FLOW Final Report

Project title : **DUWIND's far offshore wind farm design PhD's**

WP 3, Offshore Wind Power Plant control for minimal loading

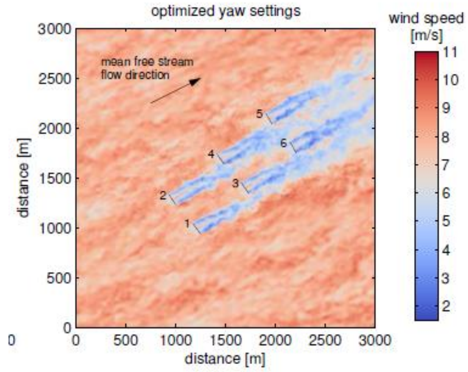
1. Project Summary

Wind turbines that are clustered in a wind plant, have interaction with each other through the aerodynamics of the wind field in the wind plant. The aerodynamic interaction effects are caused by the turbine wakes, which are the flow structures that form behind each turbine. The wake is characterized by a reduced flow velocity caused by the extraction of energy from the flow by the turbine, and an increased turbulence intensity caused by the obstruction of the flow by the turbine. The velocity deficits will cause a decrease of electrical power production of turbines standing in the path of a wake of another turbine, and the increased turbulence may increase the fatigue loads on those downstream turbines. Wind plant control that takes into account wake interaction effects in the coordination of the control actions of the wind turbines, can enhance the performance of the wind plant, in terms of total electrical energy production, and the loads on the individual wind turbines. Enhancing wind plant performance in this way, will contribute to the reduction of the cost of offshore and onshore wind energy. In this thesis two research objectives have been addressed: one is the evaluation of the potential of the different control degrees-of-freedom of the wind turbine to affect the interaction effect between the turbines, and the other is the development of data-driven algorithms for the optimization of those control settings in order to improve wind plant performance.

The control degrees-of-freedom (DOFs) of a modern large-scale horizontal-axis wind turbine are generator torque, collective and individual blade pitch, and rotor yaw. For each of the control DOFs, we explored their ability to affect the wake interaction effects in the wind plant, through high-fidelity computational simulations of setups with one or more turbines. We researched two ways in which the DOFs can control the wake effects: by axial-induction-based wake control, in which the energy extraction of the wind turbine is changed in order to affect the velocity deficit in the wake, and by wake deflection, in which the flow direction in the wake is manipulated in order to steer them away from downstream turbines. These topics can be further explained:

- Axial-induction-based control can be performed by offsetting collective blade pitch or generator torque from their turbine-level optimal settings, in order to increase the power production of downstream turbines. The potential gain from using axial-induction based plant-wide instead of turbine-level optimized control, are dependent on the particular atmospheric conditions, the wind plant configuration, and the turbine characteristics. Simulation cases presented in this thesis even show that there are circumstances in which axial-induction-based control gives no total power production increase on the wind plant, because wake expansion makes that much of the energy added to the flow by the control changes on upstream turbines, is lost to the atmosphere instead of being captured by downstream turbines.
- A better potential is demonstrated for wake redirection control. Yaw control and modified individual pitch control (IPC) were shown to be able to induce significant wake redirection. For the tested IPC-based techniques however, this wake redirection goes at the cost of loads increases, making it a less suitable candidate for practical application. Wake deflection through yaw offsets has been shown to be successful at increasing the total power production of small wind plant setups in high-fidelity simulations. Both increases and reductions of fatigue loads result from yaw-based wake redirection, depending on the

settings used. The load increases can be partially mitigated using standard load-reducing IPC. An illustrative example of wake redirection is shown in the figure below.



Two main approaches for data-driven wind plant control development were taken in this project:

1. direct data-driven approaches, in which the control settings optimization is directly based on measured data, and
2. data-driven model-based control, in which the optimization is based on models for which the parameters are identified from measured wind plant data.

Direct data-driven algorithms for axial-induction-based control are presented that optimize the axial-induction settings of each turbine in the plant with the objective of power production increase. A speed-up of the optimization is achieved by using gradient based optimization techniques with a distributed approach in which the effect on neighbouring turbines is taken into account only. Using information on the spatial configuration of the wind farm in this way, results in a much faster convergence of the power optimization than is achieved with an existing method with full communication between the turbines. This is because there are significant delays between control actions on turbines, and the response of turbines further downstream, because the wake effects need to propagate through the wind field.

Further, a data-driven model-based wind plant control strategy was presented to optimize the yaw settings of each turbine in the plant with the objective of electricity production increase. The optimization is based on predictions provided by a newly developed control-oriented model that predicts the effects of the yaw settings on the steady state wake deflection and velocity deficit. The model has a relatively small number of parameters that can be identified using time-averaged electrical power measurements of the different turbines in the wind plant (grey-box system identification). The model is computationally efficient enough to enable real-time online wind plant control optimization, using a game-theoretic search method. The application of the wind plant optimization method in a high-fidelity CFD simulation of a small wind plant, demonstrated an increase in electrical power production, and a reduction of wind turbine fatigue loads. Based on the novel data-driven model, a 1.1% electricity production increase is predicted on an annual basis, through using yaw-based wind plant control on the Princess Amalia Windpark, a full-size offshore wind plant.

The control-oriented wind plant model was further extended to include dynamics of the wake propagation delays between the turbines. The dynamic model has a feedback structure in which a linear state-space model describes the propagation of changes in the wake through the wind field. Only two tunable model parameters were added to include these dynamics, such that the tuning process is not further complicated to a large extend. The model structure allowed the development of an observer that uses Kalman filtering to correct the predicted flow field velocities on the basis of power measurements at the turbines. A relatively small increase of wind plant performance was demonstrated by going from yaw control optimization based on the steady-state model, to optimization based on the dynamic model. A practical benefit of including the dynamics is the fact that the grey-box system identification can be performed directly on the basis of the dynamic responses of the wind plant, rather than on time-averaged data. This is expected to be an important benefit when applying data-driven model-based control on a real wind plant with continuously changing ambient conditions.

This project resulted in pioneering work of data-driven wind plant controls, researching the feasibility of wake control concepts and solving practical issues to enable real-time implementation. Case studies carried out throughout the project estimate a 3.2% LCOE reduction.