# Accounting for wind direction variability and uncertainty by robust active wake deflection control in wind farms

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**Abstract**

High fidelity simulations and wind tunnel tests have demonstrated the prospects of active wake deflection control in order to mitigate wake-induced power losses in wind farms. So far it is not fully understood how wind farm control should account for the variability of the instantaneous environmental conditions in the open field as well as the uncertainty in their measurements.

The contribution will introduce a so-called robust active wake control which considers dynamic wind direction variability and uncertainty. Based on a simplified wake interaction model the turbine yaw angles were optimized and wind measurements were used to evaluate the annual energy production of wind farms. Recommendations for wake control in general and for open field tests will conclude the talk.

**Keywords:** *FLORIS, power maximization, wind farm optimization, yaw misalignment*

## Introduction

Recent wind farm control strategies take the mutual aerodynamic interactions of the wind turbines into account. These interactions in the form of turbine wakes have a strong impact on the power production of wind farms. Wind tunnel experiments and high fidelity CFD simulations have already demonstrated the potential of wake deflection strategies for increasing the overall energy yield of a wind farm. Nonetheless, it is difficult to transfer these techniques into the free-field. Fluctuating wind conditions and a high sensitivity towards the wind direction complicate the appropriate consideration of wakes in wind farm control.

In this research, a wind farm control scheme based on wake deflection techniques is presented that incorporates wind directional dynamics and uncertainties in the measurement of the wind direction.

## Method

Active wake deflection is the approach to change the trajectory of a turbine wake in order to minimize its effect on downstream turbines. A lateral shift of the wake center can be achieved by purposely imposing a yaw misalignment with respect to the wind direction on the upstream turbine. Prior studies indicate that the power gain at the downstream turbines can be higher than the power loss at the misaligned upstream turbine if used correctly. For this purpose the wake model FLORIS [1] was developed to evaluate the potential power for different control settings.

The power output $P_i$ of the individual turbines can be estimated by FLORIS, which enables to formulate an optimization problem that uses the yaw angle $\gamma_j$ of the individual turbines in order to maximize the power output of the wind farm for the wind direction $\mu$:

$$\text{find} \quad \arg\max_{(\gamma_j)_j} \sum_{i=1}^{n} P_i\left(\left(\gamma_j\right)_j, \mu\right) \quad \text{for every } \mu \tag{1}$$

In order to make the optimization of the yaw angles more robust towards wind direction dynamics and uncertainties, the objective of the optimization was extended. Instead of optimizing the yaw angle for one wind direction the new optimization aims to optimize the yaw angle for a distribution of wind directions $\rho(\mu)$ to consider wind directional variation and uncertainties:

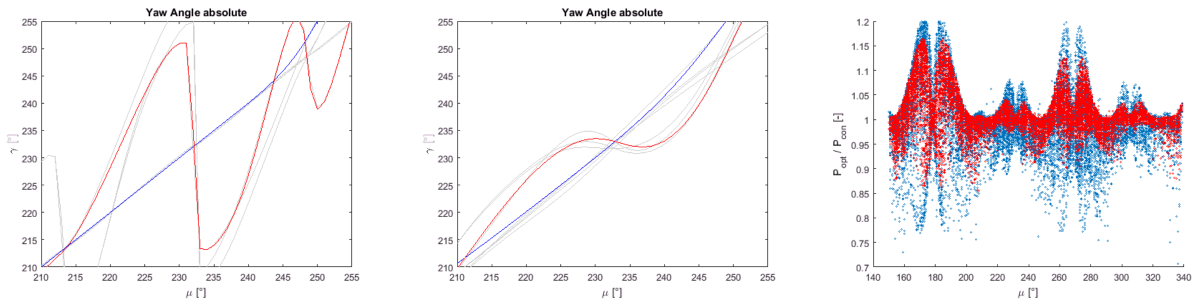
$$\text{find} \quad \arg\max_{(\gamma_j)_j} \int_0^{2\pi} \rho(\mu) \sum_{i=1}^{n} P_i\left(\left(\gamma_j\right)_j, \mu\right) \mathrm{d}\mu \quad \text{for a probability distribution } \rho(\mu) \tag{2}$$

For the probability distribution, a normal distribution was used since the majority (~75 %) of the investigated measurements (5 min intervals) passed the Kolmogorov-Smirnov goodness of fit test.

## Results

For demonstrational purpose a wind farm consisting of nine turbines in a gridded layout was used to illustrate the results of the optimizations.

In [2], a simple algorithm is introduced that can solve the optimization problems (1) and (2). Fig. 1a) shows the optimized yaw angles of two neighboring turbines in wake condition around 233° with a distance of 5D. Here a small change in the wind direction (e.g. from 230° to 234°) can cause a significant change of the outcome of the optimization. Fig. 1b) demonstrates the results of the robust optimization (2) for normal distributions with standard deviations of 8°. In this case the upstream turbine almost keeps a steady yaw angle for wind directions ranging from 224° to 242°.




a) Yaw angles of two neighbouring turbines for the optimization problem (1). In red the upstream turbine and in blue the downstream turbine

b) Yaw angles for the robust optimization (2) for a standard deviation of 8°. In red the upstream turbine and in blue the downstream turbine

c) Power gain of the opt. control strategy normalized by conventional operation. In blue for optimization (1) and in red for the robust optimization (2)°

Fig.1: Results of the optimization (1) and the robust optimization (2)

To evaluate the risks of these optimizations and the sensitivity towards wind direction variability and uncertainty, we tested the optimized yaw angles, with the help of wind direction measurements acquired at a met-mast. The 1 Hz data was split into intervals of 5 minutes and the directional mean wind directions were calculated and used as the respective reference wind directions, because conventional turbines do not continuously yaw, but rather adjusts their yaw angles approx. every 5 min. The reference wind directions were modulated with a Gaussian noise to simulate measurement uncertainties and that a conventional turbine can only react to changes in the wind direction and has not the ability to forecast the average wind direction of the next 5 minutes. This modulated reference wind direction was used as the input for the optimization of the yaw angles, while the power output was estimated using the original 1 Hz data. The results of this evaluation are show in Fig.1c). The optimization derived by (1) (in blue) often fails to increase the power output compared to conventional operation. On average, the power output was even reduced by -0.17 %. The results of the robust optimization are more compressed (in red), thus closer to the conventional power. However the average power output is increased by 1.12 %.

## Conclusion

This research shows that the transfer of wake steering method into the free-field can be risky and that uncared-for variability and uncertainty of the wind direction can lead to power decrease. The thorough consideration of wind direction dynamics and uncertainties offers a promising and easily implementable approach to reduce this risk and to improve the performance of wake steering.

More investigations can further improve this approach. E.g. wind directional dynamics strongly depend on the atmospheric conditions, suggesting that the assumed standard deviation for the robustness of the optimization should be chosen in conjunction to the stability of the atmospheric stratification.

## References

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