Paving the Way for Wind Farm Control in Industry

Title: Recommendations and best practices for testing and validation of Wind Farm Control

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1 Introduction

In order to assess and increase the confidence in the technology, FarmConners work package 1 is dedicated to the testing and validation of wind farm control (WFC) strategies. To fulfill this task, a benchmark exercise is organized and opened to the wind energy community. The scope of the benchmark exercise is designed and agreed by FarmConners consortium members, following the discussions held in the public workshops of Amsterdam (25th September 2019) and KU-Leuven (3rd and 4th February 2020) and based on their experience from previous European and national research projects.

The benchmark exercise is to be launched during the TORQUE 2020 conference hosted by TU Delft, and will be clearly defined in Deliverable D1.4. Full paper attached to the presentation is to be publicly accessible following the conference, and more info on the benchmark can be found on `www.windfarmcontrol.info/benchmark`. This Deliverable D1.5, "Recommendations and the best practices for testing and validation of WFC" comes as a complement. Indeed, while the benchmark exercise offers a framework and a comprehensive platform where various WFC strategies can be tested and compared, this deliverable details how the data that is provided for this benchmark has been obtained and processed, as well as challenges of validating WFC models and approaches.

2 Objectives

Wind farm control is a technology that brings together a lot of very different thematic of wind energy. This is illustrated by the Wind Farm Control Diagram of Figure 1. To obtain a wind farm control product, one has to combine one or several submodules in each main thematic. All of them must therefore be well understood in order to efficiently achieve a WFC objective.

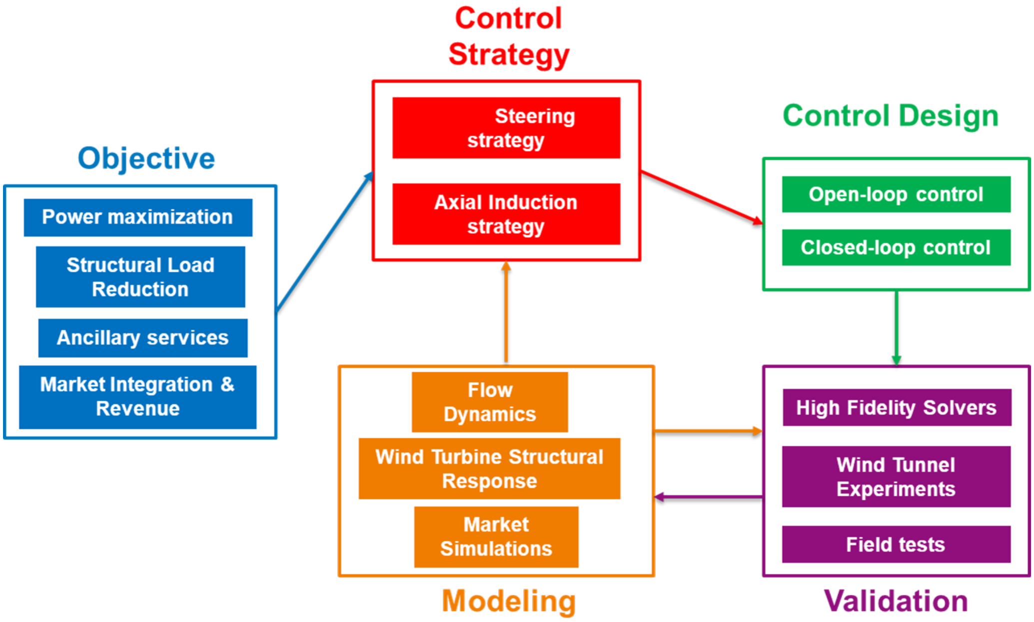

Figure 1: Wind Farm Control Diagram

This deliverable focuses mostly on the bottom right thematic "Validation". This is no easy task since the expected gains of WFC are reported to be relatively small, in the order of magnitude of 0.5 to 1% of annual energy production (AEP) (see quantitative overview of model results and field tests in e.g. [19]), and thus very difficult to detect. Effect of WFC on wind turbine loading is even more subject to discussions, with both positive and negative impacts being reported, also depending on the component and type of load under consideration. Consequently any attempt of validation of a WFC approach must be realized with great care to truly observe its benefit.

Over the past few years a large number of projects in which high fidelity simulations, wind tunnel experiments and full scale field tests have been led and involved many consortium members. This deliverable aims at gathering their feedbacks from these experiments in order to issue recommendations and a list of best practices to follow when validating WFC, and also indicate the main pitfalls to avoid.

3 Methodology

As underlined in Figure 1, wind farm control strategies and control-oriented models can be validated thanks to three different means, with their own characteristics, benefits and drawbacks: high fidelity solvers, wind tunnel experiments and field tests.

The following sections list for each of them what is feasible, and their pros, cons and limits. Data sets coming from these three sources are to be provided for the benchmark exercise, and consequently some tips and suggestions on how to prepare an experiment and post-process data afterwards are also given.

3.1 High Fidelity Simulations

In order to apply WFC strategies, a thorough understanding of the wake dynamics and the wind turbine response and subsequent loads of different components is necessary. High-fidelity simulations can provide exactly that – with lower uncertainty in the inflow as well as turbine output and response, they enable more conclusive 'observations' within the wind farm under WFC. The reduced uncertainty stems from everything being known deterministically, i.e. all velocity components and pressure are computed in each computational point for each time step. Additionally, it also implies that the same flow scenario can be reproduced indefinitely to examine the precise influence of various control settings, and with a precisely defined reference and baseline for comparison. However, high-fidelity simulations are usually focused on modelling canonical conditions, and hence simplified and idealized, see e.g [13]. Despite applying simplified and idealized conditions, direct code-to-code comparisons are non-trivial due to vast differences in implementations, see for instance the detailed comparative study by Berg et al. [4].

High-fidelity wind farm simulations are often referred as reference or virtual wind farms, which other WFC-oriented models are evaluated against [21, 15, 16]. These are typically large eddy simulations (LES) with a high spatial and temporal resolution [41]. Wind turbines are modelled using for instance the actuator line method [42], which can be coupled directly to an aero-elastic solver, which provides turbine control as well as computes the turbine response and operation, see e.g. [41]. High-fidelity simulations are computationally demanding (high cost), often requiring $\mathcal{O}(10^4)$ cpu hours for a single wind turbine simulations dependent on the spatial and temporal resolution and simulation time [13]. Conversely, dynamic wind farm control requires fast (low cost) and reliable wake models in the optimization loop. The high-fidelity models are in the current context of FarmConners primarily used to create benchmarks and provide validation and calibration data for the low cost models as well as detailed flow analyses to identify potential improvements of the low cost models. Accordingly, within the context of this document, these high-fidelity models are primarily used for controller/low cost model testing and wind analysis.

Within FarmConners benchmark, the high-fidelity database of wind farm simulations are conducted with the LES tools: SP-Wind (KU Leuven, [17, 20, 14]), EllipSys3D (DTU, [33, 43] coupled with the aero-elastic tool Flex5 [39]), and SOWFA

(NREL [38] coupled with the aero-elastic tool OpenFAST [18], run by CENER [10]). Here, a brief overview of some of the best practices and opportunities, as well as potential challenges and concerns related to testing and validation of WFC using high fidelity simulations are presented in the following sections.

3.1.1 Pre- and Post-Processing

Preparing high-fidelity simulations can require substantial efforts and computational costs, e.g. to define flow scenarios based on measurements and subsequently to perform precursor simulations used as dynamic inflow conditions for wind farm simulations [35].

The high-fidelity simulations are inherently dynamic, which present both challenges and opportunities. The initial transient periods as the flow develops is usually discarded despite high computational cost. However, transients are important when addressing dynamic wind farm control, as there is a temporal delay from an imposed control setting as it propagates downstream and impacts the downstream turbine(s). The high spatial and temporal resolution of the data results in large amounts of data, which requires appropriate handling.

The inherent dynamics can and should be exploited by moving beyond mere average statistics to higher order statistics, which quantifies the variability over extended periods and populates the distributions with more samples for increased statistical significance [2].

3.1.2 Pragmatic approaches to limit computational cost

Various approaches can be employed to broaden the application of high-fidelity simulations, and hence limit the computational costs.

High-fidelity simulations can generate detailed wake flow, which can be used as inflow to standalone aero-elastic computations, which can for instance be used to investigate the turbine performance and response at various turbine locations, see e.g. [28].

Fluid scaling laws is a fundamental approach to reduce the parametric complexity. Fluid scaling laws can provide generalized results independent of wind speed and rotor size by leveraging Reynolds number similarity, see [45]. Similarly, appropriate scaling of the turbine operation can provide faster computations of for instance AEP [46].

Finally, the deterministic knowledge of all parameters in time and space can be utilized through advanced methods such as adjoint gradient methods, which enables optimizations of wind farm control, see [36].

3.1.3 Opportunities/Advantages of high-fidelity simulations for WFC testing and power gain validation

One of the most significant advantages of high-fidelity simulations is the ability to observe and analyse detailed flow and structural loads profiles, both temporally and spatially. It also enables a more clear and conclusive physical understanding of flow and aeroelastic phenomena due to lower uncertainty in the observations. It eases parametric tests of WFC compared to field implementation, where several operational limitations might apply. Indeed, high-fidelity simulations can be used as a supporting tool for the design of field experiments.

Accordingly, it provides valuable databases with exhaustive details and generally higher sampling rate. These databases can then be utilised to obtain higher accuracy surrogates to perform WFC optimization, as well as parametric and probabilistic validation.

Higher availability of the parametric tests also enables easier model correction to estimate power gain likelihood. Power gain likelihood, $\mathcal{L}(\Delta P)$, is a probabilistic validation approach to evaluate the potential benefits of WFC in terms of power. It can be formulated as in equation 1 in terms of wind farm power production, P_{WF}, under normal operation, $Op. = Normal$ and wind farm control, $Op. = WFC$. Similar to the power gain itself, the power gain likelihood is also presented in normalised setting of the $model$ output with respect to the $Observation$, which is not limited to high fidelity simulations and can naturally be extended to wind tunnel experiments and field tests.

$$\mathcal{L}(\Delta P) = \frac{\left(P_{WF_{Op.=WFC}}\right)_{model} - \Delta P_{WFC}}{\left(P_{WF_{Op.=Normal}}\right)_{Observation}} \tag{1}$$

where

$$\Delta P_{WFC} = \left(P_{WF_{Op.=WFC}}\right)_{model} - \left(P_{WF_{Op.=WFC}}\right)_{Observation}$$

In equation 1, ΔP_{WFC} is the model error that is required to correct the WFC-oriented model results for potential bias in the predicted power gain. It should be noted that, often times the observations for the optimised WFC settings, $\left(P_{WF_{Op.=WFC}}\right)_{Observation}$, are not available. However, the prediction error of the WFC-oriented model, ΔP_{WFC}, can be interpolated for the optimized settings, if parametric observations are available in the validation dataset. An implementation of the power gain likelihood to surrogate based WFC through high fidelity simulations can be found in [28].

3.2 Wind Tunnel Experiments

Testing models in a wind tunnel has since long been a standard practice used in many different engineering fields. The opportunities offered by wind tunnel testing have clearly not gone unnoticed to the wind energy community. Even in this field, wind tunnel testing is still today the gold standard for measuring the aerodynamic performance of airfoils. Since several years, however, testing has evolved beyond airfoils. In fact, scaled wind turbine models have been developed for testing in boundary layer wind tunnels, which are designed to produce flows that mimic the characteristics of the atmospheric boundary layer (ABL). In the following sections, a quick overview of important aspects concerning wind tunnel testing applied to wind energy applications will be provided.

3.2.1 Design criteria for scaled model and wind farms

Wind tunnel models of wind turbines can be designed for different applications and goals. Depending on the application, different requirements will have be to be satisfied. For example, very different models might be designed if the focus is on aerodynamics or —instead— on aeroelasticity, if the model is actuated or not, or whether the focus is on the behavior of a single turbine or multiple interacting ones. The wind tunnel where the tests are conducted will in general also impose more constraints.

Each of these requirements implies specific challenges. However, typically not all requirements can be exactly met, and the design of the model is an exercise in finding a best compromise solution, which is quite common for most complex engineering systems.

For most applications the rotor of a scaled model should exhibit a realistic energy conversion process, which requires proper aerodynamic performance of the model at the airfoil and blade level. The correct representation at scale of aerodynamic phenomena leads not only to a realistic representation of power capture, but also of the aerodynamic loads, as well as to wakes of realistic characteristics. This last is particularly important if the models are to be used for studying plant-internal interactions. It should be noted here that the external shape of a scaled blade is not necessarily a geometrically zoomed-down version of the full-scale blade: in fact, the scaled blade will have in general to be completely redesigned in terms of its airfoils, chord and twist distributions so that desired quantities match full-scale targets [5].

For aeroelastic applications, the scaled model should be able to represent the mutual interactions of aerodynamic, elastic and inertial forces. This implies an additional level of complexity in the design, as here again the full-scale model can not be simply zoomed down, and a new design has to be devised (including the choice of appropriate materials) so that desired characteristics are matched [8].

For applications where controls are of interest, the scaled models need to be equipped with servo actuators, control laws and computing hardware. Depending on need, the models may be equipped with pitch (collective or individual), torque and yaw control. Each of these sub-systems needs specific dedicated solutions, which here again have to be custom-designed and cannot be scaled down from the full-scale system [6].

The geometric scale factor, which ultimately dictates the dimension of the model, is an important parameter that should be chosen to meet several requirements. When testing in air, reducing the size of the model implies a reduction in the chord-based Reynolds number. For large scale factors, this problem needs to be compensated by using proper low-Reynolds profiles. Clearly, a small size of the model also makes it harder to implement active controls because of the need for very small actuators and accompanying equipment, as control boards and sensors. On the other hand, the size of the models is not only constrained from below, but also from above. In fact, the model size should be matched to the cross section of the tunnel test chamber, to avoid excessive blockage due to interference with the wind tunnel walls. In addition, the scale of the model should match the one of the boundary layer generated in the wind tunnel. For wake studies, the model size may also be constrained by how many turbines one wants to simulate, by their relative downstream spacing, and by the longitudinal length of the test chamber over which desired flow characteristics can be achieved and maintained [5].

3.2.2 Simulation of realistic atmospheric conditions within a wind tunnel

The simulation of the ABL in a wind tunnel is essential in order to operate the models in conditions that are representative of the real environment. Turbulent flows can be obtained by active [26, 37] or passive means [3, 11]. Active solutions are more complex and expensive, but also more flexible and capable of generating a wider range of conditions. On the other hand, passive solutions, being relatively cheap and simple, are well-established and widely used [3, 11, 31].

Ideally, the turbulent flow generated in a wind tunnel should be in the same scale factor as the turbine model interacting with it. Large wind tunnels generate flows with integral length scales in the range of 1:100−1:200 of the full-scale ABL [12], while smaller tunnels operate in the 1:300−1:500 scale regime [32, p. 656]. A scale mismatch between tunnel and turbine model will have implications, for example on turbine performance, loading, wake meandering and others.

If possible, wind direction that dynamically changes should also be considered. For this purpose, it is important to consider the time speed-up induced by the scaling associated to the wind tunnel testing. This speed-up, defined by the ratio n_Ω between the rated rotor speed of the scaled model and of a full-scale reference machine [6], should be used to time-scale the wind direction time history.

In order to obtain significant results that could be up-scaled, wind directions changes should also be realistic, i.e. they should mimic full-scale variations. For the purpose, field wind data sampled at 1 Hz should be considered. Among the available data, just those satisfying the following criteria should however be used:

- data gathered with the met-mast fully out of the wakes shed by the neighboring machines;
- data whose wind direction varies within a range where significant wake-machines interactions are expected;
- the amount of data should be large enough to allow assessing the effectiveness, under varying wind direction, of Open-Loop wake deflection controllers; in this regard, the amount of data analyzed by [23] could be taken as

reference.

In order to reproduce the low-frequency fluctuations of the wind direction, the wind tunnel turntable could be used. Specifically, the time series of the turntable rotation should be defined so as to best reproduce the speed-up 2-min average of the met-mast data accounting for specific hardware limitations of the turntable.

3.2.3 Measurable quantities and their post-processing/formatting

Since scaled models are designed for the purpose of gathering data, they are typically highly sensorized. The types of sensors that can be installed depend largely on the scope of the model, on its size and cost. Pressure sensors can typically be used only on relatively larger models, while for smaller ones it might be possible to measure loads at specific key spots (on the blade, shaft, tower) by strain gages or with optical sensors. Accelerations can also be of interest, for verifying vibration characteristics or to implement safety protection loops. Encoders are used to measure rotor azimuth, blade pitch and yaw angle, which are necessary for the implementation of control laws.

The most common device to perform point-wise measurements of the flow speed is the Pitot tube, which is commonly capable of measuring dynamic pressure within about 0.1% and works well also when misaligned of a few degrees [32]. In the experiments described later on, a Pitot tube is typically placed 1.5 diameters (D) in front of each turbine, to measure its free-stream speed.

The detailed mapping of the flow in front and behind turbines is typically obtained by using hot-wire or hot film probes, which can provide the fast-response necessary in turbulent flows. Ideally the probes should be capable of measuring the three components of the flow field, and should be regularly and accurately calibrated. One or more probes can be mounted on an automated traversing systems, which allows for their precise positioning at each point of interest according to a programmable schedule [6]. Depending on size and configuration, the traversing system might locally affect the flow both in terms of direction and magnitude. These effects should be characterized in advance, so that they can be removed from the measurements during post-processing of the raw data.

A very interesting and valid alternative to classical measurement techniques is represented by scanning LiDARs. These devices are equipped with a steering laser beam. The line-of-sight component of the wind speed can be obtained by measuring the frequency shift of the light that is backscattered from the aerosols present in the air. This approach presents multiple advantages with respect to standard techniques. Indeed, it is possible to quickly move the laser probe from one measurement point to the next, which drastically reduces testing time. In addition, there is no local distortion effect on the flow. Two synchronized scanning LiDARs were used to measure the hub-height velocity around a cluster of three G1 models, as described in more detail in Ref. [47].

Alternatively, stereo PIV can be used to measure the three velocity components at desired planes [9]. The measurement area is typically subdivided into smaller partially overlapping windows. Here again, a traversing system can be used to automatically position the laser and the cameras at the desired locations.

For every experiment conducted within the wind tunnel, a detailed description of the number of used models, their location within the wind tunnel, as well as information concerning the reference frame adopted to report the measured flow data, must be provided. For every test conducted within the wind tunnel, structured files, which collect all the data measured during testing, should be generated. If case several acquisition systems were used, the data structures should contain the synchronized signals gathered by each model, as well as the flow measurements.

3.3 Wind Farm Field data

Wind farm control strategies can be tested directly in the field on operating wind turbines and wind farms. While in wind tunnels and high fidelity simulations the incoming wind flow can be quite easily monitored and controlled, this is not true for real wind farms which are exposed to constantly varying wind conditions, some local terrain effects and other operational constraints. Gains that can be observed in the field are consequently very consistent and reliable when investing in a WFC product. Not surprisingly, during the first public FarmConners workshop held in Amsterdam, the lack of validation campaigns was identified as the biggest research gap in WFC field from experts attending the meeting [25].

Indeed, there only have been but a few validation campaigns in operating wind farms, even though a larger number of them were led in the past few years [1, 22, 7, 23, 44, 27, 24]. This can be explained by the difficulty of organizing field tests on commercial wind farms facing a lot of operational constraints and forced to fulfill some production objectives. Also, the impact of WFC control on turbine loads is still not fully clarified, and therefore wind farm operators or asset managers can be reluctant to propose their farms for this kind of experiment.

In the following subsections, some key elements to consider when undertaking WFC field tests in an operating wind farm are developed.

3.3.1 Wind Turbine Control

In the state of the art greedy control, wind turbines are expected to optimize their own power production without considering others. When realizing WFC field tests, this behavior must be adapted in order to accomplish the WFC objective. In other words, the control system of the wind turbines involved in the experiment must be changed compared to what it was originally designed for. This can prove a challenging issue, especially if the OEM is not implicated in the tests since in that case the control system generally appears as a black box to the wind farm operator.

Realizing basic axial-induction field tests is relatively easy in the sense that it only requires to curtail the turbine, a feature that is available in the vast majority of commercial wind turbines nowadays. Implementing a very customized curtailment as in [44] (which is generally needed to demonstrate the benefit of WFC) can prove much more challenging though, since this requires to design new pitch and/or rotor speed settings for the wind turbine.

Setting up wake steering field test is more delicate because it demands the turbine to be misaligned. Two practical solutions can be applied. First, the turbine can be continually yawed by a constant offset angle for the whole duration of the tests, as in [27]. This implies that the total benefit of the WFC should only be analyzed in the full wake sector, given that for other wind direction sector the misalignment of the upstream turbine will not be profitable to downstream turbines. A more consistent solution, though harder to implement, is described in [23]: during these field tests a yaw controller was designed to modify the signal from the wind vane of the turbine in order to trick the turbine into achieving the desired yaw offset. Thanks to this system, it is possible to activate the yaw offset only for the most relevant wind directions, and also customize the offset values depending on the wind conditions.

Finally, the inertia of the wind turbine also has to be taken into account when designing open-loop control strategies as described above. Indeed, the response of wind turbine with respect to changes in wind conditions and operational parameters can be very different from one model to another, and be responsible for a difference between the expected and the observed turbine behavior [40]. Closed-loop control approaches would probably help in reducing this margin, however they require a feedback loop from the downstream turbines (or from an external sensor that would scan the emitted wake) up to the controlled turbine and are thus more complicated to implement in the scope of field tests.

3.3.2 Important Variables

Today, all commercial wind turbines are provided with a supervisory control and data acquisition (SCADA) system, which records and process data of the most important variables required for the proper functioning of the wind turbine. Depending on the contract between the wind farm operator and the OEM the list of available variables can vary but it is recommended to record at least the following signals in order to correctly analyze the output of the field tests:

- Active power: electrical power delivered by the wind turbine.
- Yaw angle (or Nacelle position): orientation of the nacelle with respect to the North.
- Wind speed: nacelle wind speed measured by the wind turbine (generally coming from the anemometer installed on the nacelle met-mast).
- (Relative) Wind direction (or Vane angle): relative difference between the nacelle orientation and the incoming wind direction. This is generally measured by a wind vane or sonic anemometer installed on the nacelle met-mast.
- (Absolute) Wind direction: absolute wind direction with respect to the North. If not available this signal can be obtained by summing up the nacelle position and the vane angle signals.
- Rotor speed: rotational speed of the turbine rotor (low-speed shaft). Alternatively the gearbox or generator speed signals (high-speed shaft) can be used.
- Pitch angle: angle of the (collective) pitch system.
- Any signal giving information about the availability of the turbine with respect to the grid.

These data are generally given as 10-min statistics containing the average, standard deviation, minimum and maximum values of each variable in a 10-min interval. However, as wind conditions can sometimes vary significantly within this time period (which complicates the post-processing analysis), it is recommended to use higher resolution data if possible. Ideally, 1 Hz data should be made available, but if that raises issues related to data management and storage then 1-min statistics could be used instead. In [40], 1-min averaging periods are reported to give the better compromise between smoothing out some high frequency components of the wind speed and direction signals while still observing the trends in energy changes predicted by theoretical analyses.

Finally, it must be mentioned that in most of the wind turbines there are no sensors to specifically measure the loads. Therefore the analysis of this characteristic will often require the installation of additional sensors (such as strain gauges or optical fiber bragg grating sensors), which can be an expensive investment. Furthermore, in operation and maintenance phase it is more complicated to install these sensors and calibrate their output signals.

3.3.3 Assessment of Incoming Wind Conditions

WFC strategies are really sensitive to external wind conditions, and in particular to the assessment of wind direction. Indeed they are to be applied on a relatively narrow direction sector corresponding the full wake effect between the turbines. Consequently these conditions must be measured as accurately as possible in the scope of the field tests.

However, as the turbine instrumentation providing this information is located on the met-mast in the back of the nacelle, just behind the rotor, the sensors are exposed to a very disturbed inflow that disturbs their measurement. These signals are generally post-processed with a nacelle transfer function (NTF) in order to convert their measure into the corresponding upstream inflow. Still, applying these NTFs is not enough to provide an accurate measurement of the incoming wind conditions because they are generic with the turbine model and do not account for site-specific effects, and also the inherent scatter of data caused by the increased turbulence in the disturbed flow behind the rotor will still be present. Furthermore, these NTFs are also impacted by changes in the turbine operating mode (change in pitch and rotor speed setpoints, or turbine misalignment), and thus not really suitable for the assessment of wind conditions during the application of WFC.

The nacelle position signal of the wind turbines is also known to be unreliable. This is due to the fact that it is not crucial for the good performance of the turbine: movements of the nacelle to align with the wind are monitored by the vane angle signal only. Therefore an offset is often observed between the real position of the nacelle and the data recorded in the SCADA system, and its value can sometimes be very significant. This "North offset" (since it marks the error between the nacelle position signal with respect to the true North) must be analyzed and corrected before launching the field tests otherwise there is an important risk that the WFC will be applied in a wrong direction sector [44]. However, by measuring the nacelle orientation with a more reliable GPS-based system, some studies showed that standard wind turbine measurement systems might be unreliable even after correcting the "North offset" [7].

Finally, wake effects within a wind farm are very dependent on atmospheric conditions, in particular atmospheric stability and wind turbulence. It is then very valuable to measure these conditions during the tests to be able to correctly assess the benefit of WFC afterwards. However this information might be challenging to obtain since it is generally not available in most of the turbine SCADA systems.

Consequently, for all the reasons listed above, it is highly recommended to install an external sensor when realizing field tests on operating wind farm. This sensor could either be a ground based lidar or sodar, or an instrumented met-mast (preferably as high as the turbine hub height). These sensors should be installed upstream of the controlled wind turbines so that they would not be affected by turbine wakes when the wind blows in the relevant wind directions. They can be used to measure accurately the incoming wind conditions, not only the wind speed and direction but also turbulence, wind profile and atmospheric stability (if using a met-mast). The cross check between the wind turbines signals and the sensor's can give more confidence in the data analysis, help to reduce overall uncertainties and prove useful to correct the wind turbine North offset. Also, when realizing a wake steering experiment, it can be interesting (though not mandatory) to install a nacelle-mounted lidar, a GPS system on the nacelle, or another instrument that can be used to monitor accurately the yaw misalignment of the turbine.

3.3.4 Data cleaning and Post-processing

Before the benefit of WFC can be assessed, the data must be cleaned in order to keep only the relevant periods for the analysis. These are the periods when no problems are detected on the wind turbine so that it should be behaving as expected, and thus the impact of WFC can truly be compared with normal operation. Other periods have to be filtered out, they can correspond to e.g. maintenance on the wind turbine, derating (for other purposes than running axial-induction tests), known sub-performance, start and stop periods of the turbine, issues in the measurements of one of the wind turbine sensors etc... This filtering should be applied to both the controlled turbine(s) and the affected downstream turbine(s). If one other turbine in the farm is used as a reference for normal operation (see next subsection), it must also be checked.

Furthermore at this stage some other tests and verifications must be carried out. If external sensors such as lidars are used during the field tests, their data must also be analyzed, filtered and validated. Then time synchronization between them and the turbine SCADA system should be checked. This can easily be done by analyzing time series of wind speed signals from both sensors and looking for any discrepancies between them (e.g. a peak in wind speed that would occur with some delay in one of the other signals).

North offsets from turbines and external wind sensors should also be studied. A common way of validating the North offset of a sensor is to look at a normalized wake event in the farm (i.e. the normalized signal obtained by diving the power from the waked turbine and the turbine emitting the wake, represented as a function of wind direction) and making sure that it is happening for the right wind direction (which can be computed knowing the wind turbine coordinates). If an offset different than zero degree is observed, then the wind direction signal must be corrected accordingly.

In the end, a cleaned and reliable dataset should be obtained, ready to be used for the validation of the WFC.

3.3.5 Validation of the Gains

The most common way to assess the performance of a wind turbine is to analyze its power curve according to the IEC standard [30, 29]. However, the gains that are to be expected from WFC are very small, and thus the power curve methodology might not be accurate enough to really highlight the benefit of the control. Indeed, a power curve basically consists in studying the output power as a function of wind speed (preferably measured by external sensor rather than nacelle anemometry). In practice, there are much more parameters that influence the power production of wind turbine, especially when focusing on wake effects, and all of them can have a greater impact on the turbine performance than the sole improvement allowed by the WFC. Methods based on stochastic modelling might be use for this purpose, since they can lead to a faster reconstruction of a power curve with a lower sensitivity on inflow conditions [34]. However, such methods typically require 1 Hz measurement data.

Consequently, it must be stressed out that the benefit provided by the controlled case (when WFC is applied) is to be analyzed for very similar wind conditions than the ones occurring in the baseline case (no WFC applied). This can be achieved by running the field tests for a relatively long time (a few months) while toggling on and off the WFC every hour. In that case it ensures that roughly the same distributions of wind conditions are observed between the baseline and controlled scenarios, as shown in [24].

Furthermore, to analyze changes in power due to the WFC a power to power comparison with a reference wind turbine nearby might be more suitable than a power curve analysis. Indeed, for the same 1-min (or 10-min) period, nearby wind turbines face roughly the same wind conditions in terms of wind speed, direction, shear, turbulence, etc... (if the terrain is not too complex). Therefore it can be supposed that the power production of those turbines are affected with almost the same effects by wind conditions, and thus this enables the changes from WFC to be spotted with a higher accuracy. Ideally, the reference turbine(s) should have a very close behavior than the controlled and downstream turbine, for example being in the same position in a neighbouring row of a regularly organized wind farm. As for onshore wind farms this kind of configuration is rarely achieved, the reference wind turbine can be obtained by looking at the closest wind turbine or by averaging the output of several nearby turbines. If none of them seems suitable for such an analysis, then a synthetic reference power can be built based on the measurement of an external sensor, as in [23].

In [23] are also discussed several methodologies to realize a power to power comparison between wind turbines. They are all based on ratios between the test and the reference turbines, but the one labeled as “energy ratio” is reported to be the most consistent thanks to its closer relationship with increase in AEP. This is also the method applied in [24], in which the gains from WFC are clearly observed. In the future, machine learning methodologies could also be investigated for dealing with this kind of analysis.

3.3.6 Summary

The validation of WFC in the field can be quite challenging. This is mostly due to the implementation of control strategies on wind farms which are generally used for commercial purposes. Therefore a lot of operational constraints can limit the extent of the field tests, and the diversity of scenarios to be tested.

Before launching the tests a special care must be taken to make sure the wind turbine will be controlled accordingly, especially if the manufacturer is not involved in the experiment. Furthermore in some case the nacelle position signal of the wind turbine can be unreliable and thus the control applied in a wrong direction sector. It is also recommended to install an external sensor to measure independently the incoming wind conditions, in particular the wind direction.

Finally, when studying data at the end of the field tests, a power to power comparison between the wind turbines should be preferred over the traditional analysis of the power curve. This is because the expected gains from WFC are very small and therefore the power curve methodology might not be accurate enough to give a definite conclusion about the benefits observed during the tests.

4 Conclusions

Several means are available for analyzing and validating the possible gains offered by WFC. In this deliverable, the main three of them have been described by FarmConners partners who have been using them for this particular goal over the past few years. A list of best practices and recommendations have also been developed for each of them, in order to help people to use them correctly and efficiently.

On the one hand, full scale wind farm field testing is the most reliable and convincing result that can be provided in order to demonstrate the benefit of WFC to a wind farm operator. Indeed, the wind turbines involved in these experiments are dealing with the same kind of operational constraints and external wind conditions that most of the wind farms experience in practice. Consequently these tests are generally the most complicated to set up, and the results which are obtained from them are also subject to high uncertainties related to data availability, post-treatment and noise. That is why only a few of them have been realized in the past, even though this number is increasing every year. In this sense, it is highly recommended to promote the execution of WFC field testing in experimental wind farms with full access to turbines control, therefore overcoming additional operational and business limitations of commercial wind farms. Furthermore, with these field tests it if often impossible to study all the characteristics of WFC; in particular the question of wind turbine loading during WFC has been mostly left unstudied and is still an open-research question.

On the other hand, high fidelity solvers provide a huge amount of data with the precise knowledge of the inflow characteristics at each instant of time and position of space, which can afterwards be converted into turbine production and loading if they are coupled with an aero-elastic solver. Therefore, they allow very easily the comparison between WFC and a reference scenario, and can contribute to give a much less uncertain answer with respect to its benefit. This information can be used as well in the design of experiments for field testing. Unfortunately, they have a very high computational cost and require high amount of storage, so they are often reduced to the analysis of very specific wind conditions. In the scope of FarmConners benchmark exercise, their role has thus been reduced to the generation of reliable data on which fast and low cost models are going to be tested and compared.

Finally, wind tunnel experiments can offer a good compromise since they stand in between high fidelity simulations and full scale field tests. Indeed, these experiments enable both a proximity with reality (since the scaled models are facing very similar conditions as the ones faced by operating wind turbines) and a good control and knowledge of the incoming inflow which is strictly measured and monitored within the wind tunnel. The scaled models can also be better instrumented than actual wind turbines, which can provide a better quantification of the gains of WFC and reduce the uncertainties. However, a very special care must be taken to the design of these experiments, in particular to the scaling of the most important flow characteristics, in order to make them consistent with what is observed in real wind farms and obtain reliable results.

For the FarmConners benchmark exercise, datasets from previous experiments involving these three means of validation will be opened to the wind energy community, for testing and comparison of several available models. It is hoped that together with this deliverable, it can contribute to further design and validate new WFC cases and confirm its benefits.

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