Wind tunnel validation of a closed loop active power control for wind farms

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Abstract. As the wind energy penetration increases, it is becoming more important for wind farms to contribute to frequency regulation, i.e. active power control on the power grid. However, before such controllers can be widely used in industry, they need to be thoroughly validated. This paper contributes to this task by presenting an experimental setup suitable for validation of wind farm control algorithms in wind tunnel experiments. A model free closed loop active power control is implemented on model wind turbines, and tested in a wind tunnel at University of Oldenburg under different operating conditions. Obtained results show that the proposed controller is sufficient for following power references, which is in accordance to numerical studies available in the literature. It is also verified that the controller can react to different disturbances, including variations in the wind farm power reference, and shut-downs of certain turbines in the wind farm. Furthermore, the possibility of coupling the proposed controller with control algorithms for reduction or fairer distribution of structural loads in the wind farm is also demonstrated.

1. Introduction
To enable further growth of wind power and increase of wind penetration, wind farms will have to be able to contribute to the grid frequency control, instead of just maximizing their power outputs. To this aim, wind farms are expected to be able to deliver the power levels demanded by the transmission system operator (TSO) to the grid. The wind farm control concept used for this purpose is often called active power control (APC) in the literature.

The main task of the APC algorithms is to adequately distribute the total wind farm power reference to individual turbines. The APC is typically achieved by de-rating, i.e. by lowering power outputs of individual turbines [1]. Mostly due to wake interactions and changes in atmospheric conditions, a precise and reliable estimation of available power for each turbine is not a straightforward task. Therefore, a closed loop solution for APC is needed.

In recent years, different APC algorithms have been proposed and analysed. A demonstration of an open loop approach and its inability to adequately track the power reference in presence of wake interactions is demonstrated in [2]. A simple but effective model free closed loop solution with a PI controller and the wind farm power measurement as a feedback is presented in [3]. There, it is shown that even a rather simple feedback controller can improve the wind farm behaviour when some turbines are operating in wakes, and an analysis of system stability is given. This approach has been further extended to offer a better distribution of the structural loads in the wind farm in [4], where contributions of individual turbines to the total power output is modified online based on the structural loads experienced by individual wind turbines.
Besides simple and model free approaches, model based optimal APC has also been researched in recent years. Examples of MPC-based solutions that take into account wake interactions can be found in [5, 6]. Another solution based on MPC, with the main focus on reduction of structural loads is presented in [7]. A distributed model predictive APC that limits the needed communication among the turbines in a wind farm is developed in [8].

All mentioned control algorithms have been validated with promising results in numerical simulations. To increase the confidence in the results, experimental validation of APC algorithms is still needed, especially in field tests. However, field tests even for simpler control concepts come with considerable costs and risks, and it is not possible to have controllable and repeatable wind conditions. To overcome this, the usage of wind tunnels and wind turbine models has been proposed for control oriented experiments, which is supposed to complement numerical simulations and field experiments, thus bridging the gap between them [9, 10].

This paper builds on the APC concept presented in [3], with the aim of its experimental validation using two model wind turbines in a wind tunnel. The control system behaviour under different conditions is analysed: dynamic variations in the wind farm power reference, inability of certain turbines to generate the desired power level, shut-down of a turbine in the wind farm, and dynamic variations of the contributions of the individual turbines to the wind farm power output (an essential part for the load reducing control algorithms, c.f. [4]).

The paper is organized as follows. Section 2 describes the experimental setup, including the wind tunnel and the model wind turbines. The wind turbine and wind farm control algorithms are described in the Section 3. The experimental results are presented and analysed in Section 4, and Section 5 concludes the paper.

2. Experimental setup
The experiments were performed in a wind tunnel at the University of Oldenburg. The closed test section measures 3 m × 3 m at a length of 30 m. Tests were conducted at constant inflow velocities up to 7.5 m/s with a turbulence intensity of $TI \leq 0.4 \%$, and no vertical profile. Further details about the wind tunnel facility are documented in [11].

2.1. Model wind turbines
Two identical model wind turbines with a rotor diameter of $D = 0.58 m$ were used. The three-bladed, horizontal axis turbines feature collective pitch and torque controls, however, only the latter was utilized in this study. A DC motor mounted in the nacelle is used as a generator, whereas its electric current $I$ is proportional to the generated torque, $M_g = kI$, with $k$ being a generator constant. To obtain the current $I$, and therefore the generator torque $M_g$, the voltage drop across a shunt resistor is measured. Therewith, the generated power becomes

$$P = M_g \omega = kI \omega,$$

with $\omega$ being the rotor speed, which is obtained by an magnetic encoder mounted on the generator shaft. A field effect transistor (FET) within the electric circuit allows for controlling the electric current and therewith the torque by varying a voltage applied to the FET, $u_{\text{FET}}$, which acts as a manipulative variable for the torque control. Data acquisition, logging and control algorithms run on a NI cRIO real-time system equipped with an FPGA as well as analog and digital modules. Further details on the design and control of the model wind turbines are described in [12].

2.2. Layout
The experiments were performed with two model wind turbines operating in the full wake ($\Delta = 0$) and half wake ($\Delta = 0.5D$) conditions, as shown in Fig. 1. The hub centre of the model turbines was 1.33 $D$ above the tunnel floor.
Although two turbine setup cannot fully represent the behaviour of a wind farm, it can show how a wind farm controller should deal with wake interactions, and it can indicate which aspects should be considered when designing a controller for larger wind farms.

3. Control system

The main objective of the wind farm active power controller is to distribute the wind farm power reference to individual wind turbines. Each wind turbine has its own controller capable of following the power reference set by the wind farm controller, and of following the standard power curve in partial and in full load. Since only partial load conditions are tested in this paper, where blades are not pitched, the description here is focused only on the torque control.

The controllers for both model wind turbines are implemented on the NI cRIO-9074 real-time system with a sampling time of 5ms, and their parameters are tuned through a series of dedicated experiments.

3.1. Wind turbine controller

The wind turbine control structure is shown in Figure 2. An internal control loop is used for following the torque reference signal by setting an appropriate FET voltage, $u_{FET}$. Being the innermost control loop, it is tuned to have the fastest response, with the following PI parameters: proportional gain $K_P = 1.42 \frac{V}{Nm}$, and integral time constant $T_I = 46$ ms.

The external control loop is in charge of the power control by setting the appropriate torque reference signal. Two different operating modes are possible – the greedy (i.e. power maximization), and the power reference tracking mode. The greedy mode is based on a look-up table, $M_{g,\text{opt}}(\omega)$, mapping the rotor speed $\omega$ to the optimal torque reference, i.e. to the torque value corresponding to the optimal energy extraction. Such a look-up table is derived.
for each model wind turbine from steady state values obtained in the dedicated characterisation experiments [13].

When the turbine tracks a power reference, it operates in a de-rated mode, which can be achieved through different combinations of pitch and torque control [14]. Here, it is achieved by reducing the generator torque, i.e. by increasing the tip speed ratio, leading to lower angle of attack and lower lift at the blades. To this aim, the error between the measured power \( P \) and the power reference \( P_{\text{ref}} \) is fed to a PI controller which sets the generator torque reference \( M_{\text{g,ref}} \). Although slower than the innermost torque control loop, high responsiveness of this control loop is needed to achieve a high quality wind farm control. Therefore, the PI parameters are chosen as: proportional gain \( K_P = 3.8 \frac{\text{Nm}}{\text{W}} \), and integral time constant \( T_I = 72 \text{ms} \). To prevent the tip speed ratio from going below its optimal value (corresponding to the maximal power coefficient \( C_P \)), an upper limit is imposed on the PI controller, \( M_{\text{g,ref}} \leq M_{\text{g,opt}}(\omega) \), which also ensures that the wind turbine operates in the greedy setpoint when the power reference is higher than the available power.

3.2. Wind farm control
The wind farm control structure is illustrated in Figure 3. The wind farm power reference \( P_{\text{TSO}} \) is distributed to individual turbines using ratios \( \alpha_i \), which might be predefined, or defined online, e.g., by control algorithms for reduction of structural loads [4]. In fact, the ratios \( \alpha_i \) determine how much each turbine should contribute to the power production. For an open loop case without wake interactions, the sum of wind turbine power references should equal the wind farm power reference, i.e. \( \sum_i \alpha_i = 1 \). If wake effects and available powers are not adequately taken into account when selecting different \( \alpha_i \), such a control strategy will not lead to proper tracking of the wind farm power references \( P_{\text{TSO}} \). Therefore, the measured wind farm power output, \( P_{\text{WF}} = \sum_i P_i \), is fed back to the PI controller that adjusts power references sent to individual wind turbines in order to achieve the desired wind farm power output. In such a closed loop approach, the ratios \( \alpha_i \) can be chosen more freely, since the PI controller will compensate wake interactions and inappropriately chosen \( \alpha_i \) by adjusting the power references.

![Figure 3. Wind farm control system.](image)

The blocks \( \text{WTC}_i, \ i = 1 \ldots N \), in Figure 3 represent the closed loop wind turbine control system, as sketched in Figure 2, which make sure that turbines follow their power references. Obviously, a high quality performance of the wind farm control system can be achieved only if the wind turbine controller (inner control loops) is well tuned. The dynamics of the wind turbine control system has to be taken into account when tuning the wind farm controller, i.e. the outermost control loop. The following PI parameters are chosen: proportional gain \( K_P = 0.44 \), and integral time constant \( T_I = 190 \text{ms} \).

4. Results
In this section, the experimental results are presented and the performance of the control system is analysed. First, the inflow conditions for the downwind turbine are characterised in
Subsection 4.1, followed by a brief analysis of the model wind turbines’ power tracking capabilities in Subsection 4.2. Power tracking at the wind farm level, and a comparison to the open loop control are presented for the full wake and partial wake configuration of the model wind farm in Subsection 4.3 and Subsection 4.4, respectively. Finally, the behaviour of the control system in presence of wind turbine faults, and a possibility to extend the presented controller for reduction of structural loads are presented in Subsection 4.5.

4.1. Inflow conditions
The upwind turbine is operating in low turbulence uniform inflow conditions with different constant wind speeds. The inflow conditions for the downwind turbine were measured with a Dantec Streamline system with six 1D hot-wire probes of type 55P16 \((l = 1.25 \text{ mm})\) positioned 5.2 \(D\) behind the upwind wind turbine at hub height. In total, \(1.2 \cdot 10^6\) points were collected with the sampling frequency of 15 kHz for each position. The wind measurements were performed without model wind turbines in the tunnel, and with the upwind one operating at the optimal tip speed ratio. The so obtained wake deficit and turbulence intensities (with and without the upwind turbine) are shown in Fig. 4. One can notice a strong wake deficit directly behind the upwind turbine, indicating a very limited power production for the downwind turbine in the full wake layout \((\Delta = 0\) in Fig. 1). Additionally, the downwind wind turbine is operating in the significantly increased turbulence intensity.

![Figure 4](image_url)  
**Figure 4.** Wake deficit and turbulence intensity at the position of the downwind turbine.

4.2. Wind turbine power reference tracking
Before analysing the behaviour of the wind farm controller, the performance of the wind turbine control system is tested. To this aim, a single wind turbine was operating in constant inflow velocities, and its response to changes in the power reference signal was recorded. Such a response obtained for the inflow velocity of 5 m/s is presented in Fig. 5. A couple of stepwise changes in the reference power from 4.5 W to 3.5 W were made, whereas the greedy control settings in these conditions would result in 6 W. The resulting time response can be modelled with a first order transfer function with a time constant of 112 ms. The wind turbine power shown in the figure demonstrates a good power tracking on the wind turbine level. The figure also shows that the de-rating is achieved by reducing the FET voltage \(u_{\text{FET}}\), which is equivalent to reducing the generator torque and increasing the rotor speed, which is in accordance with the controller description in Subsection 3.1.

4.3. Wind farm power reference tracking in the full wake configuration
Here, we verify the performance of the closed loop wind farm controller. Figure 6 shows the response of two model wind turbines in the full wake configuration \((\Delta = 0\) in Fig. 1), and for the
inflow velocity of 6.5 m/s. At the beginning of the experiment, the open loop strategy is used, whereas the upwind wind turbine is expected to produce 70% of the wind farm power reference, i.e. $\alpha_1 = 0.7$ and $\alpha_2 = 0.3$. Due to strong wake deficits at the position of the downwind turbine (see Fig. 4), it cannot produce the demanded power level, resulting in too low power production at the wind farm level. Once the closed loop wind farm controller is activated, it increases the power demand from the individual wind turbines until the desired wind farm power level is reached. Since the downwind turbine is already operating at its limit, the difference in the power generation is compensated by increasing the generation on the upwind turbine.

![Figure 5. Wind turbine power and FET voltage for constant inflow velocity and stepwise changes in the power reference.](image)

$\text{Figure 5.}$ Wind turbine power and FET voltage for constant inflow velocity and stepwise changes in the power reference.

The model wind farm power response shown in Fig. 7 demonstrates that the closed loop controller can track a changing power reference. In this case, the initial contributions from
individual wind turbines are set to $\alpha_1 = 0.94$ and $\alpha_2 = 0.06$, which ensures that, with the inflow velocity of 6.5 m/s, even the downwind turbine has to be de-rated. However, the power output of the downwind turbine is below 1 W, and its contribution to the wind farm control is, therefore, practically negligible.

![Figure 7. The model wind farm following a power reference with the closed loop controller in the full wake configuration.](image)

4.4. Wind farm power reference tracking in the partial wake configuration

Here, the control system behaviour is analysed with the model wind turbines in the partial wake configuration ($\Delta = 0.5D$ in Fig. 1). According to the wake deficits shown in Fig. 4, such a configuration should result in higher power levels for the downwind turbine, and therefore in its more active role in tracking the wind farm power reference.

![Figure 8. Comparison of the open loop wind farm controller (the marked area) and the closed loop controller in the partial wake configuration.](image)

Figure 8 compares the open and closed loop approach for the inflow velocity of 6.5 m/s, and wind turbine power contributions $\alpha_1 = 0.55$ and $\alpha_2 = 0.45$. In the open loop control, shown in the marked area of the figure, this results in a too high power reference for the downwind wind turbine, and thus in a tracking error on the wind farm level. Once the control loop is closed, the tracking error is compensated by requiring higher power output from the upwind machine.
Figure 9. The model wind farm following a power reference with the closed loop controller in the partial wake configuration.

Tracking of an arbitrary dynamically changing power reference is shown in Fig. 9. Once again, good tracking capabilities of the proposed controller are demonstrated. The results presented in the figure are obtained for the inflow velocity of 7 m/s, and the contributions from individual turbines set to $\alpha_1 = 0.7$ and $\alpha_2 = 0.3$.

4.5. Validation of the wind farm controller in specific operating conditions

After demonstrating that the proposed wind farm controller can track the wind farm power reference well, a couple of specific operating conditions, which should be handled by wind farm controllers, are tested here. All experiments reported in this subsection are performed in the partial wake configuration ($\Delta = 0.5D$ in Fig. 1).

First, a situation where a wind turbine in a wind farm suddenly stops contributing to the power output, e.g. due to a failure or an emergency shut-down, is simulated, and the results are presented in Fig. 10. The experiment is performed for the inflow velocity of 6.5 m/s, and with power ratios $\alpha_1 = 0.78$ and $\alpha_2 = 0.22$. In the moment when the downwind turbine is disconnected, a sudden drop in the wind farm power occurs. Obviously, without any feedback, and without an appropriate reconfiguration of the power ratios $\alpha_i$, the open loop approach could not compensate the resulting power drop. However, as it can be seen in the figure, the presented closed loop approach compensates the power drop by increasing the power production of the upwind turbine - or in the general case, of the still operating wind turbines.

Since de-rating of a wind farm can typically be done in different ways, the active power control can be combined with control algorithms for load reduction of a fairer load distribution in the wind farm. The control algorithm presented here could be extended to account for wind turbine loads by designing additional control loops that will manipulate the contributions $\alpha_i$, i.e. operating points of individual wind turbines. For more details on such an approach, c.f. [4].

Although the control of structural loads is out of scope in this paper, we analyse the possibility to manipulate operating points of individual wind turbines, and its influence on the tracking of the wind farm power reference. To this aim, an experiment with the inflow velocity of 6.5 m/s is performed, where the power ratios $\alpha_i$ are being dynamically changed, as shown in Fig. 11. Changing of the power ratios causes also rotor speeds and power outputs of individual wind turbines to change, thus effectively changing their operating points and loading. However, it is important to note that the total power production remains mostly unaffected by this, indicating that changing of the power contributions $\alpha_i$ can be a useful degree of freedom for reduction of structural loads.
Figure 10. Simulated failure of the downwind turbine.

Figure 11. The model wind farm response to changing the power ratios $\alpha_i$.

5. Conclusions
This paper presents an experimental validation of a closed loop wind farm control algorithm for active power control. To this aim, two model wind turbines with a rotor diameter of $D = 0.58\, m$ are used in a closed section of a $3\, m \times 3\, m$ wind tunnel at University of Oldenburg. The control algorithm, implemented on the NI cRIO real time controller, consists of a standard greedy control with additional PI-based cascade control loops needed for de-rating, i.e. power reference tracking both at the wind turbine and at the wind farm level. After demonstrating adequate control performance of the inner control loops, related to the power tracking at the wind turbine level, a series of experiments with the model wind turbines in two different layouts, and in several inflow velocities are performed. The presented wind farm control algorithm demonstrates good power
tracking performance in all experiments. It is also shown that the presented closed loop approach can outperform a standard open loop wind farm controller, when wind turbine operating points are not adequately chosen based on the available power, e.g. in a waked situation.

Besides power tracking abilities, selected additional scenarios are also tested, which need to be handled by a wind farm controller, and in which the open loop approach cannot lead to desirable results. First, a failure on one of the model turbines is simulated, resulting in a sudden loss of power production. Since the presented control algorithm uses the generated power as a feedback signal, it manages to compensate for such failures by increasing the power production of the remaining wind turbine(s), provided that the available power is high enough.

Finally, an extension of the proposed controller for reduction of structural loads is discussed. Such an extension could be actively changing individual wind turbine contributions to the generated power in order to change wind turbines’ operating points, and therefore, possibly, to achieve a reduction or a fairer distribution of structural loads. The obtained results show that changing of the wind turbines’ operating points is possible without deteriorating the wind farm power tracking performance, which motivates further research in field of wind farm control for reduction of structural loads.

Although the two turbine setup cannot fully represent the behaviour of a wind farm, it can show how a wind farm controller should deal with wake interactions. Therefore, the results and the experimental facility presented in this paper represent a step forward in the validation of wind turbine active power control. In the future, the experimental facility will be extended with additional model wind turbines, allowing for a wider variety of wind farm layouts. Planned experimental activities include testing of different wind farm control algorithms in different turbulent inflow conditions.

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