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Wind farm control: addressing the aerodynamic interaction among wind turbines

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Abstract— **Wind farms help reduce the average wind cost of energy due to many economies of scale compared to individual turbines located far from each other. However, these groupings introduce the problem of aerodynamic interaction among turbines, which can decrease the total energy converted to electricity compared to the same number of isolated turbines operating under the same wind inflow conditions. In this paper, we describe a simulation model under development to examine the aerodynamic interaction among turbines and increase the total energy captured by an array of turbines. We then discuss various control strategies to maximize the energy capture for wind farms containing multiple turbines.**

I. INTRODUCTION

In recent years, wind energy has come to be recognized as one of the most mature, cost-efficient renewable sources of electricity. The cost of energy (COE) from well-sited wind turbines is now competitive in many markets with more traditional sources, and many states have recently passed Renewable Portfolio Standards that are expected to drive installed capacity even higher in the near future. The majority of the installed wind capacity in the United States is arranged in groups of turbines called wind farms or arrays. While these farms help reduce the average wind COE due to many economies of scale, they introduce the problem of aerodynamic interaction among turbines, which can decrease the total energy converted to electricity compared to the same number of isolated turbines operating under the same wind inflow conditions. This paper describes a simulation model being developed as a test bed for development and testing of coordinated wind farm controllers. The control concepts described in the paper are aimed at increasing the total energy captured by an array of turbines compared to a baseline controller that optimizes energy for each individual turbine but does not consider the overall wind farm energy capture.

Wind turbines operate by extracting kinetic energy from the wind, so the wind speed downwind of a turbine is necessarily slower than the wind speed upwind of the turbine. Thus, downwind turbines are ”shadowed” by upstream turbines. Wind farm planners have exerted significant effort to reduce the aerodynamic interaction among turbines in an array, which decreases as the spacing between individual turbines increases. When possible, the downwind spacing (see Fig. 1) is 8 - 10 or more rotor diameters and the crosswind spacing is 5 or so rotor diameters, which can maintain array losses at less than 10% under typical wind inflow conditions [2]. (A wind turbine's “rotor” consists of the blades and the rotating hub to which they are attached.) However, conditions at a given wind farm location do not always allow for spacing at those distances. Also, crosswind spacing is rarely as large as downwind spacing, so locations in which the wind direction is frequently from directions other than the prevailing wind direction may suffer greater array losses. Additional information about wind farms can be found in [3].

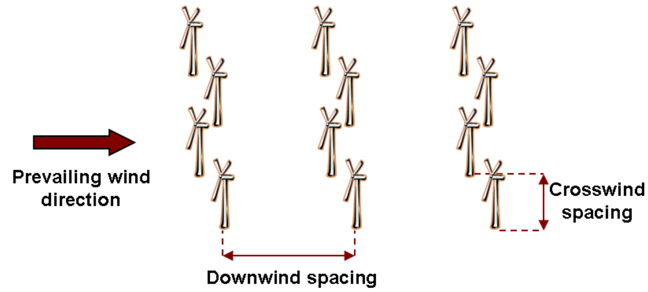

Fig. 1. Wind turbines in a farm arranged with larger distances between turbines in the prevailing wind direction (“downwind spacing”) than in the perpendicular direction (“crosswind spacing”). Although the shorter crosswind spacing reduces land use by the wind farm, energy capture can be compromised when the wind comes from a direction other than the prevailing one. Reproduced from [1].

A wind farm's “array efficiency” η_A, is defined as

$$\eta_A = \frac{E_A}{E_T N}. \quad (1)$$

In (1), the annual energy captured by the array is E_A, the annual energy captured by one isolated turbine is E_T, and there are N turbines in the wind farm.

Since modern utility-scale turbines all use active control on an individual basis, new coordinated controllers can be designed to operate with no additional sensors or actuators required. Thus, the additional cost for implementing an array-wide control should be negligible and any increase in captured energy will lead directly to a decrease in the COE from wind.

II. PROBLEM MOTIVATION

Consider an actuator disc model of a wind turbine with stream tube boundaries shown in Fig. 2. The far upwind, or free stream, wind velocity is given by V_∞ and the far downwind wind velocity is given by V_d.

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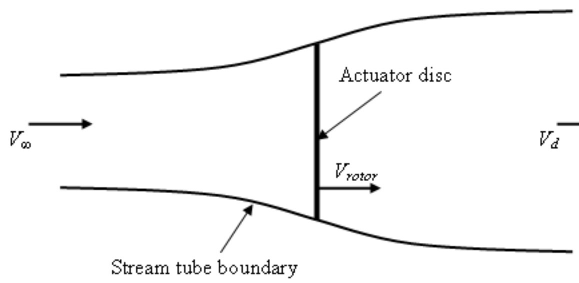

Fig. 2. Actuator disc, stream tube boundary, and wind speeds upwind, at the rotor and downwind. The actuator disc model describes the wind speed around an ideal wind turbine and is based on momentum theory

The axial induction factor a is a measure of the slowing of the wind speed between the free stream (far upwind) and the rotor plane. That is,

$$a = \frac{V_\infty - V_{rotor}}{V_\infty} \tag{2}$$

The downwind wind speed is related to the free stream wind speed by the axial induction factor in the following manner:

$$V_d = V_\infty (1 - 2a) \tag{3}$$

The power extracted by an ideal turbine is also related to the axial induction factor as

$$P = \frac{1}{2}\rho A V_\infty^3 4a(1 - a^2). \tag{4}$$

In (7), A is the "swept area" of the rotor, or πR^2, where R is the rotor radius.

The need for coordinated control of turbines located together on a wind farm can be motivated by a simple two-turbine example. Fig. 3 shows the power per unit area extracted from the wind by a two-turbine array in which one turbine is directly upwind of the other. This analysis assumes that the turbines are far enough apart that (3) holds, and V_d is both the downwind wind velocity for the upwind turbine and the upwind wind velocity for the downwind turbine. For an individual turbine, power is maximized when $a = \frac{1}{3}$ as shown in the "Upwind Turbine" curve of Fig. 3 (dashed curve). However, this axial induction factor slows the wind by (3) so that the downwind turbine has only $\frac{1}{3}$ the wind input of the upwind turbine.

The result of this simple motivational example is that the sum of the power extracted by the two turbines (solid red line) is lower when the upwind turbine's power is maximized at an axial induction factor $a = 0.33$. Coordinating the control of the two turbines by modifying the upwind turbines axial induction factor can maximize the total array power (and thus its total energy over time).

A wind turbine's axial induction factor a is a function of its blade pitch angle β and tip-speed ratio λ . Tip-speed ratio is a function of the rotor's angular velocity ω, rotor radius R, and the wind speed V:

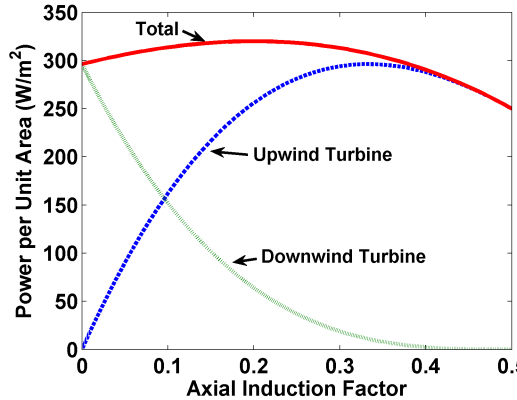

Fig. 3. Power extracted from the wind versus axial induction factor for a two-turbine array in which one turbine is downwind of the other. The upwind turbine produces maximum power at an axial induction factor of 0.33, but the two-turbine system produces maximum power when the axial induction factor of the upwind turbine is 0.20

$$\lambda = \frac{\omega R}{V} \tag{5}$$

Blade pitch angle can be controlled easily in most modern utility-scale turbines and tip-speed ratio can be controlled in an averaged sense (see [1] for a discussion of how the tip-speed ratio control can be achieved via generator torque). Thus, in principle, it is possible to maximize the total power produced by an array of two ideal turbines using either of these variables to control the axial induction factor.

The two-turbine array example motivates the two main points behind this tutorial paper. First, the optimal operating point in terms of energy capture for an individual turbine is not the same as for each turbine in an array of turbines. Second, active control can be used to find the individual turbine control parameter operating points that maximizes the energy capture from an array of turbines.

The actuator disc model used in the motivating example provides a simple representation that does not account for non-ideal turbines operating in turbulent inflow conditions. For example, turbulent inflow causes mixing downwind of a turbine, which in turn speeds up the downwind wind velocity to a value that is closer to the free stream velocity. However, some slowing is always present, and that slowing is a function of the spacing between turbines, as well as other variables. Since turbine spacing is usually not uniform in all directions, aerodynamic interaction depends on wind direction.

The turbine siting methodology used by most wind farm developers is to select the downwind and crosswind spacing based on the prevailing wind direction, local topography, and environmental and aesthetic constraints. When the wind inflow is from the prevailing direction, this methodology can work well. However, at most sites, there are seasonal variations in the wind direction that cause this arrangement to be better during some times of the year than during others. It is in these conditions that coordinated control of the wind turbines can have the most significant effect.

III. PREVIOUS RESEARCH

Numerous researchers have examined techniques for modeling and control of wind power plants as a whole, but most of these have focused on aspects other than energy maximization. Researchers at the National Renewable Energy Laboratory have developed electrical models to demonstrate that power quality and electrical reliability for wind turbines that are electrically connected within arrays compared to individual turbines [4], [5]. Other researchers have also developed advanced controllers for wind farm electrical systems [6], [7]. Zhao, Chen, and Blaabjerg [8] propose an optimization technique to maximize the capacity of new wind arrays based on physical system limits (voltage, voltage stability, thermal, load-tap changing, and generator power). These researchers use probabilistic analysis for their optimization, and do not consider aerodynamic interaction among turbines. A review of additional recent research on wind farm electrical system control is provided in [1].

Of the turbine array optimization schemes that consider the aerodynamic interaction among turbines, most involve techniques for placing turbines in a manner that minimizes the interaction rather than considering active control after the turbines are in place. Liu, Yocke, and Myers [9] consider techniques to minimize the aerodynamic effect of upstream turbines on downwind turbines, but they concern themselves with the initial turbine placement in the array. Their paper provides mathematical models of turbulent wakes behind turbines, including the effects of turbulence, surface constraints, wind shear, and topography. These aerodynamic models can be used as part of the turbine array aerodynamic interaction simulation model.

Schepers and van der Pijl [10] have also developed new modeling capability to explain the aerodynamic interaction among turbines in a wind farm, and include a discussion on how control can be used to improve the overall wind farm energy production.

Steinbuch and colleagues propose an overall wind farm control to maximize wind farm energy capture [11]. Their technique involves decreasing the tip-speed ratio λ of turbines in the upwind row by a certain factor below the optimal tip-speed ratio of an isolated turbine λ_* decreasing λ by a smaller factor for the row of turbines immediately downwind of the first row, and operating the third row at λ_*. The authors propose that trial and error be used to find the decreased in λ, but do not specify their specific approach. They also indicate that promising simulations have been performed, but do not show their simulation results, and concede that further research is necessary.

In addition to the actuator disc/momentum model used in the motivating two-turbine example, a wind farm simulation model should also account for the effects of wake rotation, airfoil shape and pitch angle, turbine operation mode (which affects both axial induction factor and airfoil stall), and turbulence in both the inflow and the wake. In particular, for a dynamic simulation, a dynamic wake model will be necessary. In addition to the models explained in [3] and [9], Frandsen [12] also studied the effects of turbine arrays on the wind speed within the array and explains several mathematical models. Depending on individual needs, a wind farm model could be based on relatively simple equations or more computationally expensive methods such as Computational Fluid Dynamics.

Much literature exists explaining mathematical models of the aerodynamic properties of wind turbines, both in arrays and operating independently. Unfortunately, data collected at multiple wind farms shows power discrepancies compared to predictions made using simulation tools. (Due to the proprietary nature of most wind farm data, we are unable to show these discrepancies in this paper.) Thus, intelligent, adaptive, or learning-type controllers may be best suited to this problem.

IV. SIMULATION DESIGN

The first step in testing new control strategies is to create a simulation model for use in the controller testing. The model described in this section has been designed to compute the power produced by each turbine in a wind farm and the total wind farm power. Because our discussions with the wind industry have shown that even the most sophisticated, computationally-expensive models do not always accurately predict the interaction among turbines in an array, we have decided to use a more basic model made up of equations found in the wind farm literature and implemented in Matlab's Simulink.

Fig. 4 shows the simulation model as we have implemented it in Matlab's Simulink. The position of each wind turbine in the wind farm is described using the coordinate system on the X-Y plane. The simulation model in Fig. 4 calculates the power produced by each turbine.

The *Overlap Factor* block determines the overlap factor between an upwind turbine's wake and a downwind turbine's rotor. The overlap factor is calculated as $\frac{A_{overlap}}{A_1^{(R)}}$ and is depicted in Fig 5, which shows the expanding area of overlap as a function of distance downwind of the turbine at the left of the figure. It also shows two overlapping circles from an orthogonal perspective, with the area of effect of the upwind turbine as the larger circle and the downwind turbine's swept area as the smaller circle.

The overlap factor is one of the inputs to the *Final Velocity* block, which calculates the wind velocity for each turbine downwind of the first row. The wind velocity deficit is determined using the the velocity deficit block according to the Modified Park Wake Model. The Park Wake Model was developed by N.O. Jensen and Katic et. al. [13]. It assumes an initial velocity deficit immediately behind the turbine rotor, which is calculated from the turbine's thrust coefficient $C_t = 4a(1-a)$ and an empirically determined wake-decay constant. This wake decay constant sets the linear rate of expansion of the wake with distance downstream.

The Modified Park model incorporates changes to the Park model developed by Garrad Hassan and Partners, Ltd. The area of overlap is not calculated as the area of intersection of

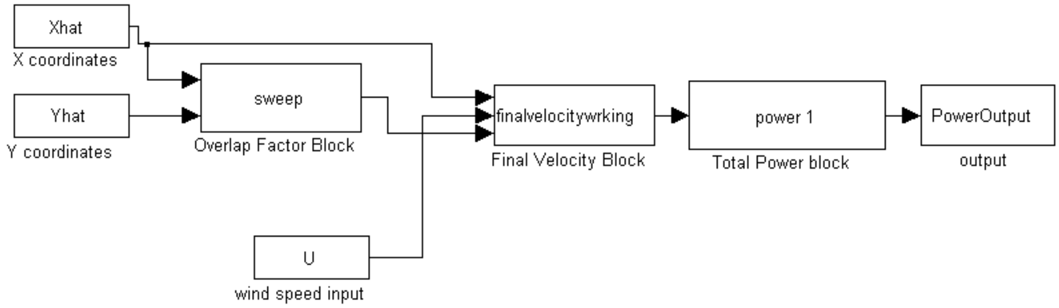

Fig. 4. Simulink model for simulation studies. This model calculates the power produced by each turbine given their positions, the wind speed input and the wind velocity input. It takes into consideration the wake effect to determine the loss in wind speed for the downwind turbines.

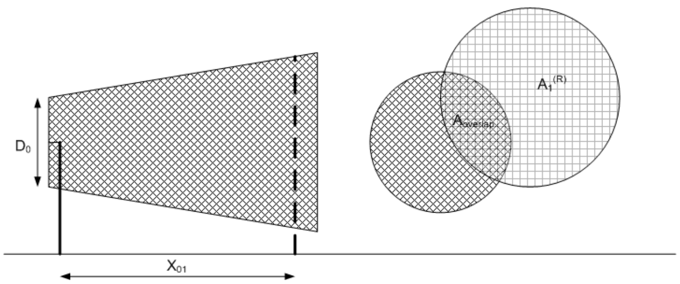

Fig. 5. Area overlap. This diagram shows the area of overlap as a function of distance downwind of the turbine at the left of the figure. Area of overlap is one of the variables used in calculating the wind speed input to downwind turbines. This figure is based on a similar figure in [13].

the wake and the incident rotor disk, as in Park. Instead, the fraction of horizontal overlap is calculated orthogonally to the wind direction but parallel to the ground, and the velocity deficit is multiplied by this fraction. These modifications produce smaller wakes than estimated by Park.

The decrease in wind velocity behind a wind turbine, or the "velocity deficit" δV_{01}, is computed as

$$\delta V_{01} = V_{\infty}.\left(1-\sqrt{1-C_t}\right).\left(\frac{D_0}{D_0+2kX_{01}}\right)^2.\frac{A_{overlap}}{A_1^{(R)}} \tag{6}$$

In (6), V_{∞} is the incident wind speed at the up wind turbine with rotor diameter D_0, C_t is the thrust coefficient, X_{01} the downwind horizontal distance between the wind turbines and k is the wake decay constant. The incident wind speed V_i for each turbine is thus the free-stream wind speed V_{∞} minus the wake deficit calculated as $V_i = V_{\infty} - \delta V_{01}$.

Once the final velocity is calculated using Modified Park's model, the power for each turbine P_i is calculated with their respective wind speed input V_i as

$$P_i = \frac{1}{2}\rho A C_p V_i^3 \tag{7}$$

where ρ is the density of air, A is the area of the turbine blade and C_p is the "power coefficient," which is a function of axial induction factor ($C_p = 4a(1-a)^2$).

Finally, the total wind farm power is given by the sum of the power produced by each individual power, or

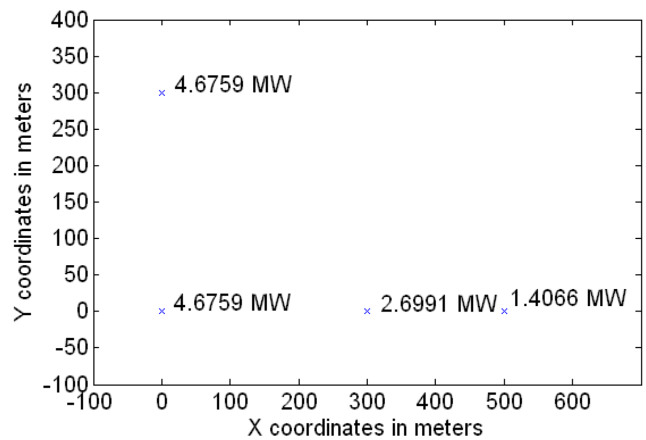

Fig. 6. Three-turbine simulation model test. This plot shows power produced by each turbine using the simulation model. As is shown by the figure, the downwind turbines produce less power than the upwind turbines.

$$P_{Total} = \sum_{N}^{i=1} P_i. \tag{8}$$

The simulation model described in this section is a work in progress and future work will incorporate ability to change the wind direction and re-compute the total wind farm power based on this time-varying wind direction.

A. Results

To test the model we used three turbine with coordinates (0,0), (0,300), (0,500) and (300,0). Here the wind speed and direction are constant with respect to time, with wind speed $V_{\infty} = 15m/s$ and wind direction $\theta = 270^o$ (a west wind).

Many of the parameters used in our model are user-generated inputs. Some of the values used for this example are shown in Table I.

With these inputs to the model, we can determine the power generated by each turbine, which is shown in Fig. 6. The two turbines in the wake of other turbines extract less power than the two turbines in the first (upwind) row.

V. WIND FARM CONTROLLER DESCRIPTION

Depending on the model, the set points corresponding to maximum energy for an individual turbine can be determined

TABLE I
PARAMETER VALUES

Parameter	Symbol	Value
Input wind speed	U	15m/s
Wake decay constant	W_d	0.1
Rotor Diameter	R_d	80m
Thrust coefficient	C_t	0.5
Air density	ρ	1.225 kg/m3

either in closed-form or using numerical methods for a given turbine array. However, the aerodynamics surrounding wind turbines is complex enough that many models have failed when tested in the field. For example, previous research has shown that the aerodynamic modeling software PROP [16] determined an optimum tip-speed ratio λ_* of 7.5 for a particular turbine, but field testing determined that λ_* is approximately 10 [17].

In response, one of the authors developed and tested a one-dimensional adaptive hill-climbing technique to maximize energy capture on an individual turbine with uncertain aerodynamic parameters [18]. This algorithm was shown to converge to the optimum tip-speed ratio λ_* under certain conditions reasonable for a wind turbine [19].

Because of the uncertain aerodynamic interactions among turbines in an array, some type of adaptive or learning control is necessary for achieving maximum energy capture in a wind farm. We have not yet developed a wind farm energy-maximizing controller in this work-in-progress research, but we plan to use a combination of Iterative Learning Control (ILC) [14] and Iterative Feedback Tuning (IFT) [15] to seek the control parameters that maximize the wind farm energy production. If the aerodynamic models available in the literature faithfully represent the aerodynamic interaction among turbines in an array, then wind farm energy maximization can be achieved by maximizing a set of turbine power equations given the constraints of turbine spacing, wind direction, and rated power of each individual turbine.

The control goal of maximizing wind farm energy capture defines a steady-state condition. We want to know, for a given wind speed and direction input to the farm, what axial induction factor set point a_i^* for each turbine i results in the maximum total wind farm energy. Since a can be controlled using blade pitch angle and tip-speed ratio, we can represent the total extracted power of an N-turbine array at time index n as a set of discrete-time nonlinear equations, where β_i and λ_i are the blade pitch angle and tip-speed ratio of turbine i,

$$\begin{pmatrix} P_1(n+1) \\ P_2(n+2) \\ . \\ . \\ P_N(n+1) \end{pmatrix} = \begin{pmatrix} f(P_1(k), V_\infty, \theta_\infty, \beta_1, \lambda_1, ...\beta_N, \lambda_N) \\ f(P_2(k), V_\infty, \theta_\infty, \beta_1, \lambda_1, ...\beta_N, \lambda_N) \\ . \\ . \\ f(P_N(k), V_\infty, \theta_\infty, \beta_1, \lambda_1, ...\beta_N, \lambda_N) \end{pmatrix}, \quad (9)$$

where P_{Total} is computed by (8).

Equation (9) gives a nonlinear multi-input, single-output representation of the wind turbine array operation and output power. The control goal is to maximize the total array power

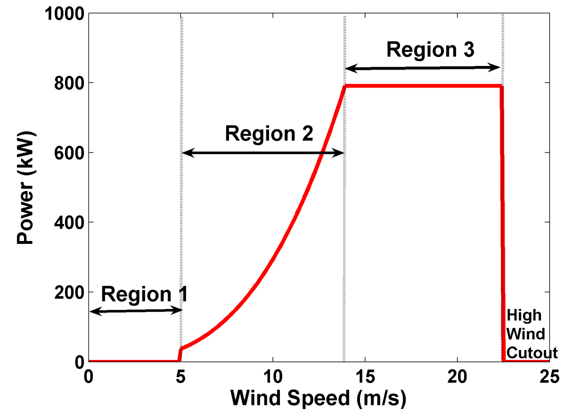

Fig. 7. Operational regions for an individual turbine. The curve denotes desired steady-state operation. The control objective for region 2 is to extract as much energy as possible from the wind, while the control objective for region 3 is to limit power so that safe mechanical and electrical loads are not exceeded

P_{Total} for a given wind velocity input using the control inputs β_i and λ_i.

The next step in the control design is to determine the desired output. The maximum power that can be extracted by a wind farm is a function of the wind speed. An individual turbine is typically controlled with several different control algorithms depending on whether it is operating in region 1, 2, 3, or stopped in high wind cut-out. These control regions are shown in Fig. 7. Region 1 includes the time during which a turbine is just starting up or waiting enough wind to start up. In region 2, we want the turbine capture as much power as possible from the wind. Region 3 is encountered when the wind speeds are high enough that a turbine must limit the power captured so that safe electrical and mechanical loads are not exceeded. Please see [1] for more information about control in each of these regions.

We emphasize that the controllers presented in this paper will investigate the steady-state control setpoints and thus will not hinder the dynamic control necessary to maintain turbine stability.

In an N-turbine array, the maximum achievable total power is NP_{i_max}, where P_{i_max} is the maximum achievable power by turbine i given the wind inflow. Although the aerodynamic interaction among turbines in an array makes it difficult to achieve NP_{i_max}, particularly during region 2 operation, this value can be used as part of a cost function for the controller. The cost function we wish to minimize is the difference between the energy that could be extracted during the time (t_0, t_f) by N individual turbines and the energy extracted by the wind farm, that is

$$J = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} [NP_{i\_max} - P_{Total}]\, dt \qquad (10)$$

Note that P_{Total} is most practically measured using the electrical power measurements at individual turbines or at the utility grid interconnection; that is, the best way to compute

(10) in the field is to use (8) with P_i measured at each turbine or to set $P_{Total} = P_{Grid}$.

However, care must be taken when using the power fed into the utility grid as a control signal, as over very short time periods this variable can be maximized by extracting all of the kinetic energy from the turbine, i.e., by stopping the turbine, regardless of wind speed.

A. Control Assumptions

In a wind farm, we can reasonably expect to measure the average wind speed V_∞ and direction θ_∞ for the overall array, the average wind speed on each nacelle (usually behind the rotor) v_{rot}, the electrical power produced by each individual turbine P_i, and the total power fed from the wind farm into the utility grid P_{Grid}. We cannot expect to measure the incoming wind to each individual turbine V_∞, the atmospheric turbulence near each individual turbine, the instantaneous wind velocity at any of the rotating blades, or the instantaneous axial induction factor a for any turbine.

We can control the pitch angle β accurately and with a time constant on the order of a few seconds, and we can control the average tip-speed ratio λ. Depending on the meteorological conditions, wind speed and direction can remain reasonably constant over a matter of days, or change drastically within seconds. It is this wind input uncertainty that leads to our proposal of a hybridized form of ILC and IFC control.

Due to the spatial arrangement of turbines in a wind farm, the aerodynamic interaction among turbines depends on the wind direction. This fact, along with the separate control operating points in the normal operational regions 2 and 3, lends itself to the idea of the beginning and ending of ILC and IFT control iterations being defined by the wind speed input. As long as the wind input remains from a certain direction and within a certain speed range, an IFT type controller will attempt to tune the control parameters λ and β to maximize the energy captured for those input conditions. When the wind speed or direction changes, a new experiment has effectively begun. Each time the wind input returns to an input condition for which experiments have already begun, the ILC part of the controller can update its information with the information contained in the new iteration.

To keep the control problem manageable, we will divide the wind input into reasonably-sized bins. For example, wind directions from 0^o - 30^o with wind speeds from 6 - 8 m/s might be considered one input set, and other sets would then be designed with 30^o divisions in wind direction and 2 m/s divisions in wind speed. The specific divisions to be used by the controller will be determined once the aerodynamic model is completed.

VI. CONCLUSION

In this paper, we have described how aerodynamic interaction among turbines on a wind farm can lead to a reduction in energy captured by the farm compared to the same turbines located individually and experiencing the same wind input as the wind farm. Using a simple two-turbine example, we have shown how coordinating the control of turbines located near each other by intelligent selection of the operational setpoint a can increase the energy captured by the array of turbines.

We have also described a simulation model under development for testing of coordinated wind farm controllers and preliminary results from that simulation model. Finally, we have proposed a hybridized ILC/IFT controller that may be effective at reducing wind farm array losses. Future work in this area will develop the proposed controller.

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