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The SOWFA Super-Controller: A High-Fidelity Tool for Evaluating Wind Plant Control Approaches

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Abstract

This paper presents a new tool for testing wind plant controllers in the Simulator for Offshore Wind Farm Applications (SOWFA). SOWFA is a high-fidelity simulator for the interaction between wind turbine dynamics and the fluid flow in a wind plant. The new super-controller testing environment in SOWFA allows for the implementation of the majority of the wind plant control strategies proposed in the literature. Case studies are presented at results from a yaw control scheme are promising.

Keywords: wind plants, control engineering, software tools

1 Introduction

Wind energy offers a great potential to realize the desired reduction in carbon emissions of 20% by 2020 in the European Union; however, the current high costs of wind energy production impede further deployment of large-scale wind parks.

The reduction of cost of energy (CoE) in wind power is at the center of many ongoing research efforts. Improved control design is one focus; advances in controls can lead to reduced loading and increased power capture, both of which can potentially reduce the CoE. In the past, much of this research focused on improving the controller of a single turbine, but recent research has shifted toward improving the performance of the wind plant as a whole through organized control operations across turbines.

Intelligent wind plant controls have the possibility to reduce the CoE of wind power by maximizing the total power output of the wind plant (instead of each individual turbine, which could be suboptimal) as well as by helping to reduce the loads experienced by turbines. These benefits are gained by accounting for the way turbines affect each other through their wakes and attempting to reduce or direct these wakes through changes to the turbine controllers. The wake following a turbine can be affected by changing the yaw orientation of the turbine and/or its power extraction level [1].

1.1 Current State-of-the-Art Wind Farm Control

Wind farm control is to date a relatively unexplored field. Recently, an increasing number of approaches for wind plant control have been proposed in the literature. Although the methods are diverse, a typical theme is to move from “greedy” algorithms, where each turbine controls itself for optimal individual performance in isolation, to centralized algorithms, which modify a base turbine algorithm to yield enhanced global performance. Examples that fit this approach include controllers modifying the axial induction factor of the turbines by adjusting blade pitch and generator torque away from individually optimal settings to reduce the wake effect ([2]–[6]) and controllers that orient the turbine yaw away from

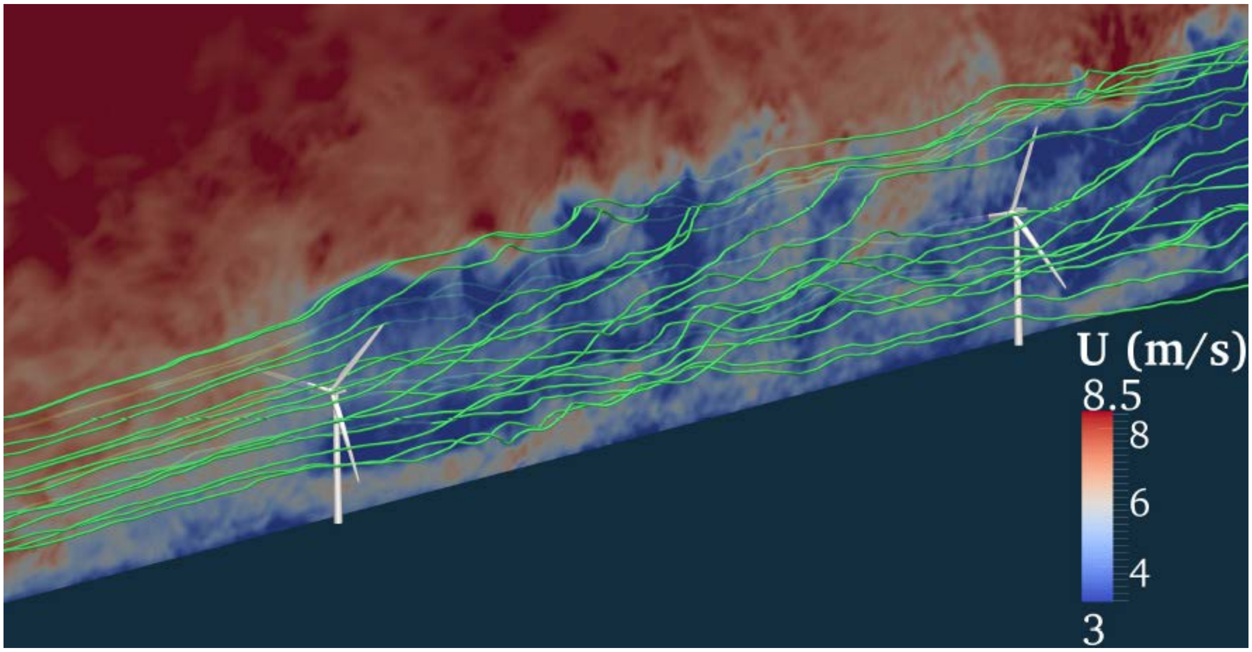


Figure 1. SOWFA simulation of two turbines subjected to an atmospheric boundary layer. The streamlines show the instantaneous velocity contours [17].

the wind to deflect the wake downstream of the rotor [7].

Many of the proposed controllers rely on strong simplifying assumptions, such as a strict separation between the wind farm controller and the local wind turbine controllers and static wind inflow to the plant. These allow implementation in current software architectures, but testing controller reaction to time-varying wake interaction is infeasible [8]–[13]. For example, in [8], it is shown that turbine power set points can be optimized for a static case; however, the computational burden of the solution of the underlying fluid-dynamics problem makes this approach unsuitable for real-time adjustments. In [10]–[11], in which the wind farm controller of the Horns Rev wind farm is presented, a slow proportional-integral (PI) controller is used to control the overall power output, but the individual power set points are generated by a static function, therefore this controller is unable to adapt to time-varying wake interaction.

Time-varying wake dynamics have a significant impact on the performance of wind plant controllers; however, many proposed wind plant control approaches to date have been tested only in a highly simplified modeling environment. Notable exceptions were the tests performed in [7], [14]–[15], which used wind tunnels or a scaled wind farm. However, a high-fidelity simulation tool in which wind plant control algorithms can be evaluated and compared is essential for researching and developing wind plant controllers. This tool should allow for testing wind plant controllers at fidelity comparable to what has been available for individual turbine controller development in the past.

In this paper, we present the Simulator for Offshore Wind Farm Applications (SOWFA), specifically the super-controller functionality that has been recently developed. The super-controller is a software architecture that can be tailored to implement the majority of wind plant control systems proposed in the literature. This new capability enables the SOWFA to perform high-fidelity simulations of wind plant controls.

In Section 2, we review the SOWFA tool itself. This is followed in Section 3 by an overview of the super-controller architecture specifically. In Section 4, we present several ongoing case studies meant to illustrate the functionality of the

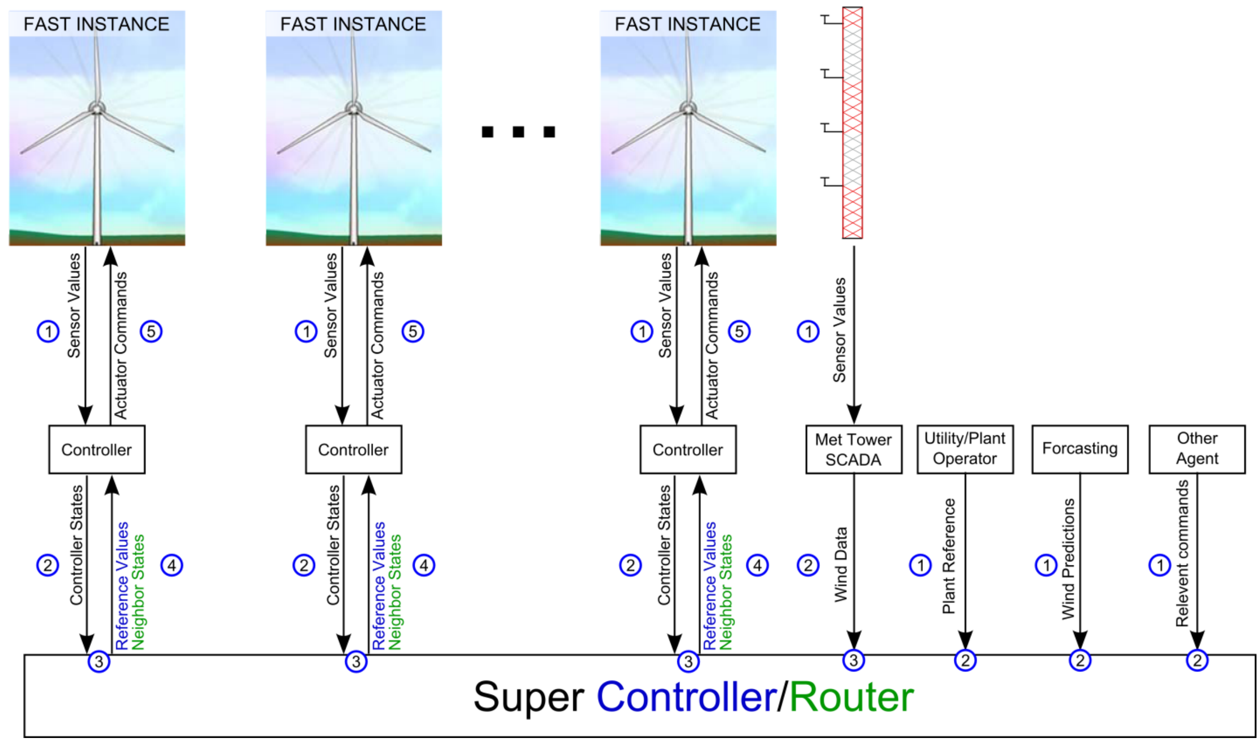


Figure 2. Control architecture in SOWFA.

tool and motivate further research. Finally, Section 5 presents conclusions.

2 SOWFA

SOWFA [16] is a computational fluid dynamics solver based on OpenFOAM (Open-source Field Operations and Manipulations) libraries [17] coupled with FAST (the National Renewable Energy Laboratory's [NREL] open-source wind turbine simulator [18]) that allows users to investigate wind turbine performance under various atmospheric conditions. The governing equations for the fluid dynamics are derived from the incompressible Navier-Stokes equations in which the buoyancy effect is computed using the Boussinesq approximation. The equations are discretized using an unstructured collocated finite-volume formulation. The second-order central-differencing scheme is employed and uses the Rhie and Chow [19] interpolation method to avoid checkerboard pressure-velocity decoupling. For time advancement, pressure implicit splitting operation is used, with three substep corrections to maintain a second-order temporal accuracy. The actuator line method [20] is used to model the turbine blades that generate wake structures. The discrete forces at the actuator points are computed by FAST, which employs the fourth-order Adams-Bashforth predictor and Adams-Moulton corrector time integration schemes. Further details are provided in [16].

SOWFA has been validated in previously published studies, and ongoing studies seek to continue the validation process. In [23], a SOWFA simulation of the 48 turbine Liligrund wind plant was compared with field data and good agreement through the first five turbines in a wind-aligned row was shown. In [24], experiments are performed which test SOWFA's ability to capture the inertial range in the turbulent energy spectra and the log-layer in the mean flow, both of which characterize a realistic atmospheric boundary layer. Future publications will document ongoing validation studies.

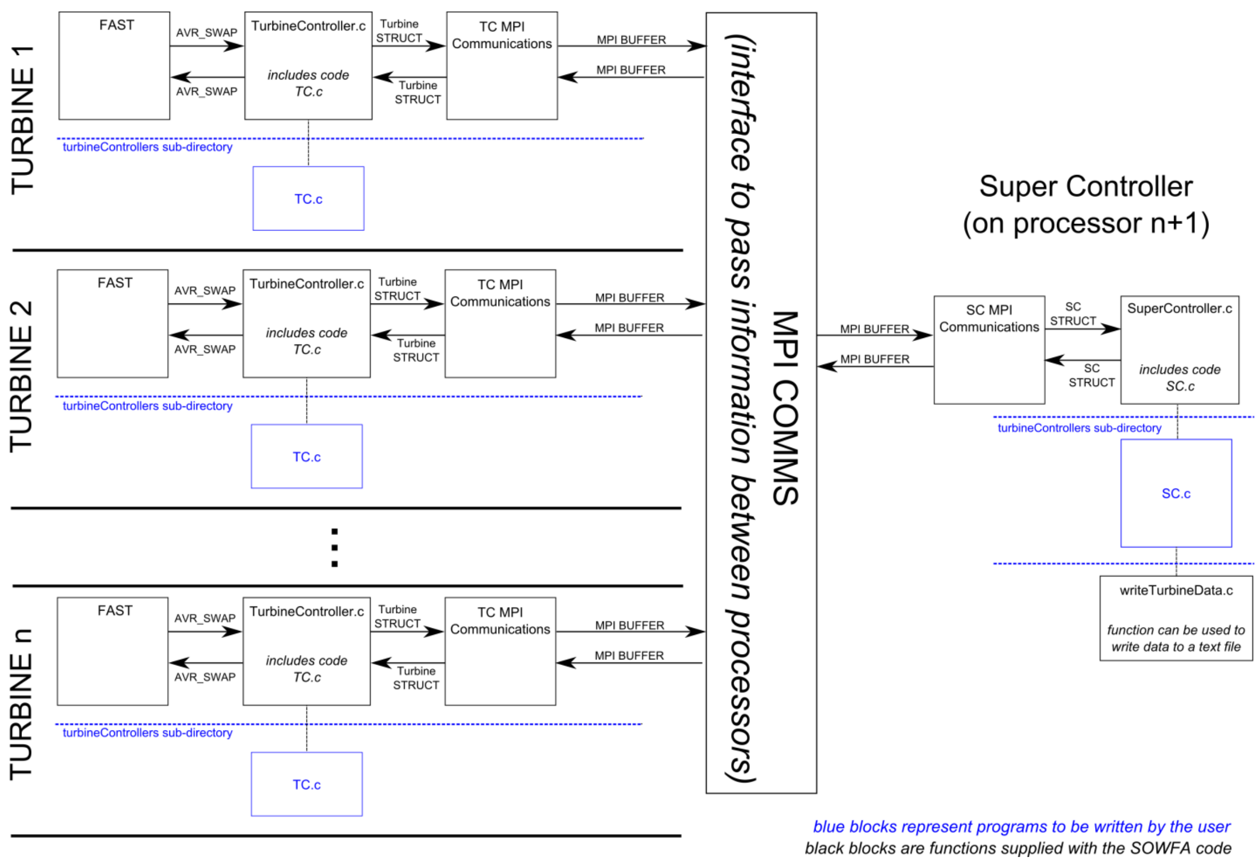


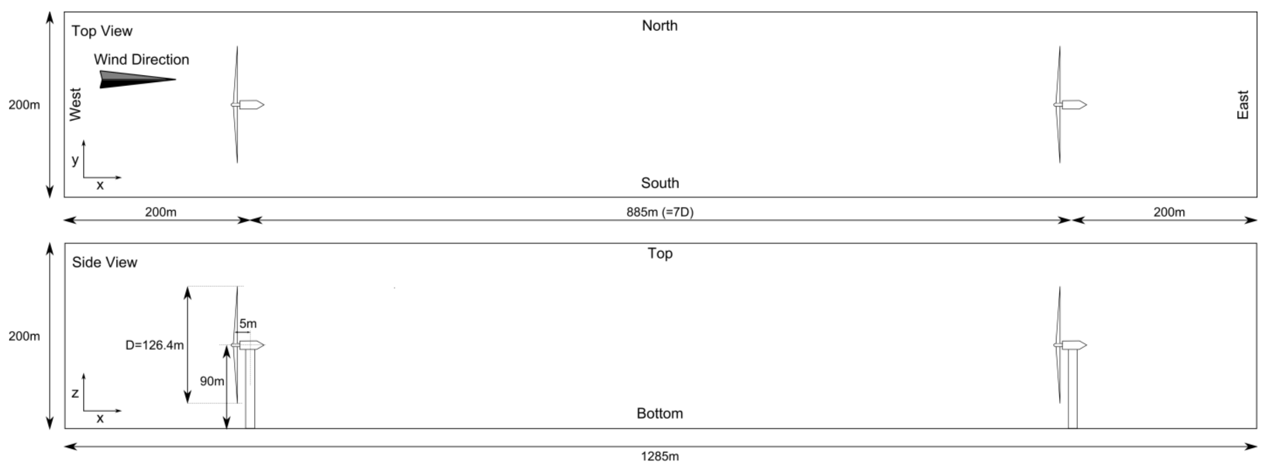
Figure 3. Communication in the SOWFA super-controller architecture.

3 SOWFA Super-Controller

Recently, a super-controller implementation was integrated into SOWFA that allows wind plant control designers to implement a multi-turbine control algorithm in a way that can realistically approximate how this might be performed in an actual wind plant. Rather than having direct control of wind turbines by a central controller, an architecture is established where a central super-controller is capable of receiving information from individual turbines and sending command messages. This occurs even when the individual turbine simulations are being performed on multiple processors in a high-performance computing cluster. Alternatively, the central controller can function to coordinate message passing between turbines to allow testing of distributed control designs. This architecture is illustrated in Figure 2.

The super-controller software architecture consists of a Message Passing Interface (MPI) that is supplied with the SOWFA code, which is illustrated in Figure 3. Implementing a certain control concept is done by writing the control algorithms for the super-controller and for the controllers of the individual turbines in C code, represented in Figure 3 by the blocks SC.c and TC.c, respectively.

The individual turbine control algorithm TC.c exchanges its input signals (sensor values) and output signals (actuator commands) with the FAST turbine simulation program by passing back and forth an array variable called AVR_SWAP. Additionally, turbine data and command values are exchanged with the super-controller through a predefined C structure called TurbineStruct, which is passed to the super-controller through the MPI. Likewise, a variable SC_STRUCT is defined in the super-controller code SC.c. These structures enable passing turbine data to the super-controller and passing command data back to individual turbine controllers. The software architecture



Block mesh generation for OpenFOAM CFD solver		
	Number of cells	Size of cell
x-direction	161	7.981m
y-direction	50	4m
z-direction	50	4m

Figure 4. Schematic of computational domain of system-identification experiment with two 5-MW turbines.

can be classified as a client/server setup in which the individual turbine controllers make requests to the super-controller program to update and pass the SC_STRUCT variable.

4 Case Studies

This section presents two case studies that illustrate the use of SOWFA for conducting evaluations of wind plant control systems.

4.1 System Identification

To show the potential of the proposed infrastructure, a simplistic example is given that illustrates the main components of the tool. In this example, two NREL 5-MW baseline turbines [21] are simulated, where the second turbine is positioned in the full wake of the first turbine. This setup is shown in Figure 4.

A super-controller is established that recieves information from the individual turbine controllers (as described in [21]) about the current state of the turbines and then returns a value by which a given turbine should scale its commanded generator torque. Both turbines are commanded to operate normally until 300 s have passed, at which point the upwind turbine is commanded to drastically reduce its torque. Outputs of the experiment are shown in Figure 5, where the main capabilities of the proposed approach are illustrated. The super-controller outputs all the signals relevant for controller design, although the flow can be visualised by OpenFoam outputs. In Figure 5, we can see that at 300 s, a step in the torque of the first turbine is applied; consequently, the power drops instantanously, with a fast dynamic component (dynamics of the drivetrain modeled by FAST). At 410 s, the effect of the step change reaches the second turbine and a large overshoot is observed before the power settles to a new, higher power equilibrium. The time scale of the overshoot can not be explained by the structural dynamics of the turbine. By looking at the velocity contour figures, a travelling wave is visible with an increased velocity at the beginning of the wave. Both effects are not covered by simplistic models that are traditonally used for wind farm control studies.

This particular case study is simplistic, but it demonstrates the operation of SOWFA with a simple hierarchical controller. Moreover, it shows that both the fast turbine structural dynamics as well as the slow wake dynamics can be captured in a single high-fidelity model.

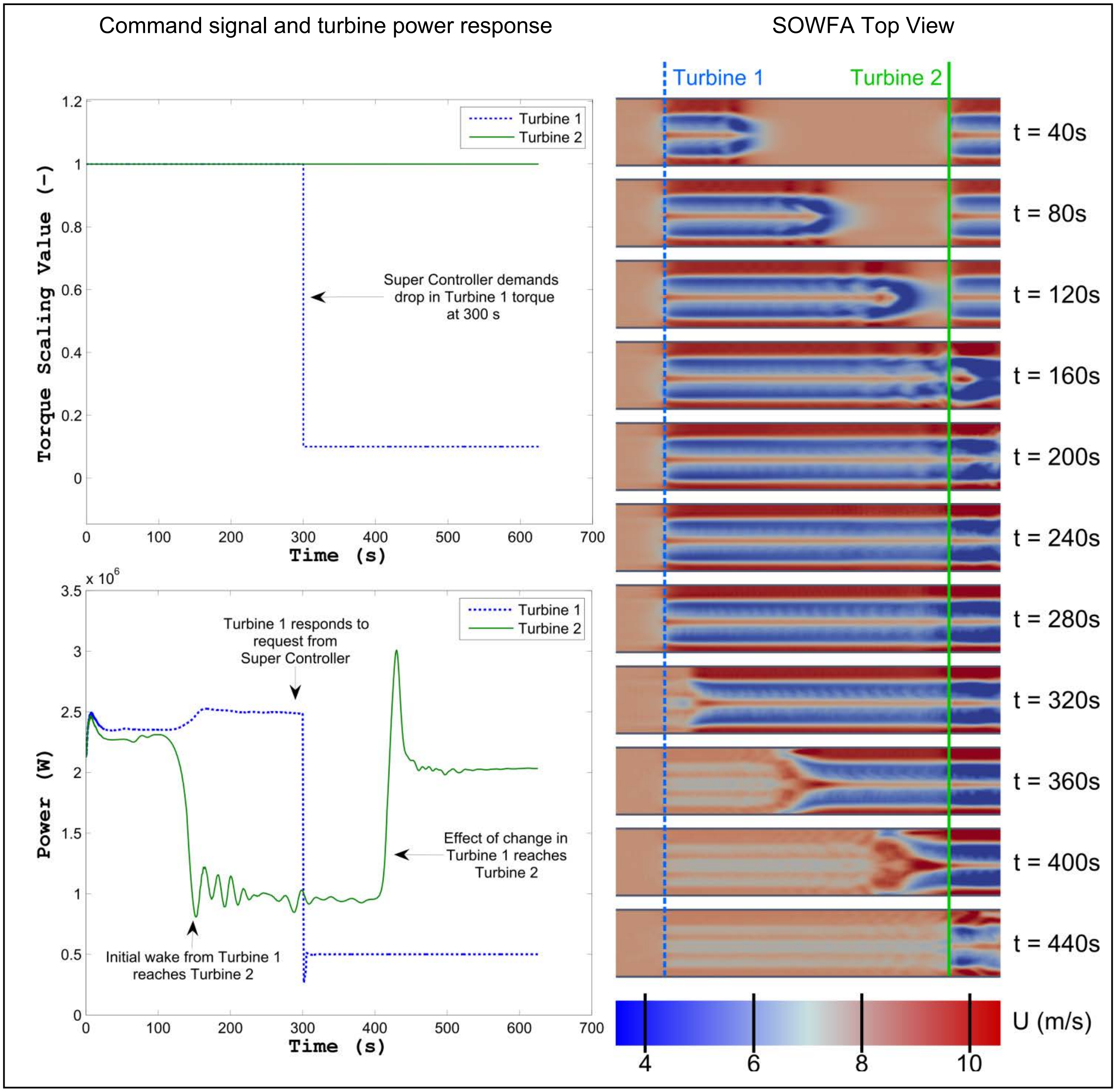


Figure 5. Results of a step response simulation with SOWFA for a two-turbine setup.

4.2 Yaw Alignment Control

A second example is provided to further illustrate the potential of SOWFA. In this example, the super-controller collects turbine data from individual turbines and provides each with a reference yaw angle. The turbines operate nominal pitch and torque control independently (as defined in [21]). This setup is illustrated in Figure 6.

Wind plant controllers that employ yaw have been discussed in the literature and focus on diverting the wake of an upwind turbine away from a downwind turbine through the intentional inclusion of yaw misalignment [7],[22].

A SOWFA study of this type of controller is ongoing. Initial results are presented here as a second case study in the use of SOWFA for evaluating wind plant control.

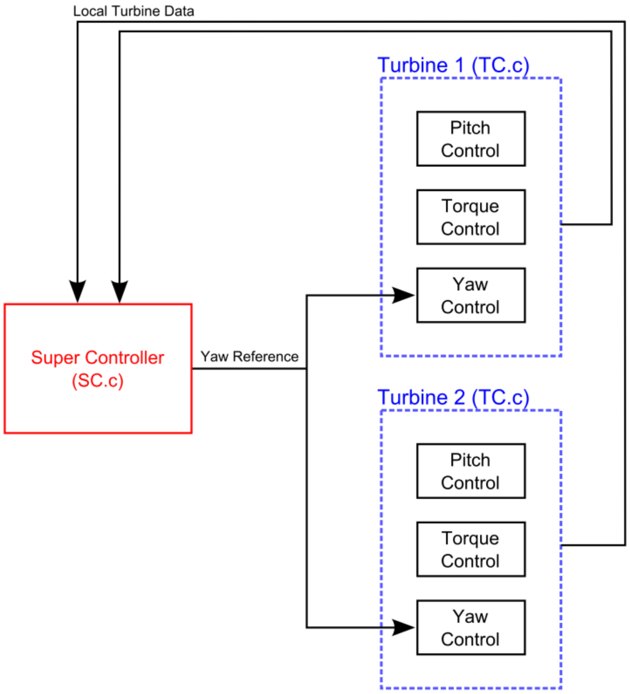


Figure 6. Yaw controller setup.

A super-controller that commands yaw angles was first established, as illustrated in Figure 6. The individual turbine yaw controllers move at a rate of 1°/s to the yaw reference. Next, a scenario was developed to simulate two turbines aligned in turbulent inflow. The turbulent scenario is that of a neutral boundary layer, which is based on a case selected from a previously published study [24]. The domain size is 3 km by 3 km in area with 1 km in height to allow atmospheric boundary layer simulation using large-eddy simulation. However, the Coriolis term was neglected to orient the mean wind direction at a targeted angle (270° incoming flow) at the turbine hub height (90 m). The mean wind speed is 8 m/s at the turbine hub height. Further details can be found in [24].

As a first step in the study, the logic of the super-controller is simplified to command a sweep of yaw angles for the upstream turbine (rather than active control laws). This way, an analysis of the benefits and costs to the upstream and downstream turbine can be performed across misalignments. Cases were run with no yaw, then the first turbine yawed in both positive and negative angles in increments of 5°. For this case study, no yaw, 10°, and 20° were selected for analysis. A full analysis will be performed in later publications; this description is intended as an application example. Screen shots of wind velocities are shown in Figure 7.

Using the tabulated turbine data recorded by the super-controller, it is possible to compare the effect of misaligning the front turbine. For this example, the focus is on the power of each turbine individually and collectively, then on the effect on blade flap bending. Flap bending is presumed to be affected in the upstream turbine because of rotor yaw misalignment and in the downstream because of changing amounts of wake and rotor overlap. These results are summarized in Table 1.

The results from SOWFA are instructive. First, in terms of power, although misaligning the upstream turbine leads to a reduction in output power, the increase gained in the downstream turbine is more substantial and the global power increases, as was hoped for. Blade flap bending is also interesting to consider, as it is shown that

Table 1. Comparing Effects of Varying Yaw Misalignment of Upwind Turbines

	Power Output (MW)				Blade 1 Flap DEL (kNm)	
Case	Upstream	Downstream	Total	% Change	Upstream	Downstream
Baseline	0.87	0.43	1.29		801	1,172
Yawed 10°	0.85	0.48	1.33	+2.64%	685	1,185
Yawed 20°	0.79	0.58	1.38	+6.16%	712	1,296

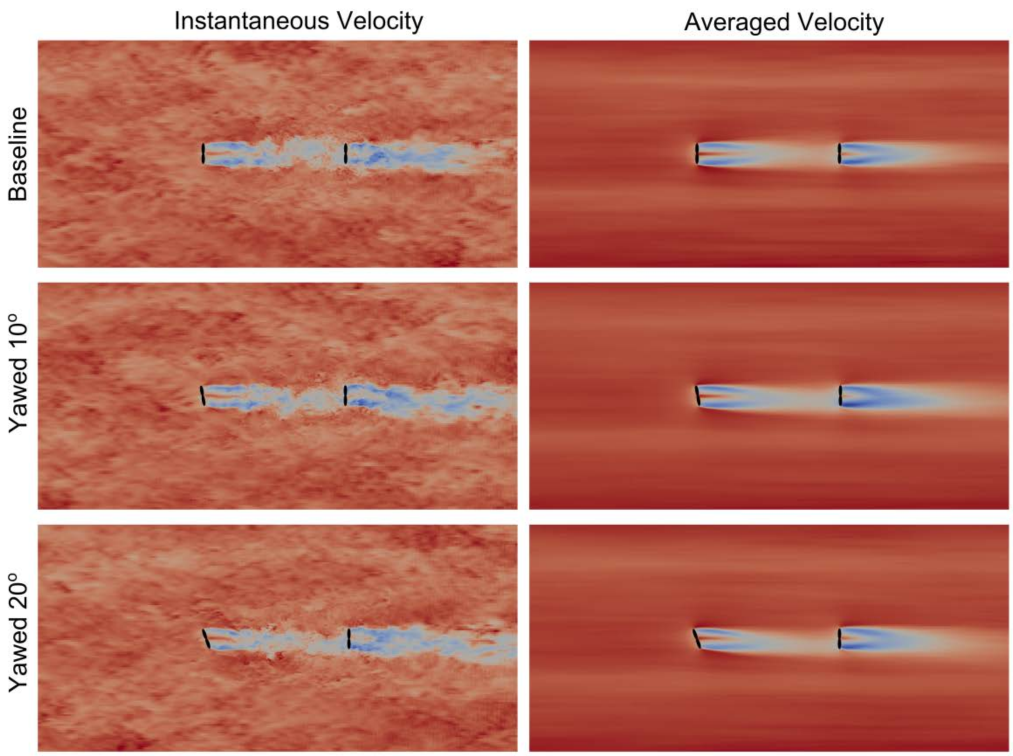


Figure 7. Examples of velocity fields calculated by SOWFA.

the yaw misalignment reduces the flap damage equivalent load (DEL) on the upstream turbine. However, partial wake overlap leads to an increased blade flap DEL for the downstream turbine.

A more detailed version of this study will explore a broader sweep in depth, and these high-fidelity results will be very useful in proposing and designing wind plant controllers for optimizing wind turbine yaw angles across wind plants.

5 Computational Expense

SOWFA requires significant computational power in order to run simulations in a reasonable amount of time. The two simulations performed in this paper represent two different examples of computer/time requirements which are summarized in Table 2. The system identification experiment was performed on the NREL supercomputing cluster Red Rocks, while the yaw misalignment study was performed on the Sandia/NREL Red Mesa supercomputer [25].

SOWFA is a high-fidelity simulator intended to provide the ability to perform realistic validation experiments. However, the computational time can be prohibitive for developing a wind plant control system. Therefore, ongoing research is investigating computationally efficient low-order models using SOWFA. One such example is the development of a dynamic wake-meandering model [26]. Additionally, system-identification studies within SOWFA are being performed to identify controller-order models.

6 Conclusion

Wind plant control is an exciting research field, with possibilities for making improvements in wind power performance and CoE. With many proposed plant controllers arriving in the literature, a good method for testing these algorithms is required to make meaningful evaluations. We believe the open-source and freely distributed SOWFA with the super-controller will provide this essential functionality. The tool is flexible enough to implement and evaluate any wind plant controller currently being proposed in the literature.

Table 2. Statistics for simulations in this paper

	System Identification	Yaw Misalignment
Time Step	0.02 s	0.02 s
Domain Size	1285 m x 200 m x 200 m	3 km x 3 km x 1 km
Number Cells	161 x 50 x 50 = 402,500	250 x 250 x 83 = 5,187,500
Processors	64	128
Computer time per step	0.36 s	3.3 s
Simulation Time	600 s	1000 s
Approximate Execution Time	3 h	46 h

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