Comparison of actuation methods for wake control in wind plants

P. M. O. Gebraad, P. A. Fleming, and J. W. van Wingerden

Abstract—In recent research, cooperative wind turbine control strategies have been proposed to optimize overall performance of wind plants by taking into account the aerodynamic interaction effects that the wind turbines have on each other through their wakes. Wind plant control strategies have different ways of using the control degrees-of-freedom (DOFs) of the turbine. Conventional control DOFs of a wind turbine are the pitch angles of the blades, the generator torque, and the yaw angle of the rotor. In most wind plant control approaches in literature, the generator torque and/or blade pitch control DOF is used to affect the wake velocity deficit (referred to as axial-induction-based control). In recent studies, an alternative control method is used, where the direction of the wake is changed using the yaw DOF, such that the overlap of the wake with downstream rotors is avoided or reduced (wake redirection control). In this paper, we present a high-fidelity CFD simulation case study, in which the potential of both control methods is compared, in terms of their effect on power production of a two-turbine setup. In this case study, wake-redirection control is shown to have a larger potential to improve wind plant performance. A further analysis is performed on the wake to show the underlying causes, which are wake expansion and meandering.

I. INTRODUCTION

Grouping the turbines in wind plants helps to reduce land- or sea-area use and landscape impact, and reduces the costs of grid connection, installation and maintenance. A downside of placing wind turbines in larger plants, is that the aerodynamic interaction between the turbines caused by the turbine wakes, may have a negative effect on the total electrical power production of the wind plant, and may increase loads on the turbines. Cooperative wind turbine control strategies have been proposed to optimize overall performance of wind plants, in terms of electrical power production and/or loads on the turbines, by taking into account those aerodynamic interaction effects that the wind turbines have on each other through their wakes (see [1] for a literature overview on wind plant control).

Wind plant control strategies have different ways of using the actuation degrees-of-freedom (DOFs) of the turbine. Most wind plant control studies in literature use an axial-induction-based control strategy, [2], where generator torque or blade pitch control is used to optimize the velocities in the wakes. Alternatively, the direction of the wakes can be optimized using control [3]–[5]. In this paper, we compare the effectiveness of both approaches for the optimization of the electrical power production, in high fidelity computational fluid dynamics (CFD) simulations.

In Section II we give a further introduction into wind turbine wakes. Then, in Section III we discuss the wind turbine actuation DOFs and how they affect the wakes. In Section IV and V we discuss the simulation tool and scenarios used. The results the simulation study are discussed in Section VI. Finally, in Section VII our conclusions are summarized.

II. WIND TURBINE WAKES

The wind turbine wake is the flow structure downstream of a wind turbine, that is characterized by (1) a reduced flow velocity caused by the extraction of energy from the flow by the turbine, (2) an expansion of the wake cross-sectional area, and (3) an increased turbulence intensity caused by the obstruction of the flow by the turbine, and the resulting velocity gradients in the flow (shear). These three properties of the wake have been studied extensively, see [6] for a literature overview. They are of interest for the control of wind turbines in wind plants, since the velocity deficits will cause a decrease of power production of turbines standing in the path of a wake of another turbine, and the increased turbulence may increase the loads on those downstream turbines. The amount of wake interaction between turbines is not only dependent on the overlap area of the wake of the upstream turbine with the rotor of the downstream turbine, but also on the distance between the turbines. This is because as the flow in the wake moves downstream, it will recover to the surrounding flow conditions (speed, turbulence intensity, and main direction) through convection and diffusion (see Fig. 1). The turbulence in the flow promotes this process of wake recovery by mixing the flow in the wake with the surrounding stream. Apart from the turbulence and shear caused by turbine and the velocity deficits in the wake itself, also the roughness of the ground surface, and thermal effects in the atmosphere cause turbulence and (vertical) shear in the inflow and downstream in the wake and the surrounding flow. Hence, the ambient atmospheric conditions also influence the amount of wake recovery, and thereby also the amount of interaction between turbines in a wind plant. Another effect that influences the amount of wake interaction, consists of the large oscillating movements of the velocity deficit area in the lateral and vertical direction, called wake meandering. Meandering makes that the wake overlap with a downstream
The characteristics of the turbine are the power coefficient, as explained in Section II. Important as on the atmospheric conditions that influence the wake on the aerodynamic characteristics of the turbine, as well be achieved by axial-induction-based control, is dependent decrease in wind velocity between the free-stream and the wake, in Section III-B.

A. Axial-induction-based wake control

The power extraction of turbines can be adjusted to influence the velocity deficits in the wakes. This control method is referred to as axial-induction-based control, since the control settings are adjusted to influence the axial induction factor of the turbine. The axial induction factor, $a$, is the fractional decrease in wind velocity between the free-stream and the turbine rotor (cf. Fig. 1). Blade pitch angle and generator torque, which are standard inputs on a modern turbine, can be used to adjust the axial induction.

The amount of total power production gain that can be achieved by axial-induction-based control, is dependent on the aerodynamic characteristics of the turbine, as well as on the atmospheric conditions that influence the wake recovery properties, as explained in Section III. Important characteristics of the turbine are the power coefficient $C_p$ and the thrust coefficient $C_T$, which are functions of the tip-speed ratio (TSR) and the pitch of the blades, $\beta$ [9]. The TSR is given by:

$$\lambda = \frac{\omega R}{U} \quad (1)$$

where $R$ is the rotor radius, $\omega$ is the rotor speed, and $U$ is the free-stream velocity. The rotor speed, and thus the TSR, can be influenced by adjusting the generator torque or changing the lift forces on the rotor blades by adjusting blade pitch. The $C_p$ determines the efficiency of the rotor in extracting power from the wind; the steady-state power extraction of the rotor, $P$, is given by:

$$P = \frac{1}{2} \rho A C_p (\beta, \lambda) U^3 \quad (2)$$

where $A$ is the area swept by the rotor and $\rho$ is the air density. The $C_T$ coefficient determines the rotor’s thrust force on the flow, $F_T$, given by:

$$F_T = \frac{1}{2} \rho A C_T (\beta, \lambda) U^2 \quad (3)$$

The thrust of the rotor determines the reduction of velocity over the rotor plane, i.e. the axial induction $a$. From the actuator disk momentum theory it follows that, if it is assumed that there is no recovery of the wake, the extraction of energy over the rotor reduces the velocity in the wake behind the turbine to:

$$U_{wake,min} = U (1 - 2a) \quad (4)$$

where axial induction, $a$, can be related to the thrust coefficient, $C_T$, by:

$$a = \frac{1}{2} \left( 1 + \sqrt{1 - C_T} \right) \quad (5)$$

In reality, there is wake recovery through convection and diffusion of momentum, therefore $U_{wake,min}$ can be considered to be a lower bound on the wind velocity in the wake (cf. Fig. 1). In below-rated wind conditions, the axial-induction-based control concept relies on the fact that at the maximum operating point of a single turbine, the power production sensitivity is small. This is a result of the $C_p$ surface being flat around its optimal pitch angle and TSR, while the thrust force is more sensitive to the pitch and TSR around that operating point, Fig. 2. By deviating a small amount from the point of maximum $C_p$ of the upstream turbines, the power production of that turbine will reduce only a small amount, while the axial induction will reduce enough to significantly increase the velocity in the wake. The ratio of the gradients of the $C_T$- and $C_p$-surfaces around optimum operation thus determine how much the wake velocity can be increased by reducing the power production of the upstream turbine. Under the right
circumstances, this increase in velocity downstream of the rotor will increase the power of the downstream turbine more than the loss in power production on the upstream turbine.

**B. Wake deflection control**

An alternative approach to controlling wakes in wind plants is to redirect the flow direction if the wake rather than to only optimize induction. In [11] three methods were considered to induce wake redirection: (1) rotor actuation in the tilt direction, which is effective but not a conventional DOF on current utility-scale turbines, (2) individual pitch control, which is shown to be effective at inducing wake redirection, but at the cost of a large increase of structural loads, and (3) and yaw actuation, which was shown to be effective at wake redirection with limited effects on loads. The yaw-based method is studied further in this paper. The yaw drive rotates the rotor and nacelle around the tower. In conventional wind turbine control, the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. In the control concept studied here, the rotor is misaligned with the wind direction, which makes that the changes. In the control concept studied here, the rotor is also the axial induction of the rotor decreases with increasing the yaw offset, which then increases the wind velocity in the wake. The above explanation is simplified, a more detailed analysis is found in [12].

**IV. SIMULATOR FOR ONSHORE/OFFSHORE WIND FARM APPLICATIONS (SOWFA)**

SOWFA is a high-fidelity wind plant simulation tool developed at the National Renewable Energy Laboratory (NREL). In Section [VI] this tool be used for simulation studies on wake control. SOWFA is a CFD solver based on OpenFOAM coupled with NREL’s FAST wind turbine simulator [13]. SOWFA uses an actuator line model coupled with FAST to study turbines in the atmospheric boundary layer. The CFD calculations consist of solving the three-dimensional incompressible Navier-Stokes equations and the potential temperature transport equations, which take into account the thermal buoyancy and Earth rotation (Coriolis) effects in the atmosphere, using a large eddy simulation method. In this way, SOWFA calculates the unsteady flow field in the wind plant, and it then uses the FAST turbine simulation to compute the time-varying power production and loads on each turbine. High-fidelity accuracy computations with SOWFA take in the order of days to run on a supercomputer using a few hundred processors. The simulations run for this study were performed on the NREL Peregrine supercomputer [14].

**V. SIMULATION SCENARIOS**

In Section [VI] two SOWFA simulation scenarios will be simulated to study the actuation methods for wake control: a single turbine scenario and a scenario with two turbines aligned in the flow spaced 7 rotor diameters (7D) apart, a typical spacing in wind plants. Details on the positioning of the turbines in the domain in each case are given in Fig. 4. The spatial discretization mesh for CFD is refined in two steps in a rectangular region, with the smallest cells containing the turbine rotors, the axial induction zones of the rotor, and a large part of the wake. Further away from the turbines the mesh is coarser to reduce computation time. In each case, the conditions simulated in SOWFA are based on the study reported in [13]. They consist of a neutral atmospheric boundary layer with a low aerodynamic surface roughness value of 0.001 m, typical for offshore conditions. The generated inflow, coming from the southwest (300°), has a horizontally-averaged wind speed 8 m/s and turbulence intensity of 6% at the turbine hub-height. These low ambient turbulence conditions induce a relatively large amount of wake interaction in the two-turbine, since wake recovery is slow.

**VI. EVALUATION OF YAW-BASED AND AXIAL-INDUCTION-BASED ACTUATION METHODS**

We have performed a test of the wind plant control concepts described in Section [III] on the two turbine setup, Fig. 5 presents the results. For each of the studied control DOFs (blade pitch, generator torque, yaw), a range of set-points is tested on the front turbine (turbine 1), with each set-point held constant in individual simulations with a 1,000s of simulated time. In each case, the control setting that yields maximum individual turbine power (baseline control) is set on the downstream turbine 2. For each setting of each DOF, Fig. 5 shows the mean power over the last 800s of the simulation (the first 200s are discarded since in that time range the wakes develop), normalized with the power of front turbine for baseline control.

For the results in the left plot in Fig. 5 the axial induction was modified for the front turbine, through offsetting the collective blade pitch angle from the baseline setting which is zero pitch offset. It shows that the turbine-level power optimal setting (zero pitch offset) also yields maximum
power production for the total wind plant. Although the effect of reduction of the axial induction on the front rotor causes an increase on power of the second turbine in the row, the power lost on the first turbine by offsetting the pitch is not regained on the second turbine.

For the results in the middle plot in Fig. 5, reductions in axial induction of the front turbine are achieved through modifying generator torque in order to change the TSR. A scaling factor, $\alpha$, is applied on the regular below-rated rotor speed control law $[10]$ of the front turbine, so that the applied generator torque is $T = \alpha \cdot K \cdot \omega^2$. In this control law we deviate from the turbine-level optimal gain $K$ for maximum power production, when $\alpha \neq 1$. For the applied torque scalings, the TSR ranged between 7.3 and 10. A decrease in TSR is needed to decrease $C_T$ (cf. Fig. 2) and thereby the rotor axial induction factor. This is achieved by increasing generator torque ($\alpha > 1$). When increasing torque on the upstream turbine, an increase of power at the downstream turbine can be observed. Compared to pitch, the $C_T$ is less sensitive to the TSR though, as is also shown in Fig. 2. As in the pitch case, there is also not enough power increase on the downstream turbine to compensate for front turbine power production loss from adjusting torque, and a decrease in total power production results.

In this high-fidelity simulation example it is shown that even when two turbines are aligned in the wind direction, under certain realistic inflow conditions, no increase in power is achievable by using the axial-induction-based control concept using generator torque or blade pitch control offsets.

For the results in the right plot in Fig. 5, yaw offsets with the main wind direction were applied on the front turbine to redirect the wake. In this case, there is a potential to increase the total power production level of the setup, if yaw offset in the positive direction is used (the counter-clockwise direction in a top view). The flow field comparison in Fig. 6 shows that with using yaw offset, indeed the wake can be redirected...
away from the downstream turbine, and the wind velocity in the wake can be increased, resulting in a higher inflow speed and production increase at the downstream turbine. Fig. 5 shows that for yaw offsets between 0 and 40 degrees, the production increase on the downstream turbine is higher than the loss of production on the upstream turbine, and there is a maximum total power increase of 5.9% for a 25 degree yaw offset.

We further investigate why there is improvement using wake-redirection, and not using axial-induction-based control, by studying the simulated wake of a single turbine, comparing a baseline control case with a yaw and pitch offset case. For both simulations, we extract flow data at planes perpendicular to the mean wind direction, at several distances downstream, and calculate the flow power density:

$$ P_{\text{density}} = u_{\text{axial}} \left( \frac{1}{2} \rho \vec{U} \vec{U}^T \right) \quad (6) $$

where $u_{\text{axial}}$ is the axial component of the velocity and $\vec{U}$ is the flow velocity vector. By subtracting the slices of the baseline case from those of the offset case, the kinetic energy added to the wake by introducing the control offsets (pitching blades or yawing the rotor), can be calculated. In Fig. 8a, the time-averaged difference in flow kinetic power density is shown for a two-degree pitch case, at several distances downstream (multiples of the rotor diameter $D$). When visualizing the rotor plane of a ‘virtual’ downstream rotor of equal size placed downstream aligned in the wind direction in Fig. 8a, it can seen that the kinetic energy conserved in the flow by using an pitch angle offset on the turbine, is mostly going outside of that rotor plane of the ‘virtual’ downstream turbine, because the wake expands and mean-ders outside of the downstream rotor area. Therefore, the power reduction on the front turbine would mostly be ‘lost’ to speeding up the flow surrounding a downstream rotor, rather than increasing the power production of downstream turbine, especially when that turbine would be placed further downstream (note that $6D$ to $8D$ are common distances in
real wind plants). A second cause for a limited ability to improve production at the downstream turbine through pitch control offsets on the upstream turbine, is suggested in [15]: a reduction in thrust force on the front turbine may reduce turbulence in the wake, and thereby the wake recovery, which has a negative effect on the velocity at the downstream turbine. For the yaw-based redirection case, for which we have shown the instantaneous power density differences after 300s in Fig. 8b, the induced velocity increase is better concentrated within the rotor area of a virtual downstream turbine placed downstream at a distance more than 4D. The resultant energy balance of Fig. 8a is computed in Fig. 7a where the total added wind kinetic power through a potential downstream rotor placed downstream, $\Delta P_{\text{wind}}$, is compared to the power lost at the upstream turbine by pitching or yawing, $\Delta P_{T1}$ (each of the quantities is normalized with the baseline wind power production of the upstream turbine, $P_{T1,\text{baseline}}$), for a range of downstream distances. When considering that the downstream NREL 5-MW turbine can operate at a maximum $C_{p,\text{max}} = 0.48$ efficiency, the predicted maximum energy gain of a downstream turbine is $C_{p,\text{max}}\Delta P_{T1}$. Then, this balance predicts that it is impossible to recover the energy lost through offsetting the pitch of the upstream turbine, because $C_{p,\text{max}}\Delta P_{\text{wind}} < \Delta P_{T1}$ when the downstream turbine is placed at any realistic spacing (more than 2D), and thus an increase of total power is infeasible. For the tested yaw offset, the balance (Fig. 7b) predicts we can increase total power when the downstream turbine is placed at distances between 4D and 8D, with the possible exception of 6D.

VII. CONCLUSIONS

The potential gain from plant-wide instead of turbine-level optimized control, is dependent on the particular atmospheric conditions, the wind plant configuration, and the turbine characteristics. The high-fidelity simulation cases presented in this paper, even show that there are circumstances in which the concept of total wind plant power increase through axial-induction-based wind plant control is infeasible, because wake expansion and meandering makes that much of the energy added to the flow by control changes, is lost to the atmosphere. However, simulations with the same ambient conditions have shown that there is significant potential to increase power production using yaw-based wake redirection techniques. A model-based method for optimized control of the yaw in a wind plant, was presented in [5]. Future research is aimed at quantifying the effect of atmospheric conditions on the potential of the control methods.

REFERENCES

Fig. 8: Added kinetic flow power by a control offset, for a range of distances downstream.


