Detailed field test of yaw-based wake steering

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Abstract. This paper describes a detailed field-test campaign to investigate yaw-based wake steering. In yaw-based wake steering, an upstream turbine intentionally misaligns its yaw with respect to the inflow to deflect its wake away from a downstream turbine, with the goal of increasing total power production. In the first phase, a nacelle-mounted scanning lidar was used to verify wake deflection of a misaligned turbine and calibrate wake deflection models. In the second phase, these models were used within a yaw controller to achieve a desired wake deflection.

This paper details the experimental design and setup. All data collected as part of this field experiment will be archived and made available to the public via the U.S. Department of Energy's Atmosphere to Electrons Data Archive and Portal.

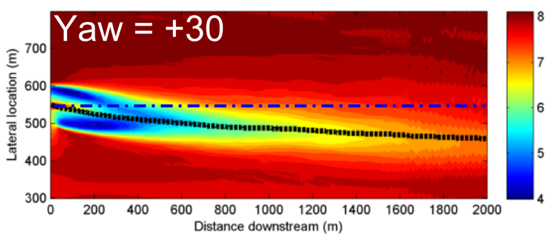
1. Introduction

Wind farm control is the coordination of individual controllers of wind turbines located within a farm to optimize total performance with respect to energy capture, loads, or some combination thereof. Wind farm control has demonstrated potential in previous modeling and simulation studies in both of these areas; for example, improved average power capture was shown in [1] and turbine load reduction was shown in [2, 3]. The coordination of turbine controllers in wind farm control can be implemented through adjustments of axial- and yaw-based control methods. Significant research has investigated improved power capture through the coordinated setting of axial induction through either pitch or torque control loops (see, for example, [4, 5, 6, 7, 8])

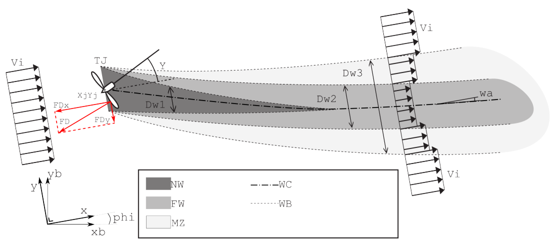
The alternative approach, often referred to as wake steering, has shown significant potential. In wake steering, the turbine's yaw angle is misaligned to the inflow wind direction, causing a redirection of the turbine wake [9]. Wake steering has shown promise in simulation studies to increase total wind farm energy capture. For example, [1] used high-fidelity wind farm simulations to show an average power increase for a two-turbine wind farm. In a study presented in [10], similar results were obtained using turbines positioned to wake each other in a wind tunnel. Looking ahead at how this technology could benefit wind energy, [11] shows that when combined with layout optimization, wake steering can yield layouts that substantially increase the power produced by the same area, whereas [12] demonstrates that wake steering can be used to increase annual energy production at an example wind farm when combined with layout optimization, with the total increase being far beyond what is possible with layout optimization alone. Finally, similar to axial control, wake steering has the potential to reduce wind turbine loads. Although most current work on wake steering has focused on power maximization, improvements to turbine loads have also been observed as a result of wake steering [1, 2].

To realize these benefits, validated models of wakes are critical. Higher-fidelity models are necessary to understand the underlying physics of wind turbine wakes, assess their controllability, and reliably predict wind turbine and farm performance. Control-oriented phenomenological engineering models, on the other hand, are required for the design and optimization of wind farm control systems.

In previous work conducted at the National Renewable Energy Laboratory (NREL), researchers developed two models capable of predicting wake redirection from turbine properties and yaw misalignment. The high-fidelity simulator used is the Simulator fOr Wind Farm Applications (SOWFA) model, which is a coupling of the FAST turbine simulator with the OpenFOAM computational fluid dynamics software package [13]. Figure 1a shows a SOWFA-simulated, time-averaged, two-dimensional (2D) cut-through slice of the three-dimensional (3D) wind flow downstream of a turbine that is misaligned 30 degrees from the inflow direction. The wake redirection is visible, with the wake center indicated by the dotted line. The second model is the FLOw Redirection and Induction in Steady State (FLORIS) model, illustrated in Fig. 1b. FLORIS is a control-oriented engineering model of wakes, with wake-steering capabilities built into the model [14]. The model of wake steering built into the FLORIS model is based on that of [15].



(a) SOWFA model of a turbine performing wake steering [16].



(b) FLORIS model of wake steering from [14].

Figure 1: Wake redirection visible in the outputs of two simulation models: (a) SOWFA and (b) FLORIS.

Although SOWFA has been validated against power production supervisory control and data acquisition (SCADA) data (see, for example, [17]), a dedicated field test is required to evaluate the performance of both SOWFA and FLORIS, especially with regard to wake redirection. Existing studies in the open literature related to verification or validation of wake-steering models and tools include wind tunnel tests [10], radar detection of wakes of a commercial wind turbine [18], and field testing at a scaled wind farm [9]. However, to better validate the FLORIS and SOWFA models or comparable alternatives, a dedicated field-test experiment to obtain more detailed data over a wider range of inflow conditions is required. This dedicated field test is the primary topic of this paper.

Currently, NREL and Sandia National Laboratories (Sandia) are jointly undertaking a research campaign to generate high-quality experimental data that can be used to validate SOWFA, FLORIS, and other models of wakes and wake steering. In this paper, we document the experimental design of this field-test campaign.

The field test will occur at Sandia's Scaled Wind Farm Technology (SWiFT) facility. Two turbines, aligned so that one will often wake the other based on the site's prevailing wind direction, will be used in the experiment. A nacelle-mounted lidar is additionally employed to directly measure the wake.

All data collected as part of this field experiment will be archived and made available to the public via the U.S. Department of Energy's Atmosphere to Electrons Data Archive and Portal accessible at [19]. Further, results will be presented at the Science of Making Torque from Wind conference in October 2016.

The remainder of this paper will document the test site, turbines, lidar, meteorological (met) tower, control, load sensing, and test plan for the project.

2. The SWiFT Facility

The field campaign utilizes the SWiFT facility operated by Sandia [20]. The site, located west of Lubbock, Texas, is on flat terrain on a decommissioned air field, surrounded by agricultural land (Figure 2). The SWiFT facility consists of two 60-m met towers and three highly modified Vestas V27 wind turbines. A detailed historical analysis of the SWiFT site's atmospheric characterization can be found in [21]; winds are predominantly from the south, with occasional high winds from the west-north-west. The turbines are expected to operate most frequently in the southerly winds, which allowed the SWiFT to be designed with the met towers positioned to the south of the turbines to measure the prevailing winds.

Figure 2: The SWiFT facility.

2.1. Turbines

The SWiFT facility includes three highly modified Vestas V27 wind turbines, which each have a hub height of 32.6 m, a rotor diameter of 27 m, and a rating of 192 kW. Characteristics of the test turbines are provided in Table 1.

This experiment will use the rightmost two turbines in Figure 2 as they are intentionally placed to be aligned with the prevailing wind direction at the site. Therefore, the downstream

Table 1: SWiFT turbine characteristics.

Characteristic	Value
Hub Height	32.6 m
Nacelle Tilt	4 degrees
Blades	OEM Vestas V27
Rated Power	192 kW at 44 rpm
Power Converter	Variable speed, full conversion
Pitch Control	Collective

turbine is frequently waked. The upstream turbine will implement wake-steering control and face the nacelle-mounted Technical University of Denmark's (DTU's) SpinnerLidar in the rear direction to characterize the wake. The downstream turbine will collect loads and power data to characterize the impact of different wake-steering control configurations.

2.2. Meteorological Tower

The SWiFT site includes two 60-m met towers located 67.5 m (2.5 rotor diameters) in front of the upstream turbines with respect to the predominant wind out of the south. The met towers provide critical details of the inflow wind to the two-turbine pair. The heights of the various sensors installed on the towers are given in Table 2.

Table 2: Meteorological tower sensors.

Sensor	Location Above Ground (m)
Sonic Anemometer	10, 18, 31.5, 45, 58.5
Cup Anemometer	18, 31.5, 45
Wind Vane	29
Relative Humidity	2, 27.5, 58.5
Temperature	2, 27.5, 58.5
Barometric Pressure	2, 27.5, 58.5

2.3. Site Layout

Figure 3 shows that the two turbines used in this campaign, SNL1 and SNL2, are aligned with the predominant wind direction and separated by a distance of 5 rotor diameters. The met towers are located south of the two front row turbines at a distance of 2.5 rotor diameters. The entire site is on a fiber-optic network, which generally logs over 500 data channels at a frequency of 10 Hz, synchronized to a GPS time signal.

3. Lidar

DTU's SpinnerLidar [23], as seen in Figure 4, is a critical addition to the baseline site instrumentation. The scanning lidar will be mounted in the nacelle of the upwind turbine, facing downwind. This location will allow for direct measurements of the wake during the experiment.

The device is a scanning continuous-wave Doppler lidar from ZephIR Lidar, Inc., and has been modified to include a two-stage prism optical head to produce a rosette scanning pattern to better image a vertical plane of a wind field [24]. The lidar is capable of adjusting its focal

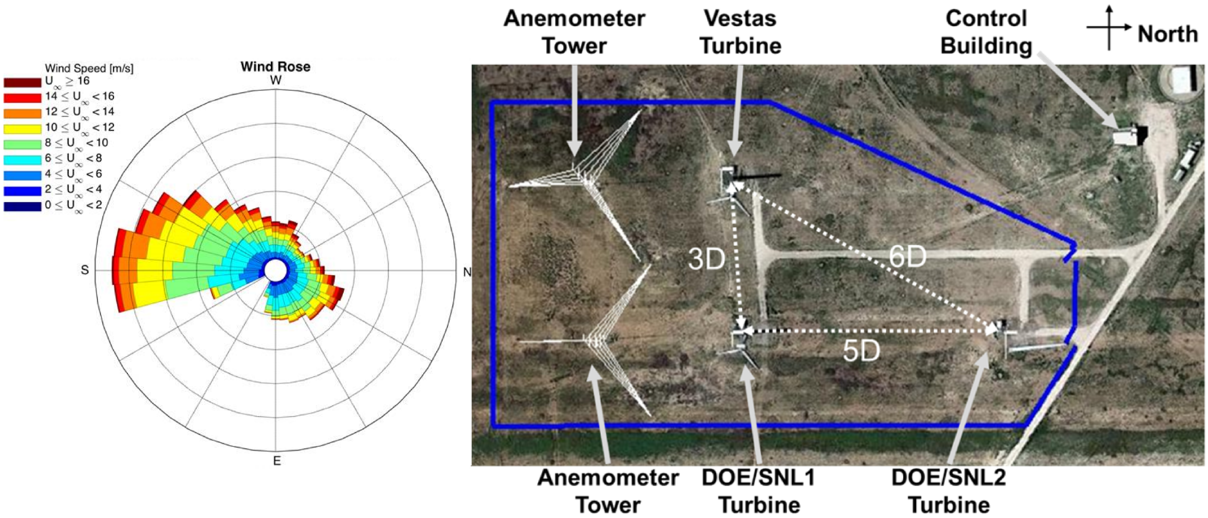


Figure 3: Layout of the SWiFT facility with the 77-m wind rose (north is right in both figures). The turbines are spaced relative to each other according to the rotor diameter D = 27 m. Wind rose reproduced with permission from [22]. Photo by Sandia National Laboratories.

Figure 4: The DTU SpinnerLidar installed on the SWiFT turbine. Photo by Tommy Herges, Sandia.

distance to scan at different ranges downwind. For more information on the lidar as well as the physics of how lidars measure the wind field see [23].

The design and simulation of the lidar mount and scanning behavior was a critical component of this work and is discussed fully in the companion paper by Churchfield et al. [25]. Here we focus only on the mount design. Simulations performed in SOWFA and FLORIS were used to determine if the lidar was capable of measuring the wake under different experimental configurations, including when the turbine operated with an intentional misalignment to the wind. An example of this analysis is shown in Figure 5. The analysis identified fixed lidar yaw offset angles that would enable the lidar scan pattern to capture sufficient portions of the turbine wake under various turbine yaw offsets.

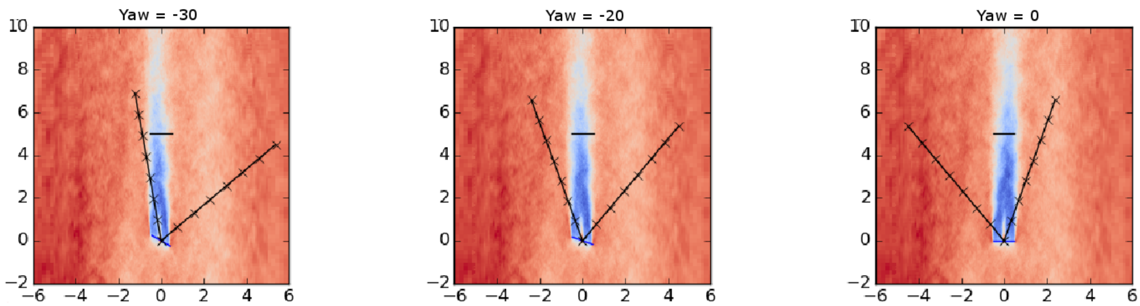
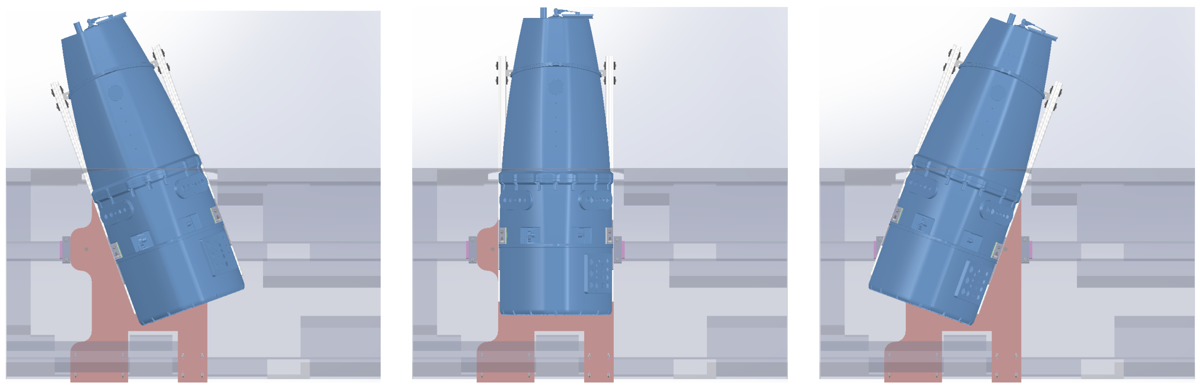


Figure 5: Possible lidar offsets. The upstream and downstream turbine rotors are indicated by the short black lines, whereas the lines with x-markers indicate the boundaries of the lidar scan.

Based on the simulation results, a custom lidar mount with an adjustable offset angle was designed and is shown in Figure 6. The mount allows the lidar to pivot about its own yaw axis $\pm\ 20^o$ (independent of the turbine yaw position), where 0^o represents when the lidar's scan axis is aligned with the rotor axis.



(a) The lidar mount shown in a +20-degree yaw position.

(b) The lidar mount shown in a 0-degree yaw position.

(c) The lidar mount shown in a -20-degree yaw position.

Figure 6: The lidar mount developed to support the DTU SpinnerLidar pointing out of the nacelle downwind of the wind turbine.

The lidar is configured such that it sequentially scans at several downstream distances, performing a complete rosette pattern at each distance as shown in Figure 7. Each rosette scan takes 1–2 seconds, depending on the prism motor speed, with a fraction of a second to

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refocus at the next distance. With five scanning distances, this results in a full scan of the wake approximately every 7–12 seconds. Prior to installation, the lidar scanning pattern was extensively calibrated in space using an infrared camera and a total station to quantify and minimize the experimental uncertainty. Custom data processing methods convert the raw lidar scan data into a metric that defines the wake center. This wake data along with the met and turbine data channels will be used to validate the FLORIS and SOWFA models. Table 3 provides important information about the DTU SpinnerLidar.

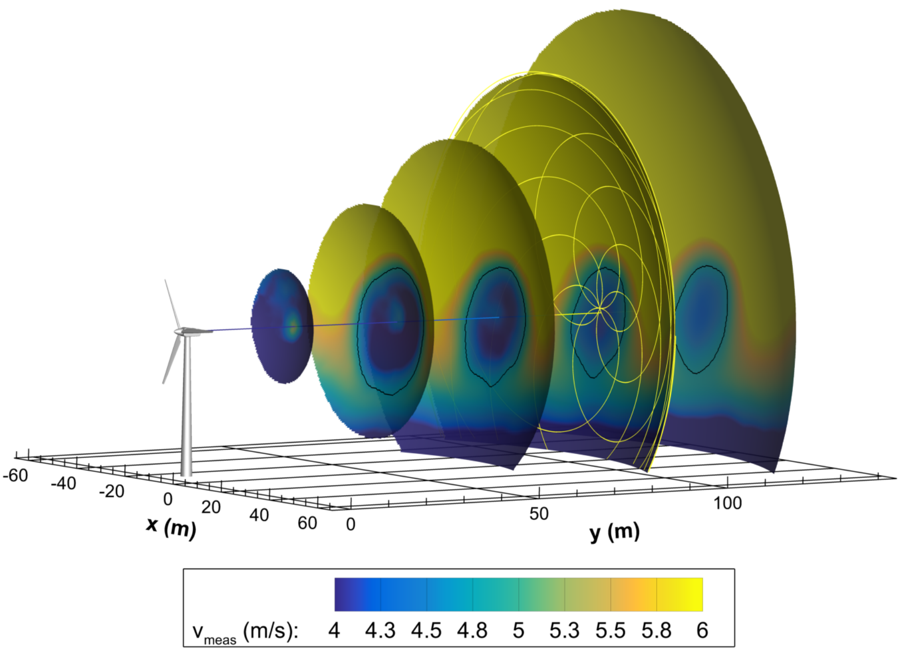

Figure 7: A schematic of the DTU SpinnerLidar scanning pattern that will be implemented at the SWiFT site overlaid on velocity profiles extracted from virtual lidar simulations. Illustration courtesy of Tommy Herges, Sandia.

Table 3: Details of the lidar.

Detail	Information
Measurement Range	9 m to 150 m
Scan Pattern Periphery Opening Angle	±30°
Sample Rate	50 to 400 Hz
Line-of-Sight Speed Range	1 m/s to 39 m/s
Minimum Time Per Scan	1–2 s
Laser Wavelength	1,565 nm
Measurement Type	Continuous-wave Doppler lidar

4. Directional Conventions

To avoid later confusion, we explicitly specify the following rules for angular conventions. For angles that are measured with respect to north, the normal compass rule applies and angles increase clockwise when viewed from the top. For all relative angles, the standard right-hand rule is applied and angles increase counterclockwise.

Therefore, for example, when the nacelle is located counterclockwise of the wind direction, we will consider it as a positive yaw misalignment (as shown in Figure 8). This is because the yaw angle is defined relative to the tower center axis that points upwards from the ground. Making this convention clear is important because the behavior of wake redirection with yaw is not necessarily symmetric (see, for example, [1]).

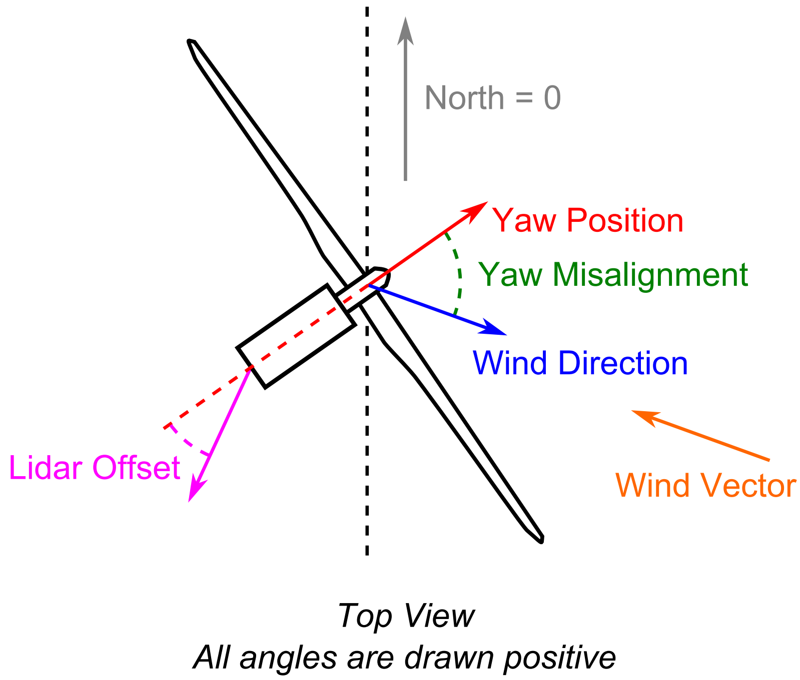

Figure 8: Directional conventions used throughout this work. Yaw position and wind direction follow the compass and increase clockwise, whereas yaw misalignment and lidar offset follow the right-hand rule and increase counterclockwise.

5. Loads Measurements

An important output of this experiment will be to study the impact of wake-steering control, which increases the percentage of time a wind turbine spends misaligned to the wind, on the extreme and fatigue loads of both the upwind and downwind turbines. These experimental measurements can then be used to assess how well models predict the loading impacts from yaw misalignment (for example, from [26] or [16]). Additionally, the data can inform follow-on studies in which loads are typically impacted significantly relative to normal turbulence-induced loads.

These data sets are valuable both because published load studies from turbines operating in a persistently yawed state are rare, and because impact on turbine lifetime is a critical question in considering whether these methods are employed. Few turbines are instrumented adequately to capture detailed loading data even if they are operated in yawed conditions. The turbines at the SWiFT site are highly instrumented, operate at a high data rate, are GPS time-synchronized, and the data are all public, overcoming many of the limitations of other experimental data sets.

The load sensing to be captured throughout the experiment is shown in Figure 9 and described in detail in Table 4.

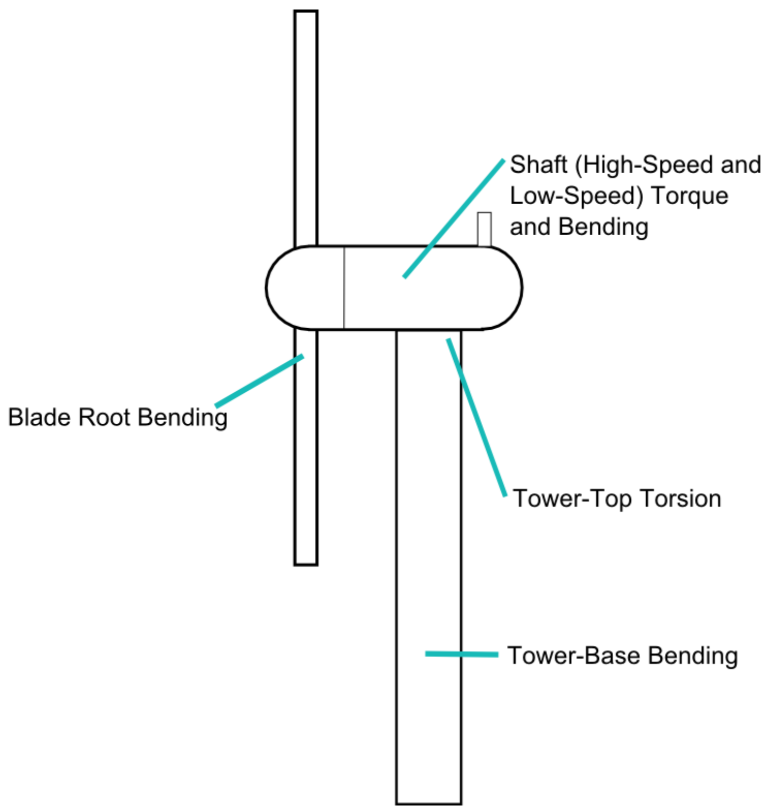

Figure 9: Layout of sensors on the SWiFT turbine.

Table 4: Turbine sensors used in the field-test campaign.

Sensor Name	Description
Blade-Root Strain	Edgewise and flapwise bending moment for each blade
Low-Speed-Shaft Strain	Torque moment on low-speed shaft
Tower-Top Strain	Yaw moment at top of tower
Tower-Base Strain	Bending moment at tower bottom
Yaw Encoder	Absolute turbine yaw position
Low-Speed Shaft Rotation	Rotor rpm
Rotor Azimuth Encoder	Rotor orientation
Pitch Actuator Aignal	Pitch angle position
Generator Power	Electrical power output
Nacelle Wind Sensor	Wind speed and direction

6. Field Experiment and Test Plan

The overall project plan is to run a test campaign in two phases. In the first phase of the study, the upstream turbine operates with a modified yaw controller (described later), so that it operates with a prescribed yaw misalignment with respect to the incoming flow. Several yaw misalignment values are set for prolonged periods of time for a range of inflow conditions, whereas the wake is measured using the DTU lidar described in Section 3. This approach provides a large sample of data under different inflow conditions.

The data collected from the first phase is then used to calibrate the FLORIS model of wakes and wake steering. In the second phase, these calibrated models will be used to derive a new controller that can achieve a desired wake deflection, given known inflow conditions. In one test within this phase, the controller can be derived to yaw the upstream turbine to the misalignment predicted to yield optimal two-turbine power output.

6.1. Yaw Control

As described, two yaw control strategies are proposed for this work. First, an offset controller is designed, which maintains a given offset from the wind direction. The controller is based on the yaw controllers employed in the Controls Advanced Research Turbines at NREL, as documented in [27]. The offset controller modified this control system only by applying a fixed error to the wind vane measurement. A second controller is developed once the FLORIS model has been validated to the collected data, called the wake-steering controller. This controller uses a lookup table derived from FLORIS to predict a yaw offset that would produce a desired amount of wake steering. The two controllers are shown in Figure 10.

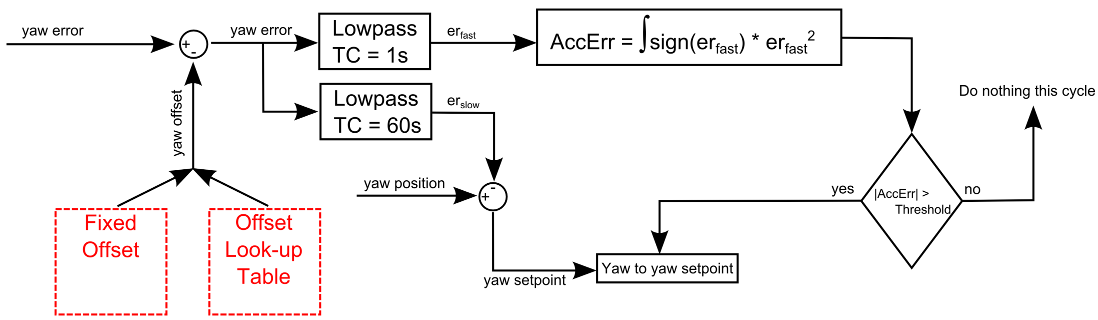

Figure 10: Diagram of the two yaw controllers used in the field-test campaign. In phase 1, an offset controller causes the yaw controller to track a fixed offset with the wind direction. In the wake-steering controller, a desired amount of wake steering is obtained by determining the proper offset from a look-up table derived from FLORIS.

Figure 10 shows that controllers read the yaw error from the vane. The error is in the upper pathway accumulated, and when that value exceeds a particular threshold, the turbine yaws to a new position given by a slowly filtered version of the error. The difference between the two controllers is whether a fixed offset is applied or if the offset is derived from a look-up table.

An important component of the test plan is that during testing of either controller, it is expected that the control will automatically toggle between operating points. This practice allows a data set to be accumulated in which various control settings are applied in approximately equal amounts of the same operating conditions (versus applying one 1 day and another the next, which could bias the results).

7. Conclusions

This experiment is expected to yield important data that can be used to evaluate and improve models critical to the implementation of wind farm control. All data collected as part of this field experiment will be archived and made available to the public via the U.S. Department of Energy's Atmosphere to Electron's Data Archive and Portal [19]. Results and analysis of the data will further be provided in a number of expected reports that will be made publicly available and presented at The Science of Making Torque from Wind conference.

Acknowledgments

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