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Launch of the FarmConners Wind Farm Control benchmark for code comparison

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Abstract.
Careful validation of the modelling and control actions is of vital importance to build confidence in the value of coordinated wind farm control (WFC). The efficiency of flow models applied to WFC should be evaluated to provide reliable assessment of the performance of WFC. In order to achieve that, FarmConners launches a common benchmark for code comparison to demonstrate the potential benefits of WFC, such as increased power production and mitigation of loads. The benchmark builds on available data sets from previous and ongoing campaigns: synthetic data from high-fidelity simulations, measurements from wind tunnel experiments, and field data from a real wind farm. The participating WFC models are first to be calibrated or trained using normal operation periods. For the blind test, both the axial induction and wake steering control approaches are included in the dataset and to be evaluated through the designed test cases. Three main test cases are specified, addressing the impact of WFC on single full wake, single partial wake, and multiple wake. The WFC model outcomes will be compared during the blind test phase, through power gain and wake loss reduction as well as alleviation of wake-added turbulence intensity and structural loads. The probabilistic validation will be based on the median and quartiles of the observations and WFC model predictions. Every benchmark participant will be involved in the final publication, where the comparison of different tools will be performed using the defined test cases. Instructions on how to participate are also provided on `farmconners.readthedocs.io`.

1. Introduction and objectives of the FarmConners benchmark

Wind farm (flow) control, commonly referred as WFC, brings a collaborative approach to wind power plant design and operation, promising to mitigate the losses due to turbine-turbine interaction within the plant. Technology for coordinated WFC is currently under development at numerous research institutes, industry and certification agencies globally. However, the uncertainty remains high, and hence well-documented and clearly presented benchmark cases for validation of different control-oriented models under different control settings are still lacking.

The FarmConners project (28) aims to remove the barriers for commercial implementation of WFC by coordinating a reliable assessment of the state of the art in this technology. In order to truly assess the performance of wind farm controllers, the efficiency of the WFC models should be evaluated. Accordingly, to increase confidence in the models and eventually in the technology itself, FarmConners introduces a comprehensive validation platform for WFC-oriented flow and load models, where high-fidelity simulation results ('synthetic' data set), wind tunnel experiments and the field data from a full-scale wind farm in real atmospheric conditions are brought together.

The goal of the FarmConners benchmark is to provide common test cases to demonstrate the potential benefits of wind farm control, such as increased power production and mitigation of loads. Different flow and aeroelastic models are to be evaluated against the same database, which includes both axial induction and wake steering control scenarios. As a result, FarmConners aims to quantify and increase the reliability of potential WFC benefits via a well-supported and well-documented test environment.

One of the most relevant successful benchmarks is organised by IEA-Task 31 Wakebench: Towards a protocol for wind farm flow model evaluation (19; 17). Similar to Wakebench, FarmConners aims to promote data sharing and standardisation for validation processes. On the other hand, the main emphasis of the FarmConners benchmark is the performance evaluation under controlled operation, rather than characterising normal operation (without WFC) as in Wakebench. Although the lessons learned from the comprehensive Wakebench experience (13) are attentively taken into consideration, the two benchmarks diverge in terms of test cases, quantities of interest and validation metrics. In that regard, an important outcome of the FarmConners benchmark will be to extend the international Verification and Validation (V&V) framework on wind farm models to include WFC operation in wake research.

The FarmConners benchmark is a collection of data sets, test cases and validation metrics to evaluate control-oriented models under WFC operation. These components of the benchmark, as well as how to participate, are detailed in the following sections. For more detailed information and registration, see `farmconners.readthedocs.io`.

2. Provided data sets

At the FarmConners kick-off meeting, held on 26th September 2019 in Amsterdam, the consortium agreed to build a test benchmark using available data sets from previous and ongoing campaigns. These data sets are collected and released as common test benchmark case for code comparison.

As shown in Figure 1, the benchmark contains data from high-fidelity simulations, wind tunnel measurements, and a full field experiment consisting down-regulation and wake steering operation periods. This variety allows comparison across site-specific dynamics.

Figure 1: FarmConners Benchmark 'data texture'

The data set is divided into 2 periods to resemble field application of WFC models. The first period (calibration) is to be used to calibrate the control-oriented models for the normal operation and a limited control set-points, where both input and output parameters are provided. In the second period (blind test), the calibrated models are to be run 'blindly' where only the input signals are available for a number of control settings applied. In that regard, the blind comparison is expected to show the overall performance of the state-of-the-art WFC models, as well as the common trends and differences among them. All the data involved in the benchmark are available in open access upon registration on `farmconners.readthedocs.io`. The overview of the provided data set is presented below.

2.1. Synthetic data set - Large Eddy Simulations

Validation of control-oriented engineering models requires accurate reference data. In addition to the available field measurement data, which could be limited to certain operation setpoints, high-fidelity large-eddy simulation (LES) tools provide a virtual wind-farm environment from which synthetic measurements can be taken under controlled conditions. They are often used to calibrate (or train) and validate the lower fidelity (and computationally lower cost) models, as seen in *e.g.* (21), (2), (5).

2.1.1. TotalControl data set: One of the core activities within the TotalControl (29) project is the development and validation of appropriate end-to-end wind-farm simulation models that cover the whole chain from flow model over aero-elastic model to power-grid model. In this regard, a high-fidelity reference database is generated using two independent numerical platforms: SP-Wind by KU Leuven and EllipSys3D by DTU.

SP-Wind is a high-order pseudo-spectral flow solver developed over the last 12 years at KU Leuven (9; 18; 3). Subgrid-scale stresses are modelled with a standard Smagorinsky model with wall damping, and the wind turbines are modelled using an actuator sector mode, which has been coupled to a nonlinear flexible multi-body model.

EllipSys3D is a general-purpose flow solver (23; 30), solving the discretized incompressible Navier–Stokes equations in general curvilinear coordinates using a block-structured finite-volume approach. The subgrid-scale stresses are here modeled using the model by Deardorff (31). The turbines are modeled using the actuator line method (20), which have been fully coupled to the aero-elastic tool, Flex5 (26).

The database is constructed for the TotalControl Reference Wind Power Plant (TC RWP) consisting of 32 turbines in a staggered pattern (4), as shown in Figure 2. The reference turbines are the DTU 10 MW turbines (6), with a hub height of 119 m and a rotor diameter of 178 m. The database consists of simulations of different atmospheric conditions and different orientations of the TC RWP.

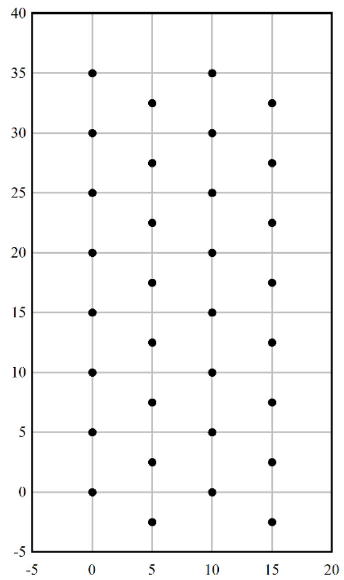


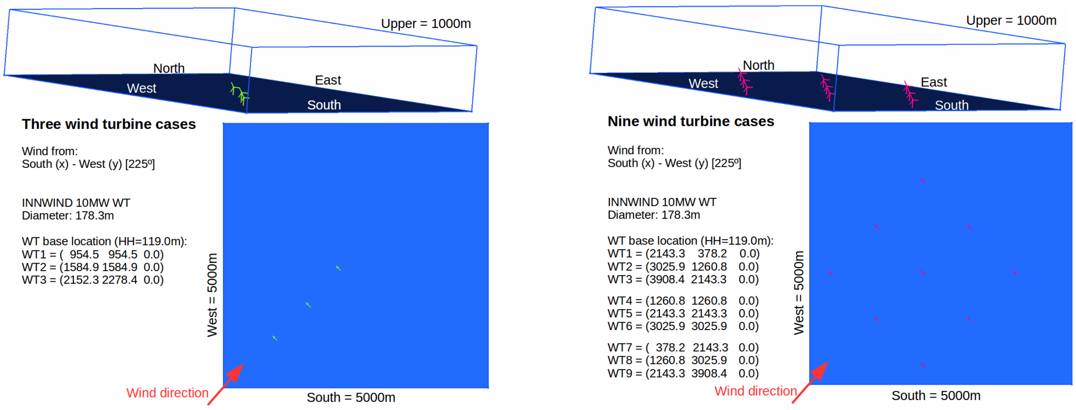
Figure 2: Layout of the TC RWP (4). Axes are distances normalised by the rotor diameter, *i.e.* s/D, where $D = 198$ m

2.1.2. CL-Windcon SOWFA simulations data set: The CL-Windcon project (27), as one of the major European research projects on wind farm control, has established different pillars for validation of farm models and control strategies. Among them, high-fidelity simulations have played a relevant role. Specifically, a set of SOWFA simulations has been performed and made accessible to the community through a public database. SOWFA (24), developed by NREL, is an open-source numerical simulation system employed for the high-fidelity simulation of turbulent atmospheric flows together with the analysis of wind plant and wind turbine fluid physics and structural response. The tool builds on top of the OpenFOAM Computational Fluid Dynamics (CFD) tool-kit (25) and NREL's aeroelastic wind turbine simulation tool OpenFAST (15).

Several combinations of wind speeds (3), turbulence intensities (3), and roughness lengths (3), together with yaw misalignment (up to +/-30°), and also de-ratings of wind turbines (in 5% power steps) have been computed at single wind turbine (WT), 3WT and 9WT scenarios. The turbine model is the 10 MW wind turbine developed in INNWIND.EU project (22).

The available outputs are: 1) Flow: final time step (volumetric) solution and flow slices in planes sampled at every 10 seconds along the wind turbine wakes; 2) Turbine response: turbine properties and all the data obtained from the turbine during each simulation, with detailed analysis in blades, rotor, nacelle and tower components.

Further definition of the flow characteristics and breakdown of simulated cases is included in CL-Windcon deliverable (1). The generated data, together with a summary supporting case selection, can be found in great detail at CENER's FTP server, where all the relevant data used as input and generated by these computations is stored. Further access instructions can be found in (27).



(a) 3WT scenario (b) 9WT scenario

Figure 3: CL-Windcon high-fidelity layouts (3WT and 9WT)

2.2. *CL-Windcon Wind Tunnel Experiments*

Data from experiments conducted in CL-Windcon project (27) within the boundary layer test section of the Politecnico di Milano wind tunnel (7) and with fully actuated and sensorized scaled models is made available for the benchmark exercise. The experimental setup is reported in Fig. 4: a scaled wind farm composed of up to three scaled wind turbine models was installed on the 13 m diameter turntable, which could be rotated to simulate different wind direction.

The wind turbines used during the experiments are three identical G1 scaled models, whose rotor diameter, hub height and rated rotor speed are 1.1 m, 0.825 m and 850 rpm, respectively. The models, already used in several previous research projects (12; 10; 11), are equipped with active pitch, torque and yaw control. They also feature a comprehensive onboard sensorization, including measures of shaft and tower bending moments, and they have been designed with the goal of achieving a realistic energy conversion process and to support the development and testing of wind farm control strategies. Each wind turbine model is also controlled by its own real-time modular Bachmann M1 system, where supervisory control functions, pitch-torque-yaw control algorithms, and all necessary safety, calibration and data logging functions are implemented. Further details about the G1 design, its aerodynamic performance, its control and several its applications can be found in (8).

Within the wind tunnel, two different atmospheric boundary layers (ABLs) were simulated through the use of spires placed at the inlet of the test section. The two ABLs can be considered quite typical of both onshore and offshore sites (with neutral atmospheric stability) and are characterized by vertical wind profiles that are best-fitted by exponential laws with exponent 0.14 and 0.21, respectively for the offshore and onshore ABL. The turbulence intensities at hub height are instead approx. 6% and 13% for the offshore and onshore ABL, respectively.

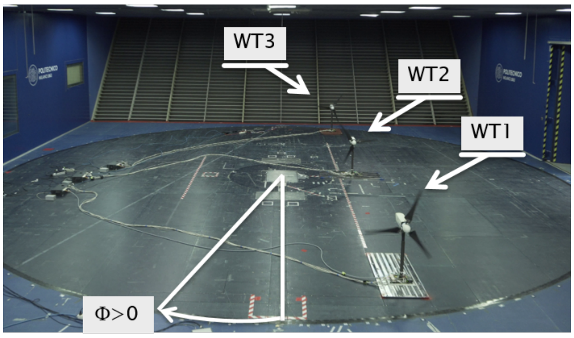


Figure 4: Wind tunnel setup for WFC testing

The available dataset consists of time series of several signals (rotor speed and azimuth, blades pitch, nacelle angle, shaft and tower loads) measured onboard each of the scaled wind turbine within the cluster, as well as time histories of the flow speed measured, by means of three components hot-wire probes, at many locations within a single and multiple wake shed by wind turbines operating at a wide range of conditions. Particularly, the single wake shed by a de-rated and yaw misaligned wind turbine has been traversed along horizontal and vertical lines at several distances downstream. Similarly, the wake shed after the second wind turbine of a 2-machines cluster has been traversed along horizontal lines.

2.3. Wind Farm Field Data

Data from a commercial wind farm is made available for the benchmark exercise. The wind farm is Sole du Moulin Vieux (SMV), which has been used for the wind farm control field tests of the SMARTEOLE research project (14). It is made of 7 wind turbines Senvion MM82 2.05MW, and its layout is represented on Figure 5. The terrain at this wind farm is not complex, though some local effects can be observed, in particular due to the presence of a forest south of the farm.

The available dataset consists of twenty-nine months of 10-min statistics (average, standard deviation, minimum and maximum values) SCADA data covering the 20 most critical signals[1], for each wind turbine in the farm. Twelve months of data with wind farm under normal operation will be used for the calibration of the models, while the remaining dataset (including another twelve months of normal operation and five months during which both wake steering and axial induction tests were led on turbine SMV6) will be used for the benchmark. 10-min statistics data from a ground-based lidar Windcube V2 located closed to turbine SMV6 (see Figure 5) will also be provided so that the misalignment of the SMV6 wind turbine can be precisely calculated for each 10-min during the wake steering field test and be fed into any wake deflection model. Details on data availability can be found on Figure 6.

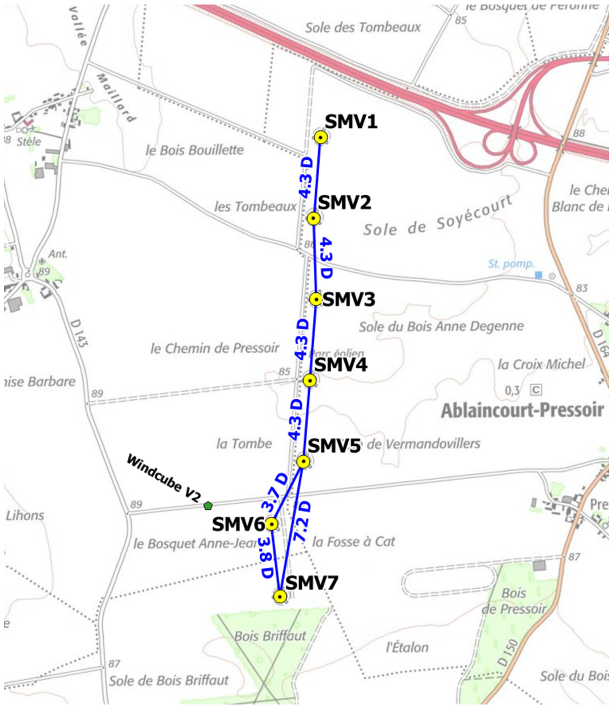


Figure 5: Layout of the SMV windfarm. Distances between wind turbines are normalised by the rotor diameter where $D = 82$ m. Additional measurements via lidar Windcube V2 during WFC tests

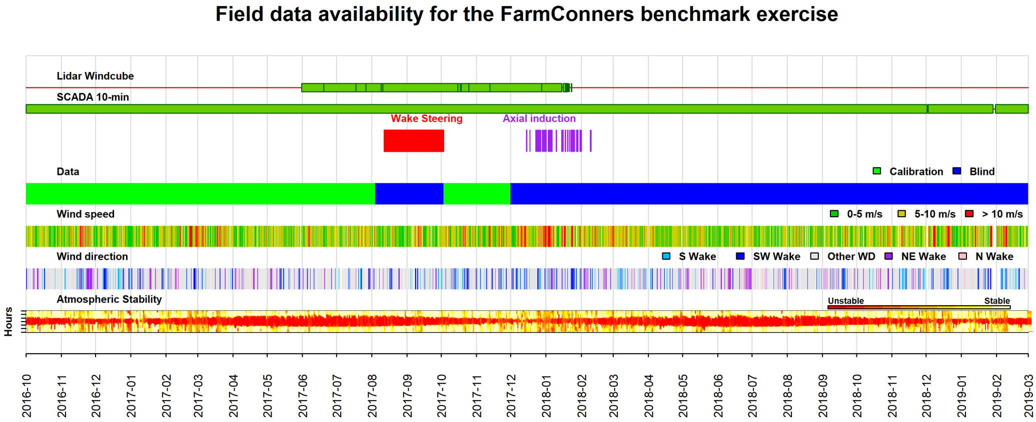


Figure 6: Overview of SMV field data provided for the FarmConners benchmark exercise. Availability of both lidar Windcube and wind turbine 10-min SCADA is indicated, along with the different periods used for calibration and blind test. External wind conditions are also shown: wind speed and wind direction are taken from SMV1 SCADA signals while atmospheric stability is derived from MERRA2 data at grid point N50 - E2.5 (the closest from the wind farm). For the wind direction the five sectors are : South wake (175-200°), South-Western wake (200-225°), North wake (355-20°), North-Eastern wake (20-45°) and no wake (other wind directions).

Table 1: Summary of data sets available in the FarmConners benchmark.

Data set	**Period for**		**Sampling**	**Available signals**	**Applicable**
	calibration	**blind test**	**rate**		**test cases**
TotalControl SP-Wind EllipSys-3D	40 min	20 min Normal Op. Additional WFC Op.	>1 Hz	Full simulation: Flow & turbine signals	3.1, 3.2, 3.3
CL-Windcon (CLW) SOWFA	600 – 800 s cases	600 – 800 s cases	Flow (10 s), turbine (0.03 s)	Flow & turbine signals	3.1, 3.3
CLW wind tunnel experiments	several hours	several hours	250, 2500 Hz	Flow & turbine signals	3.1, 3.2, 3.3
Wind farm field data	12 months	12 months Normal Op. 5 months WFC Op.	10 min	SCADA[1] Windcube lidar	3.1, 3.3, 3.3.1

3. Test cases

The test cases follow an increasing complexity level, *i.e.* starting from easier configurations (*e.g.* 1-2 turbines with quasi-stationary flow and higher availability of information/data regarding the input and output features of the models). The test cases then gradually converge to several turbines and real atmospheric conditions with relatively limited measurements with higher uncertainty. The collected results from all the test cases will be further classified with respect to inflow conditions including wind speed and turbulence intensity to assess the sensitivity to incoming flow conditions. Due to limited availability in convection measurements/observations in the provided dataset, the sensitivity analysis with respect to atmospheric stability (and shear) is omitted from the benchmark, although authors recognise its relevant effect in wake effects. The main focus has finally be set on the variation of WFC operation.

[1] Full list of available SCADA signals from all the turbines can be found at the example test case in the public git repository: ENGIE Wind Farm Field Data FarmConnersBenchmark Multiple Wake

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It should be noted that for some of the available dataset, the configuration is a subset of the wind farm, *i.e.* there are additional blockage effects. The spacing between the turbines are also varied per data set.

3.1. ***Single Full Wake under WFC***

The test case aims to investigate the quantities of interest in the single wake behind a controlled turbine, for a fully aligned 2-turbine configuration, as shown in Figure 7. Both the axial induction and wake redirection WFC approaches will be evaluated under this test case.

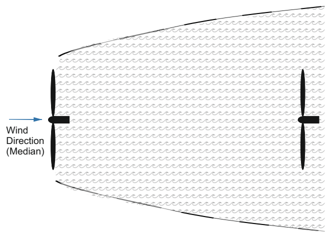

Figure 7: Single Full Wake test case configuration, representative

Available data sets for that benchmark:

- TotalControl: Both SP-Wind and Ellipsys3D, 5-diameters distance between the turbines in a wind farm environment, see Figure 2.
- CL-Windcon SOWFA simulations: subset of 3WT and 9WT scenarios.
- CL-Windcon Wind Tunnel: 5-diameters spacing between the wind turbines. Axial induction is implemented by modifying the values of the reference rotor speed and torque. Wake steering WFC approach is conducted with the first machine misaligned of -40°to 40°with steps of 10°.
- Wind Farm Field Data: 3.7-diameters spacing between turbine pairs SMV6-SMV5, see Figure 5. Axial induction is implemented via down-regulated power curve. Wake steering WFC approach is conducted with 13°to 15°yaw misalignment of the first turbine.

3.2. ***Single Partial Wake under WFC***

In this test case, the objective is to assess the added value of implementing wake steering WFC approach in a two-turbine configuration with lateral distance, as shown in Figure 8. Similar to the other scenarios, only the first turbine in the 2-turbine wind farm is controlled.

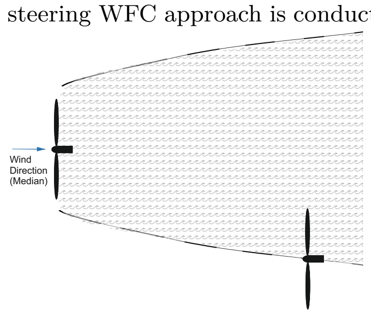

Figure 8: Multiple Wake test case configuration, representative

Available data sets for that benchmark:

- TotalControl: Both SP-Wind and Ellipsys3D, 5-diameters axial and 2.5-diameters lateral distance between the nacelle positions. Similar to test case 3.1, 2-turbine configuration is a part of the wind farm environment, see Figure 2.
- CL-Windcon Wind Tunnel: 5-diameters longitudinal spacing between the wind turbines, 0.5-diameter lateral spacing. Wake steering WFC approach is conducted with the first machine misaligned of 30°.

3.3. ***Multiple Wake under WFC***

The test case aims to investigate the quantities of interest in a row of turbines, as shown in Figure 9. For this scenario, only the first turbine in the wind farm is controlled.

Available data sets for that benchmark:

- TotalControl: Both SP-Wind and Ellipsys3D high-fidelity simulations, 8 turbines with 5-diameters uniform spacing, isolated from wind farm environment, see Figure 2.
- CL-Windcon SOWFA simulations: subset of 3WT and 9WT scenarios
- CL-Windcon Wind Tunnel: 3-turbine configuration with uniform 5-diameters spacing. Axial induction is implemented by modifying the values of the reference rotor speed and torque. Wake steering WFC approach is conducted with the first machine misaligned of 30°.

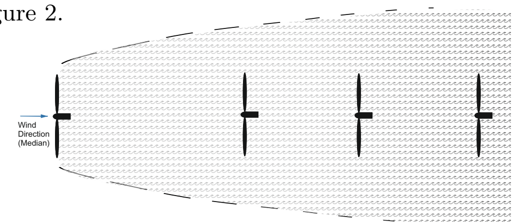

Figure 9: Multiple Wake test case configuration, representative

- Wind Farm Field data: 6-turbine with 3.7 and 4.3-diameters, *i.e.* SMV6 – SMV1 in Figure 5.

3.3.1. Additional Exercise on AEP level optimisation This case is particularly designed to assess the differences and similar trends in the participating models, when run for maximised annual energy production (AEP). It is important to note that this case is not a part of the benchmark, where the main objective is to evaluate the performance of the WFC models in a standardised validation process to increase the overall confidence. This additional exercise aims rather to investigate the potential differences of the model based optimisation results, when run for AEP maximisation. The resulting AEP gains are to be evaluated considering the performance of the model (in terms of error distribution, considered as model uncertainty), which is quantified in the *Multiple Wake under WFC* benchmark. This exercise is limited to Wind Farm Field Data.

4. Quantities of Interest & Validation Metrics

The performance of the WFC model participating in the benchmark is to be evaluated based on wind speed, power and turbine response criteria. It should be noted that the models should be run according to their capabilities. Meaning that if the participants do not get the load output from the setup used for the benchmark, they can opt out for those. Similarly, if the models run for the benchmark are limited to statistical properties only, it is not required to submit a full time series as expected results. Due to the control-oriented character of the benchmark, mainly steady-state and quasi-dynamic low-cost models are expected to provide solutions. However, depending on the model fidelity, the statistical quantities (*i.e.* mean, median, standard deviation, etc.) from time series of 3-dimensional flow fields can also be extracted.

The resulting quantities of interest for the benchmark are listed below. In order to provide a generic overview, the metrics to be used for validation and comparison are non-dimensionalised. The statistical metrics to be used for these quantities are the median and quartiles of both the observation and simulation ensemble. The uploaded results will be processed by the benchmark organisers to diagnose quantities of interest with the publicly released notebooks.

For the final analysis of the quantities of interest, the flow and turbine response behaviour under WFC is to be compared with the normal operation conditions. Therefore, for a fair comparison, it is of utmost importance that the inflow for both WFC and normal operational cases are statistically similar. The corresponding data processing techniques will be the core of the publicly released notebooks.

4.1. ***Power gain***

Commonly referred in literature (see *e.g.* (16) for a comprehensive review), the potential power gain under WFC should be assessed with respect to the normal operation for the whole wind farm in question.

$$\Delta P = \frac{(\sum_{i=1}^{n} P_i)_{Op.=WFC}}{(\sum_{i=1}^{n} P_i)_{Op.=Normal}} \tag{1}$$

n is the total number of turbines considered in the test case, P is the power produced by turbine i, and $Op. = WFC$ and $Op. = Normal$ correspond to operation under WFC and normal operation, respectively.

4.2. ***Wake loss reduction***

Although highly correlated to power gain, the potential reduction in the wake losses under WFC is another quantity of interest for the WFC technology stakeholders. This is mainly due to the more scalable character of the wake loss reduction from simpler 2-turbine configurations to more complex wind farm layouts. It also has the benefit to be able to partially mitigate wind-to-power conversion uncertainties for certain WFC models.

$$\Delta u = \frac{\sum_{j=1}^{n-1} (U_{up} - U_{1+j})_{Op.=Normal} - \sum_{j=1}^{n-1} (U_{up} - U_{1+j})_{Op.=WFC}}{U_{up}} \tag{2}$$

Δu is the non-dimensionalised wake loss at the wind farm level, U is either the hub height or rotor effective wind speed which represents the spatially averaged wind speed over the rotor; at the upstream (free-wind), U_{up}, or downstream (waked) turbine(s), U_{1+j} for the given incoming wind direction.

4.3. Reduction in wake-added Turbulence Intensity (TI)

The added TI is an important feature for the wind farm flow, which increases both the variability in power production and structural loads of the downstream turbine(s). Accordingly, a potential reduction in wake-added TI with WFC techniques is a quantity of interest.

$$\Delta TI_i = \left(\frac{\sigma_{U_i}}{\overline{U_i}}\right)_{Op.=Normal} - \left(\frac{\sigma_{U_i}}{\overline{U_i}}\right)_{Op.=WFC} \quad \text{where} \quad i = 2, n \tag{3}$$

4.4. Load Alleviation

One of the important use cases for WFC is the mitigation of structural loads on the turbines. In order to evaluate the model performance on potential load reduction under WFC in the defined test cases, the validation and the comparison of the models will be based on the normalised Damage Equivalent Loads (DEL) of the flapwise root bending moment $FlapM$, total shaft bending moment $ShaftM$ and total tower bottom bending moment $TBBM$. Similar to power gain and wake loss reduction metrics, the reduction in loads is assessed in comparison to the normal operation, as indicated in Equation 4. Note that the dataset to assess this quantity of interest is limited to high-fidelity aeroelastic simulations in Section 2.1 and wind tunnel measurements in Section 2.2, as the available field measurements are deemed to be inconclusive for such an analysis at this stage.

$$\Delta DEL_{\substack{FlapM \\ ShaftM \\ TBBM}} = 1 - \left(\frac{DEL_{\substack{FlapM \\ ShaftM \\ TBBM\ Op.=WFC}}}{DEL_{\substack{FlapM \\ ShaftM \\ TBBM\ Op.=Normal}}}\right)_i \quad \text{i = 1, n} \tag{4}$$

5. How to participate?

To sign up for participating in the benchmark, please fill the form under 'How to Participate' tab in the benchmark documentation `farmconners.readthedocs.io`. The registered participants will then receive a personal link to a cloud folder to upload their results. The results will first be presented in WESC 2021 and then sent for publication in collaboration with all the participants. For further questions, please refer to the 'FAQ' section under the documentation and feel free to 'Contact Us'.

6. Conclusion

The FarmConners consortium launches its common benchmark for WFC-oriented models comparison. All the benchmark data is available open access for non-commercial purposes and all the WFC enthusiasts are welcome to participate. For a more detailed information and registration for participating in the benchmark, visit the benchmark documentation on `farmconners.readthedocs.io`.

The provided data sets and the identified test cases represent different levels of complexity. The WFC-oriented models will be compared in terms of distribution of power improvements and mitigation of wake losses as well as load reductions, where applicable. Results of the models comparison under the given quantities of interests will be presented in Wind Energy Science Conference (WESC) 2021 and published in collaboration with all the benchmark pariticipants.

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