind farm control techniques; they are a collection of techniques operated by the farm control system that aims to find a control law applicable to the farm to maximize overall power production.

2. Wind farm control techniques

These techniques work by looking for a configuration that maximizes the power produced by the whole farm, not the one that makes every single turbine at its higher power output.

2.1. Wake Redirection

Wake redirection aims at reaching this goal by steering the upwind turbines moving the wake further away from the rotor of the downwind ones. Due to the conservation of momentum law, the wake also changes direction when changing the orientation of the operational plane of a turbine. The downside of this strategy is that the steered turbine operates at lower power and may experience higher structural loads than it is rated for[2, 3].

2.2. Axial induction control

Another control strategy used to maximize power production is axial induction control. This strategy acts by artificially derating the turbine it is applied on, making it operate at lower power than what it is rated for. This process results in the wake being more energetic, and the downwind turbines operate much better and can compensate for the lost power. While this strategy offers modest power increments compared to the wake redirection, it shows a decrease in structural loads compared to the uncontrolled case [2, 3].

3. Wind farm control formulation

This thesis studies a strategy featuring the combination of these two techniques; this hybrid approach looks for the best combination of yaw angle and derating amount to keep the loads equal to the one experienced in standard operating conditions.

3.1. Wind farm model

Thanks to work done by previous studies at Politecnico di Milano [2, 3], the structural loads as a function of derating and yaw have already been computed. The turbine for which this process has been carried out is the DTU 10MW [4]; this machine is inspired by the NREL 5 MW [5] and is used for research applications. This model has never, nor was it designed to be ever manufactured. Its scope is to serve as a research tool, and it achieves this by featuring state-of-the-art design elements while having all components open source. This allows researchers worldwide to use this design as a meaningful benchmark for their studies.

3.2. Constraint formulation

By performing most of the aeroelastic simulation required for the certification of a wind turbine for each combination of yaw and derating, it is possible to build a database of the loads registered. From these results, a curve that links the derating level and yaw angle can be computed. This curve describes the necessary derating to maintain the loads equal to the one registered in the 0° yaw case but for all yaw angles. This curve is called the constraint curve and is in fig. 1, representing the structural limitation that must be considered when optimizing power production [2, 3].

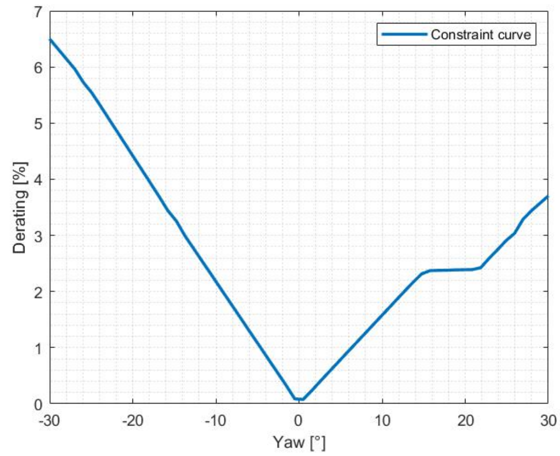

Figure 1: Constraint curve, from Dadda G. [2]

3.3. Definition of the optimization strategies

This thesis uses three different power optimization strategies to compare and contextualize the results obtained.
The first strategy implemented is the unconstrained yaw-only optimization; as suggested by the name, for this problem, it is considered only the yaw angle as a variable, and the derating with no derating. While this strategy is not compliant with the constraints, it represents the best-case scenario, and this result is often the maximum possible output obtainable by the wind farm control.
The second strategy is called *suboptimal yaw+derating optimization* and relies on starting from the yaw-only result and making it compliant with the constraint curve. In practical terms, this means building a solution constituted by the optimal yaw-only result as the yaw angle and as the derating the value of the constraint curve for that yaw angle.
The third and most important strategy is a *constrained yaw+derating optimization*. This technique consists of the solution of a two-variable constrained optimization problem; the variables are yaw and derating, while the objective function is the power produced by the farm. The solution to this problem is the combination of yaw and derating that produces the highest amount of power while complying to the structural constraints of the problem.

3.4. Simulation software

The program used for simulating the behavior of the farm and its power output is FLORIS. This software relies on engineering models of the wake and flow field to simulate the interaction between multiple turbines in a farm.

3.5. Simulation parameters

Four parameters have been defined to simulate a wide array of operating conditions: wind speed, rotor offset, turbulence intensity, and impingement. Respectively they represent the speed of the incoming flow,the distance between the turbines along the flow, the level of turbulence, and the overlap between the wake and the downstream turbine. The following set of the parameter has been simulated: Offset = [3 4 5 6 7] D, Wind Speed = [7 10 11.4 12 12.5 13 14] m/s, Impingement = [-1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1], TI = [0.02 0.06 0.1]. This set leads to a total of 945 combinations and, therefore, 945 optimization problems solved through Matlab automation of the python program FLORIS.

4. Results analysis

Thanks to the numerous simulations, it is also possible to find what parameters influence the effectiveness of this strategy. In the cases where the strategy is deployed (percentage power increase>0.5%), the average power increase is 6.5%. This is visible from fig. 2 where the percentage power increase of all strategies in all cases is depicted.

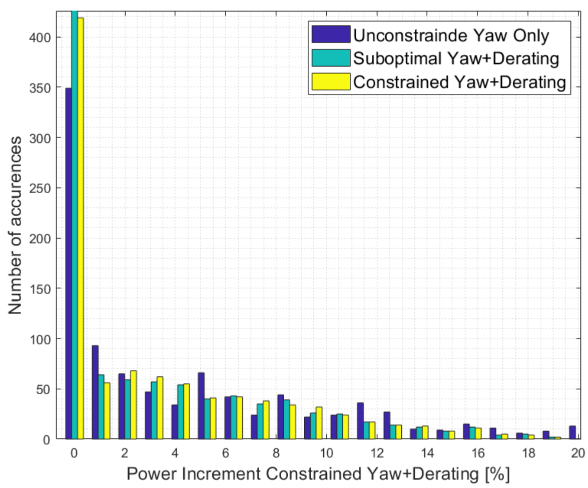

Figure 2: Histogram representation of the percentage power increase of all three optimization strategies.

The result of this analysis is very encouraging; in terms of offset, the results show that the best performances are obtained for an offset of 5/6 diameters, as shown in fig. 3. This is particularly interesting as this offset is often used in commercial wind farms.

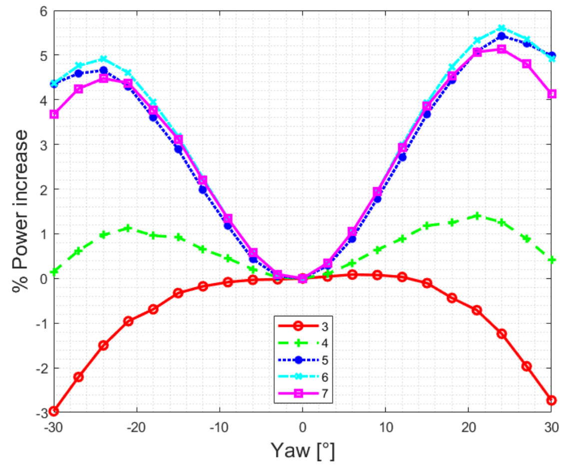

Figure 3: Percentage power increase VS yaw angles curves for different offset values [wind speed=11.4 m/s, impingement null, TI=0.06]

In terms of wind speed, this study shows an interesting trend: for values of wind speed slightly higher than the rated speed of the turbine, the strategy's effectiveness is at its highest. This is a piece of excellent news as for these speeds, the farm's performance is close to its maximum, and reaching percentage power increase levels of up to 12.5% translates into a massive improvement in total power. This is visible in fig. 4.

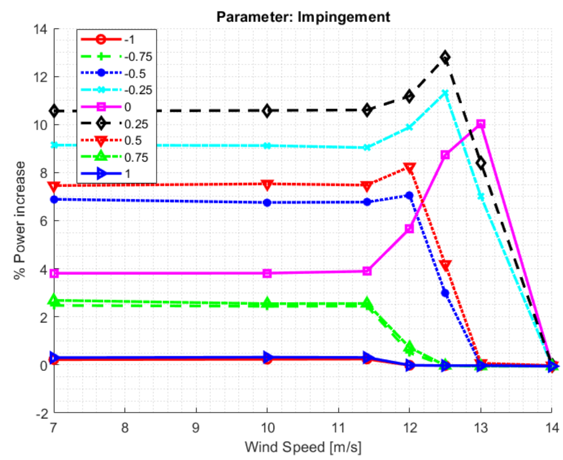

Figure 4: Percentage power increase VS wind speed curves for different impingement values [offset=5D and TI=0.06]

It is also worth mentioning that since the strategy features the axial induction control, it has been found that when the spacing is low, it is better to apply this technique instead of the yaw redirection. The complete optimization strategy can only obtain this result since the optimal point usually is not resting on the constraint curve. However, in most cases, the suboptimal strategy is a suitable approximation of the complete one with a -0.069 % average power difference, this is visible in fig. 5.

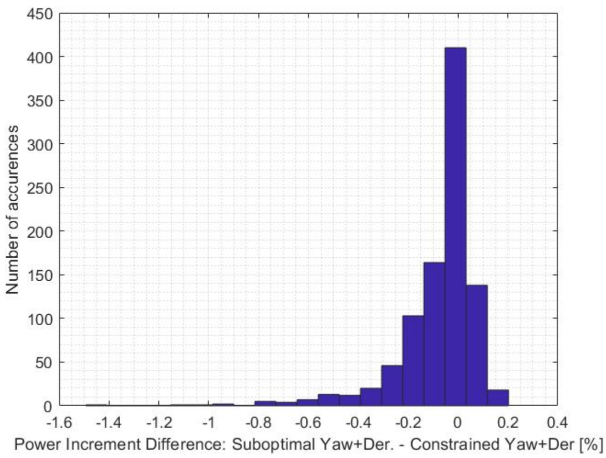

Figure 5: Histogram representation of the power difference between the constrained yaw+derating strategy and the suboptimal yaw+derating

This result is backed up by a comparison in terms of optimal yaw angles, in fig. 6. Here it is visible that the vast majority of cases lead to a 0° difference between the two strategies.

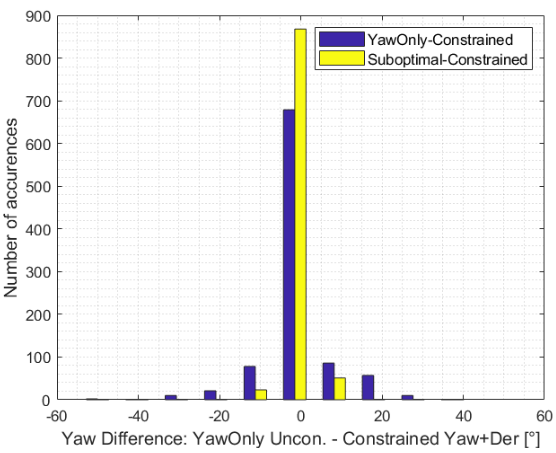

Figure 6: Histogram representation of the power difference between the constrained yaw+derating strategy and the suboptimal one

5. Conclusions

Based on these results it is possible to conclude that this strategy is a viable solution for already existing wind farms. It is undeniable that in a substantial amount of cases applying this technique delivers non-negligible improvements. In terms of applicability there is a lot of potential as the constraint curve can be computed for each situation and model every wind turbine already deployed. The absence of any structural upgrade or modification necessary is an excellent asset as it can keep the costs associated with applying this control strategy. It is also worth noting how closely the suboptimal strategy follows the optimal results. This is very important because it allows us to reduce the complexity of the problem and the number of variables involved making it more accessible to add complexity in other ways.

5.1. Future developments

Future developments on this topic could include the application of this control law to a more complex farm with more turbines, modeling additional environmental variables, and considering the possibility of steering the turbines downstream. Researching the results following the application of different constraint curves could also be an interesting direction for future work as this can be a disruptive variable in the application of this control law.

References

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