Evaluating Tilt for Wind Farms

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Evaluating Tilt for Wind Plants

Jennifer Annoni, Andrew Scholbrock, Matthew Churchfield, and Paul Fleming

Abstract— **The objective of this work is to demonstrate the feasibility of tilt in a wind plant. Tilt control, much like other wind plant control strategies, has the potential to improve the performance of a wind plant. Tilt control uses the tilt angle of the turbine to direct the wake above or below the downstream turbines. This paper presents a study of tilt in two- and three-turbine arrays. Specifically, the authors show that the power production of a two-turbine array can be increased by tilting turbines in a specific orientation. When adding more turbines, as is shown with the three-turbine array, the overall percentage of power gain increases. This outcome deviates from some of the results seen in typical wind plant control strategies. Finally, we discuss the impact this type of control strategy has on the aerodynamics in a wind plant. This analysis demonstrates that a good understanding of wake characteristics is necessary to improve the plant's performance. A tilt strategy such as the one presented in this paper may have implications for future control/optimization studies including optimization of hub heights in a wind plant and analysis of deep array effects.**

I. INTRODUCTION

Wind energy is a fast growing source of renewable energy and is a key component to meet renewable energy standards set throughout the United States [1]. Achieving these targets requires increasing the efficiency of and reducing the cost of wind energy. Wind plant control can be used to maximize power production of a wind plant, reduce structural loads to increase the lifetime of turbines in a wind plant, and better integrate wind energy into the energy market [2]–[5].

Typically, wind turbines in a wind plant operate individually to maximize their own performance—regardless of the impact of aerodynamic interactions on neighboring turbines. Despite this, there is the potential to increase power and reduce overall structural loads by properly coordinating turbine control actions. Two common wind plant control strategies in literature include wake redirection and axial induction control. There has been a significant amount of work done on wake direction, showing that this method has the most potential to increase power production [6]. Wake redirection typically uses the yaw drive of the turbines to redirect the flow around downstream turbines. Various computational fluid dynamics (CFD) simulations and wind tunnel experiments have shown that this method can increase power without substantially increasing turbine loads [7], [8]. Yaw-based wake redirection control has also been used in optimization studies of turbine layouts to improve the annual energy production of a wind plant [9].

Work has also been conducted in the area of axial induction control [2]. Axial induction control uses the blade pitch angle and generator torque of the turbines to change the characteristics of the flow in the wake, by increasing the power available to the downstream turbines. This approach can help improve power production at the downstream turbines and reduce loads [2], [10]. Axial induction control has not yet conclusively been demonstrated to have a very positive effect on total power (see for example [8], [11]). However, positive implications for using axial control to reduce loads without power loss [12] and applications in active power control or other grid services scenarios have been noted [13], [14]. A combined controls approach using axial induction control and wake redirection can provide wind plants with more control authority.

This paper addresses another kind of strategy using the tilt of the turbines. Tilt has been described in previous studies as a way to redirect the wake in a wind plant [15]–[17]. This idea was proposed as a complement to wake redirection using yaw control. The main difference with tilt is that the primary objective is to deflect the wake above or below the downstream turbines, rather than in the lateral direction. This control strategy is orthogonal to the objective of yaw-based wake redirection and can improve the overall controllability of a wind plant. Because the wakes are being redirected in the vertical direction, this may encourage entrainment (i.e., vertical flow into the wind plant), and further increase energy production. Tilt can have implications when doing optimization that involves varying the hub height of turbines in a wind plant. It can also have implications when considering deep array effects in large wind plants [18]. Deep array effects involve large amounts of vertical entrainment. These topics will be considered as a part of our future work.

To date, tilt has only been considered in a few detailed studies using high-fidelity modeling analyses. This paper looks to expand on the past work of [16], [17]. The paper contributes several important novelties to the existing literature. First, tilt is simulated for a range of wake overlap conditions, rather than of only considering total overlap. This approach is important, as real turbines will mostly experience various levels of partial overlap, instead of the "perfect" condition of full overlap. Second, the paper focuses on results from two-and three-turbine array scenarios that provide detailed insights into the potential of tilt. Finally, analysis of the upward and downward controllability of wakes is provided at a more detailed level than had been previously accomplished.

The paper is organized as follows. The tilt problem is introduced in Section II. Various simulations have been run to investigate the effects of tilt on two- and three-turbine arrays. In addition, the effects of tilt in different spanwise

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offsets are investigated for two-turbine array scenarios. The simulation setup is described in Section III. The results of these various simulations are discussed in Section IV. The results also analyze the impact of tilt on the aerodynamics in the wind plant. Finally, conclusions and future work will be presented in Section V.

II. TILT FOR WIND PLANT

Tilt uses the tilt angle of a simulated turbine nacelle and rotor to deflect the wake up or down from the downstream turbine. This section will formulate the tilt optimization problem for a two-turbine array, shown in Figure 1. Let P_1 and P_2 denote the power from the upstream turbine and downstream turbine, respectively. Assume the blade pitch angle and generator torque of the turbines are set to operate at the optimal operating point of the individual turbine [19]. The power generated by the first turbine depends on the inflow wind speed, U, and the tilt angle, γ_1, of the turbine. The power generated by the upstream turbine can be expressed as:

$$P_1 = \frac{1}{2}\rho A U^3 C_P(\cos(\gamma_1))^{pP} \tag{1}$$

where ρ [kg/m^3] is the air density, A [m^2] is the rotor area, and C_P [-] is the power coefficient. A correction factor of $(\cos(\gamma_1))^{pP}$ is added to account for the effects of tilt misalignment. This is a similar approach used for a yaw control study in [6]. In that study, the exponent pP was found to be $pP = 1.88$ for the National Renewable Energy Laboratory's (NREL's) 5 -MW turbine operating in the Simulator fOr Wind Farm Applications (SOWFA). The larger the tilt angle, γ_1, the less power the turbine will generate. For simplicity, the power generated by the upstream turbine can be expressed as a function of the inflow velocity and the tilt angle, $P_1(U, \gamma_1)$. The operation of the upstream turbine disturbs the flow, thereby impacting the operation of the downstream turbine, such that the operation of the downstream turbine depends on the tilt angle of the upstream turbine. Thus, the averaged power generated by the downstream turbine has a functional form of $P_2(\gamma_1, \gamma_2, U)$. The total power generated by the two-turbine array is thus given by:

$$P_{tot}(\gamma, U) = P_1(\gamma_1, U) + P_2(\gamma_1, \gamma_2, U) \tag{2}$$

where the vector $\gamma := [\gamma_1 \quad \gamma_2]^T$ is defined to simplify the notation. A similar approach can be applied for a three-turbine array, where the power of the third turbine can be written as $P_3(\gamma_1, \gamma_2, \gamma_3, U)$. The main objective of tilt is to maximize the total average power output:

$$\max_{\gamma} P_{tot}(\gamma, U) \tag{3}$$

This problem formulation assumes a constant free-stream velocity, U, which is a steady-state formulation. A more realistic formulation treats the free-stream velocity as unsteady and turbulent. In this case, the objective is to maximize the average power generated by the two-turbine array. Moreover, the unsteady flow and the tilt angles cause significant structural loads on the tower and blades of both turbines. The formulation can be extended to include constraints on the loads. Alternatively, additional terms can be included in the objective function to trade off the power capture and loads. However, the inclusion of loads is considered outside the scope of this paper and is reserved for future work. This paper investigates tilt for a two- and three-turbine array arranged in various layouts using a high-fidelity wind plant simulation tool. The simulation tool and simulations scenarios are described in the next section.

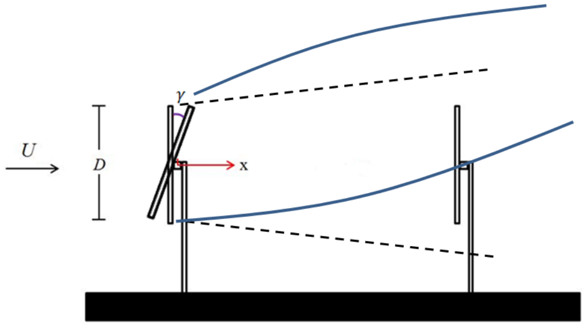

Fig. 1. Two-turbine setup for evaluating tilt. In this figure, a negative tilt angle, γ, is shown for the upstream turbine.

III. SIMULATION SETUP

A. *Simulator fOr Wind Farm Applications*

SOWFA is a high-fidelity, large eddy simulation tool that was developed at NREL for wind plant studies. It is a CFD solver based on OpenFOAM and is coupled with NREL's FAST modeling tool [20]–[22]. SOWFA has been used extensively in previous wind plant control studies [6], [16], [23].

The tool uses an actuator line, or actuator disk, model coupled with FAST to study turbines in the atmospheric boundary layer. This study will use turbines modeled as actuator disks. SOWFA solves the three-dimensional incompressible Navier-Stokes equations and transport of potential temperature equations, which take into account the thermal buoyancy and Earth rotation (Coriolis) effects in the atmosphere. The inflow conditions for these simulations are generated using a periodic atmospheric boundary layer precursor with no turbines.

SOWFA calculates the unsteady flow field to compute the time-varying power, velocity deficits, and loads at each turbine in a wind plant. This level of computation, with high-fidelity accuracy, takes on the order of hours to days to run on a supercomputer using a few hundred to a few thousand processors, depending on the size of the wind plant. The simulations run for this study were performed on Peregrine, NREL's high-performance computer [24].

It should be noted that studies have been performed to validate SOWFA. For example, it has been compared with the 48-turbine Lillgrund wind plant field data and shows good agreement through the first five turbines in a row aligned with the wind direction [25]. In addition, SOWFA has been tested to verify that it captures the inertial range in the turbulent energy spectra and log-layer in the mean flow, both of which characterize a real atmospheric boundary layer [22]. Further validation studies are ongoing. Additional details can be found in [20], [26].

B. Simulation Scenarios

Actuator disk simulations of two- and three-turbine array scenarios were performed using SOWFA. The turbines were simulated using the NREL 5-MW reference turbine [27] at a 90.0-m hub height and were operated in a variety of scenarios to analyze the effects of tilt on the flow. The turbines were spaced 7 diameters (7D) apart in the downstream direction. These scenarios were simulated under neutral atmospheric conditions with an 8 m/s mean wind speed and 10 % turbulence intensity. The two- and three-turbine arrays were simulated using an aligned case. Additional studies were performed on the two-turbine case to observe the effects of spanwise offsets.

Each case was set up and run in SOWFA. The simulations each ran for approximately 2000 s of simulated time. From each case, several metrics were extracted. First, the power of all turbines was averaged from a period beginning after wakes had developed. Second, average flows were extracted from planes of data within the CFD simulation for visualization and analysis of the patterns seen in the power data. The results were analyzed and are presented in the next section.

To investigate the effects of tilt, the upstream turbine(s) was operated in several tilt conditions, and the power of the two- and three-turbine arrays were recorded for the various scenarios. Typically, turbines have some fixed nonzero tilt angle, $\gamma \approx -5°$ in the case of the NREL 5-MW reference turbine, to ensure that the blades of the turbine do not hit the tower, known as a tower strike. It should be noted that a negative tilt angle refers to a turbine tilted toward the upward direction, see Figure 1, and a positive tilt angle refers to a turbine tilted toward the downward direction. This study tilts the turbines at $\gamma = -25°$ and $\gamma = 25°$. Although tilting the turbine $\gamma = 25°$ would result in a tower strike, this would be a realistic tilt angle for a downwind wind turbine [28]. Downwind turbines may be more present as turbines become larger and larger for offshore wind applications [29].

1) Aligned: Tilt was first investigated in this paper under aligned conditions using a two-turbine array (see Figure 2). In the top plot, the two turbines are operated normally, i.e., each turbine has a tilt angle of $\gamma = -5°$. The middle plot shows the front turbine tilted at an angle of $\gamma = -25°$. The turbine exerts a upward thrust force on the flow forcing the wake to travel up. The bottom plot shows the front turbine tilted at an angle of $\gamma = 25°$. In this scenario, the turbine exerts a downward thrust force on the flow, which forces the wake to move down toward the ground. In addition to the two-turbine array, a three-turbine array was used to analyze the effects of tilt as rows of turbines increase. Figure 3 shows the three-turbine array, operating under different tilt settings. Specifically, the top plot shows the front two turbines operating under normal tilt conditions, $\gamma = -5°$. The second plot shows both of the turbines operating under tilt conditions, $\gamma = +25°$. Note that the figures only show the turbines operating at $\gamma = +25°$. However, both $\gamma = -25°$ and $+25°$ were used. The third and fourth plots show one turbine operating at normal tilt conditions and one turbine operating at a tilted condition. This analysis is useful for understanding the effects of tilt in larger wind plants.

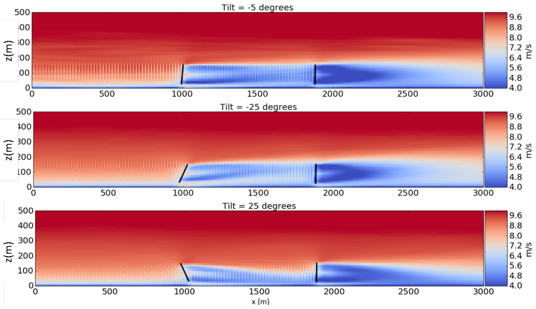

Fig. 2. Two-turbine setup with no tilt (top), negative tilt at the upstream turbine (middle), and positive tilt of the upstream turbine (bottom).

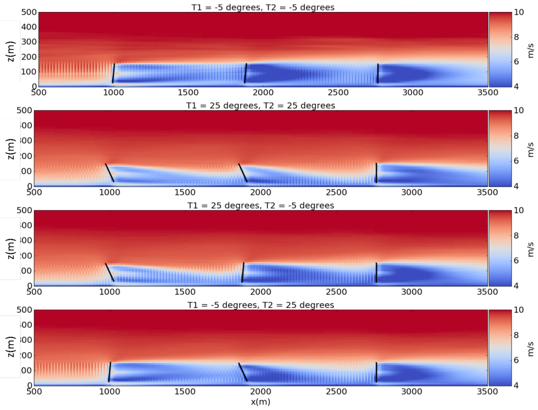

Fig. 3. Three turbine setup. All turbines are operating at baseline tilt, $\gamma = [-5°, -5°]$ (top). Turbines 1 and 2 are operating at $\gamma = [25°, 25°]$ (second). Turbines 1 and 2 are operating at $\gamma = [25°, -5°]$, respectively (third). Turbines 1 and 2 are operating at $\gamma = [-5°, 25°]$, respectively (bottom).

2) Offset: In addition to the aligned case, several simulations were done to investigate the impact of tilt at different spanwise offset conditions. Specifically, simulations were run with the downstream turbine offset in the y direction, i.e., perpendicular to the mean wind speed, by -1.0D, -0.75D, -0.5D, -0.25D, +0.25D, +0.5D, +0.75D, and +1.0D in the spanwise direction. The tilt angle of the upstream turbine was varied between $\gamma = -25°$, $-5°$ and $25°$. These simulations indicate the range of control using a tilt strategy. As mentioned earlier, turbines rarely operate in "perfectly" aligned conditions. Demonstrating that there is some benefit to tilt in partially overlapped conditions will be useful in determining the advantages of tilt in a wind plant.

IV. RESULTS

The results from the various scenarios described in Section III are presented here.

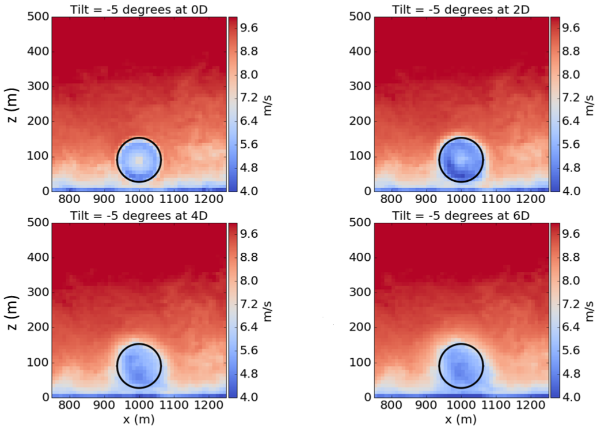

Fig. 4. No tilt case, which is directly behind the upstream turbine (top left). 2D downstream (top right). 4D downstream (bottom left). 6D downstream (bottom right). The black circle indicates the rotor area of the turbine. Also, note that the downstream turbine is located at 7D.

A. Aligned

In the two-turbine aligned case (Figure 2), it is shown that there is potential to improve wind plant performance by tilting the upstream turbine. Specifically, tilting the turbine in the positive direction, i.e., $\gamma = 25°$, provides the most potential for power increase in aligned conditions. In this case, the two-turbine array experienced an 8.3% power gain. Tilting the upstream turbine in the negative direction ($\gamma = -25°$) results in a 3.8% power loss. As mentioned earlier, although positively tilting a turbine is not feasible with the current horizontal upwind turbines, this type of strategy may be employed with downwind machines.

To understand the effects of tilting in the two-turbine array, mean vertical slices were taken of the flow field at 0D (right behind the turbine), 2D, 4D, and 6D downstream. This approach helps characterize the aerodynamic effects of tilt, which may have implications when studying larger wind plants. Figure 4 shows the propagation of the wake through several plane slices downstream of the upstream turbine when the turbine was operating in a no-tilt baseline scenario at $\gamma = -5°$. The black circle in each vertical slice indicates a virtual rotor area to provide some insight into the impact of the wake on the downstream turbine. These slices show the baseline behavior of the wake without any off-nominal tilt applied for wake redirection. The slices illustrate the tendency for wakes to expand and mix as they propagate away from the turbine.

Figure 5 shows the mean vertical slices for the negative tilt case, i.e., $\gamma = -25°$. In this case, the turbine is tilted up, and an upward force is exerted on the flow. This upward force moves the wake up and changes the velocity profile at the downstream turbine. To illustrate this, the streamwise velocity profiles in the vertical direction (z-direction) of the no-tilt, negative-tilt, and positive-tilt cases are shown in Figure 7. In particular, Figure 7 shows the impact of the wake on the shear layer as it is directed up and down by the tilting of the upstream turbine. SOWFA simulates a shear layer wherein the velocity is zero at the ground and increases exponentially with height. With respect to the no-tilt case, the negative-tilt case pushes the wake up and forces the slower free-stream velocities (the lower part of the shear layer) to impact the downstream turbine, as shown in Figure 7. Although the downstream turbine is experiencing more free-stream velocity, it is generally experiencing slower velocities that correspond to the bottom of the shear layer. This response, combined with the power loss the upstream turbine incurs from its tilt angle, results in a power loss compared to the baseline scenario.

Conversely, in the positive-tilt case, the upstream turbine is tilted down, and a downward force is exerted on the flow. The downward force moves the wake down and the slower velocities from the wake displace the slower free-stream velocity (see Figure 7). The downstream turbine experiences higher velocity that is generated by the shear layer. It is important to note that this generates a significant amount of vertical shear across the rotor. In addition, the wake is forced downward and impacts the ground at 2D (see Figure 6). The ground forces the wake to spread out, which allows the downstream turbine to experience higher free-stream conditions the result from the upper part of the shear layer. Again, this resulted in a combined power gain when tilting the upstream turbine in the positive direction.

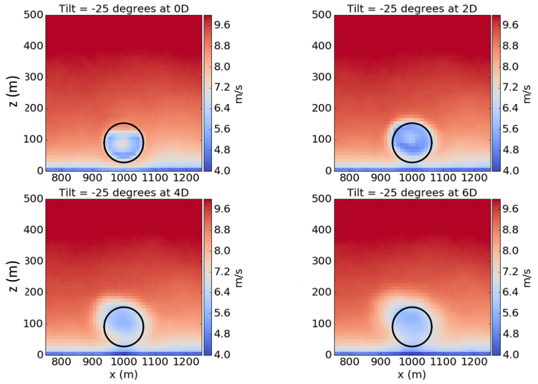

Fig. 5. Negative tilt; directly behind the upstream turbine (top left). 2D downstream (top right). 4D downstream (bottom left). 6D downstream (bottom right).

As mentioned earlier, both two-turbine and three-turbine aligned cases were simulated to understand the overall effects of tilt. The results of the three-turbine aligned cases are shown in Table I. There are a few things to note in these cases. First, the three-turbine array experiences the most power gain when the two upstream turbines are operated in positive yaw conditions. This is significant because the percent of power gained (from baseline) in the three-turbine array is about 1.5 times the amount in the two-turbine array, at approximately 13.0%. This is an exciting result, in that it suggests that the benefits of tilt are amplified, and not diluted, by repeated application within a wind plant. Second, the reason for the dramatic power increase can be seen in Figure 3. Specifically, the first turbine (operating under positive tilt conditions) pushes the wake down towards the

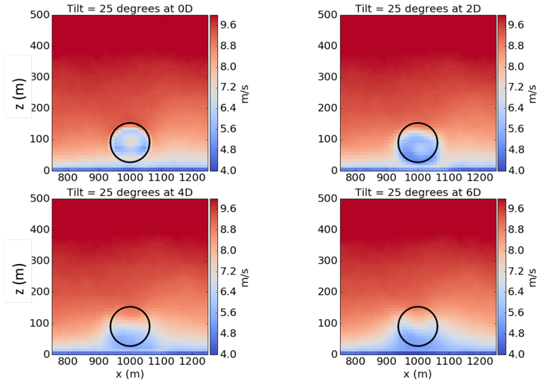

Fig. 6. Positive tilt; directly behind the upstream turbine (top left). 2D downstream (top right). 4D downstream (bottom left). 6D downstream (bottom right).

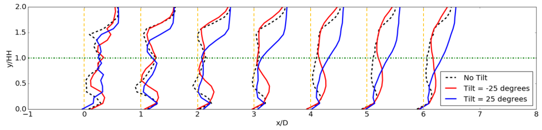

Fig. 7. Streamwise velocity profiles at different points downstream of the upstream turbine. The dotted black line indicates the velocity profile behind the upstream turbine when the rotor is not tilted. The red line shows the velocity profile when the rotor is tilted at a -25° angle. Finally, the blue line indicates the velocity profile when the rotor is tilted +25°.

ground, just as in the two-turbine array. However, as the wake passes through the second turbine, also operating in positive tilt conditions, the wake behind the second turbine is pushed down even farther, exposing the last turbine to higher amounts of free-stream velocity, resulting in a higher power gain across the three-turbine array. Negative tilt of the three-turbine array provides similar results to the two-turbine array and does not produce a power gain.

B. *Offset*

In addition to the aligned case, multiple simulations were run to analyze the effects of tilt considering other wake overlap conditions including various amount of partial waking. Tables II show the power gain results from a two-turbine array, in which the downstream turbine is offset by spanwise distances in the positive and negative directions.

The present analysis indicates, that at least for the interturbine distance considered of 7D, the only consistent way to generate enough additional power downstream is to deflect the wake downward when the turbine is in above 75% overlap conditions, as indicated in Table II.

Turbine 1 Tilt	Turbine 2 Tilt	% Gain
-5°	-5°	-
-25°	-25°	-3.6%
-25°	-5°	-1.3%
-5°	-25°	-1.7%
25°	25°	13.0%
25°	-5°	6.6%
-5°	25°	-0.5%

TABLE I
POWER INCREASES FOR THE THREE-TURBINE ARRAY.

Offset	Tilt -25°	Tilt 25°
-D	-5.0%	-10.9%
-0.75D	-5.1%	-7.0%
-0.5D	-4.2%	-1.6%
-0.25D	-3.3%	6.0%
0D	-3.8%	8.3%
0.25D	-3.7%	2.1%
0.5D	-3.5%	-3.2%
0.75D	-3.7%	-12.4%
D	-4.0%	-17.1%

TABLE II
PERCENT POWER GAIN IN A TWO-TURBINE ARRAY WITH SPANWISE OFFSETS. EACH CASE IS COMPARED TO THE CASE WITH THE SAME OFFSET WHILE USING THE DEFAULT TILT SETTING, $-5°$.

C. *Discussion*

This paper is primarily concerned with exploring the controllability and power benefits of wake-redirection via tilt. Varying amounts of partial overlap can be used to inform the choice of tilt actuation. A "passive" solution might be to simply adopt a new permanent tilt angle.

The overlap analysis provides a preliminary indication that for typical turbine spacings, the benefit of tilt is limited to majority-overlapped conditions. Thus, the benefits accrued in these wind direction ranges would need to outweigh the losses in all others. This could suggest a more conservative tilt angle.

For active control, in which the tilt angle is able to be modified, we observed total power improvements for the larger overlaps. However, for smaller overlaps, although the downstream turbine produces some additional power when the upstream turbine is tilted (even with 1D displacement), it does not overcome what is lost by the upstream turbine. This outcome suggests that to maximize the application of tilt, the tilt offset should be ramped from nominal as conditions approach full overlap. An important subject for future work is identifying optimal tilt angles for a range of spaces and overlaps.

V. CONCLUSIONS AND FUTURE WORK

This study demonstrated the impact of tilt in the context of wind plant control. Tilt control uses the vertical motion of the turbine to redirect the wake and can act as a complement to the typical yaw-based wake redirection strategies, which move the wake in the lateral direction. The largest impact on power production using tilt occurred when tilting the upstream turbine(s) in the positive direction, i.e., tilting the turbine down. This control action is more realistic for downwind turbines, rather than upwind machines.

One important result of this study is that for the range of wake conditions in which downstream turbine is more waked than not, tilt shows good potential to improve overall power production. However, for the tilt angles and distances considered, there is less potential to improve power production when there are small amounts of overlap. A mechanism for active tilt should be optimized to adjust tilt to concentrate only on zones of high overlap for further spacings.

A second novel and important result is that the percent improvement noted in the three-turbine case is almost twice that of the two-turbine case. This finding suggests that the process by which energy is added into the flow for the downstream turbine is amplified by repetition. It provides the exciting possibility that adding more turbines to this type of control strategy may result in higher possible power gains when considering a full plant.

An important subject for future work will be to identify a method for selecting optimal tilt angles across scenarios of turbine separation and overlap. In yaw-based wake steering, a control-oriented model, FLOw Redirection and Induction in Steady State, or FLORIS, was developed for this purpose, as it is impractical to run CFD for every possibility. Expanding wake models to tilt and optimizing and designing controllers using these wake models may lead to improved control capabilities of wind plants.

Finally, future work includes analyzing tilt in large wind plants where deep array effects are evident and there are large amounts of vertical entrainment present. In addition, this type of tilt strategy can be implemented on simplified models and used in optimization problems in which turbine hub height and rotor size are varied within large wind plants.

VI. ACKNOWLEDGMENTS

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