Wake redirection for active power control: a realistic case study

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Abstract. This paper presents a realistic case study of how wake redirection can be used to provide ancillary grid service. Wake redirection is a wind farm control approach in which the wake of a wind turbine is redirected by imposing a yaw misalignment to minimise the flow interactions with downwind wind turbines. The increase in power is controlled in our approach to meet a requested power increase. The methodology is implemented in FAST.Farm, a mid-fidelity wind farm simulation tool. In a case study with 12 wind turbines the applicability of the methodology is analysed. Hereby, provision of active power control was achieved in some cases. Structural loads were investigated at tower base, blade root and drivetrain of the turbines, indicating that the concept tends to increase the fatigue damage compared to a baseline case where all turbines are operated with zero yaw misalignment.

1. Introduction
In electrical grids balance between electricity generation and consumption must exist in order to keep the grid frequency stable. In general this balance is achieved on the electricity market where electricity is traded in order to meet the predicted electricity demand at a certain time. However, this balance is not always gained completely and for instance unexpected events can lead to deviations in grid frequency. Therefore, transmission grid operators (TSO) can activate power reserves (negative or positive) as one type of ancillary services to stabilise the grid frequency in case of deviations from the nominal value [1]. In the past, these power reserves were normally provided by conventional power plants (e.g. coal, nuclear) because of their capability to be actively controlled. The future energy mix will be dominated by renewable energy sources which will then have to provide grid stabilisation support [2]. Consequently, there has been increasing interest in providing active power control (APC) by wind farms. Especially, automatic generation control (AGC) as one type of APC was investigated in more detail in the past [3].

In AGC, the total power of a system follows a signal which is provided by the TSO. AGC can be divided into primary and secondary control, which are activated automatically, as well as tertiary control activated by automatic or manual commands [4] [5]. In Germany, tertiary control reserves must be completely activated within 15 minutes and then supplied in 15-minute-blocks.

The present study looks at tertiary control in more detail; hereby wake redirection control is used below rated wind speeds in wind farms to provide positive power reserves. This is motivated first, by the need of tertiary control; for example in Germany the total energy of tertiary reserves used was 127 GWh for positive and 64 GWh for negative power [6]. Second,
wake redirection control works on the time scale of minutes which is the reason why it is only applicable for secondary and tertiary control.

In wind farms provision of positive active power reserve is most challenging in below rated conditions since the turbines are already operating at maximum. Wake losses are high due to the high thrust coefficients in this conditions. However, with the wake steering concept wake losses can be reduced by intentionally yawing upstream located turbines and hence reducing the effect of their wakes on downstream located turbines. The concept was evaluated by other researchers in high fidelity simulations \[7\], wind tunnel tests \[8\] and also first field testing campaigns were performed \[9\]. Besides increasing the power output of wind farms wake steering also offers potentially load mitigation of turbines normally located in the wake of other turbines. However, this is not always the case especially when partial wake situations are increased through the application of wake redirecțion control \[10\]; or the yawed turbine itself experiences higher fatigue loads compared to non-yawed conditions \[11\]. This leads to the conclusion that especially for older turbine generations wake steering should not be applied constantly but at specific events. Therefore, one possible application is to use wake steering for tertiary control during a limited time period.

This study investigates an operational control method in order to provide positive minute reserve by wind farms. Hereby, the objectives are introduced in section 2. The developed control method and the simulation tool for assessing the approach are introduced in section 3. The scenario for application and its obligations are explained in section 4. Within a two steps approach the results of this study are presented in section 5: First, the general capability of providing positive minute reserve from the wind farm alpha ventus is examined; Second, the impact of the control method on structural loads is investigated.

2. Objectives
Wake redirection control is mostly used to increase the total power yield of a wind farm. The approach was investigated with different reduced order wake models and various activities were performed to include physical effects into the reduced order models.

The classical wake steering approach reads as

\[
\min_{\alpha_i} \sum_i -P_i(\alpha_i)
\]

subject to \(P_i = \Pi_i(\alpha_i, v_0, \gamma)\)

with \(P_i\) the power output and \(\alpha_i\) the yaw angle of wind turbine \(i\), respectively. The wake model is included in \(\Pi_i(\alpha_i, v_0, \gamma)\) which describes the power of wind turbine \(i\) with respect to \(\alpha_i\), the wind speed \(v_0\), and the wind direction \(\gamma\).

The objective of this paper is to derive a closed-loop formulation to realise power provision for minute reserve with wake redirection control. Further, a possible application of the wake steering control concept for active power control in a realistic scenario is studied. Hereby, the developed controller is used in a simulation study based on the alpha ventus wind farm in the North Sea. Special attention is paid to loads of individual turbines, which in the end is crucial for the certification of such a control concept. Simulations were performed with FAST.Farm, which offers the capability to resolve wake effects and individual turbine loads adequately. Additionally, many simulations can be performed with FAST.Farm overcoming the limitation of usually applied large eddy simulations (LES) of considering only a few load cases.

3. Methodology
3.1. Open-loop approach
The objective of providing positive minute power reserve with wake redirection is to increase the power output of a wind farm by a certain amount to stabilise frequency of the electricity
grid. This power boost is limited by the maximum power which is achievable through wake redirection \( P_{\text{farm,max}} \). Assuming a power increase \( \Delta P \) of

\[
\Delta P < P_{\text{farm,max}}
\]  

\(2\)

the optimisation problem of Eq. 1 yields the nonlinear equation

\[
\Delta P = \sum_i (P_i(\alpha_i) - P_i,\text{norm}) = \sum_i \delta P_i,
\]  

\(3\)

with \( P_i,\text{norm} \) the original power of turbine \( i \) with \( \alpha_i = 0, P_i,\text{norm} = P_i(0) \).

Additional considerations need to be taken into account to properly solve the equation. A reasonable approach is to include structural loads and try to minimise them. However, the estimation of structural loads and the consideration in the optimisation is a challenging approach. We assume, that smaller yaw misalignment angles result in less additional loads for the wind turbine compared to higher yaw angles. Thus, Eq. (3) can be extended to a constrained optimisation problem. Then, the (open-loop) constrained optimisation scheme for obtaining the yaw angles reads as

\[
\min_{\alpha_i} \sum_i \alpha_i^2 \\
\text{s.t.} \Delta P = \sum_i \delta P_i.
\]  

\(4\)

3.2. Closed-loop approach

There are two main reasons of realising a closed-loop controller for tertiary control: 1) model uncertainties in the pre-calculation of the yaw angles according to Eq. (4), and 2) the variability in the flow and atmospheric conditions that need continuous adaption. Both aspects weaken the control performance and therefore a feedback of the wind farm power output \( P_{\text{farm}} \) is used. Figure 1 shows the herein proposed closed-loop concept. A feedback controller is derived that uses the actual farm power and a desired power output fulfilling Eq. (2). The feedback consists
of a proportional-integral controller and gives a generalised output which is then distributed according to the actual gradient of the individual wind turbines. The gradient is derived beforehand by means of a lookup-table using a reduced order model (see section 4.3). This approach enables distributing the contribution to the power demand according to the global potential of a turbine.

Triggered effects on the wake of turbines due to changes in turbine yaw set points are affecting downstream turbines with a time delay depending on the wind conditions (e.g. wind speed, magnitude of yaw misalignment, turbulence intensity). Increasing the yaw misalignment of upstream turbines will first result in a power drop of the farm power production. Therefore, the time until the effects of changing operational set points of upstream turbines are visible at downstream turbines must be taken into account. In this study, the wake propagation time, which is the time an air particle takes to propagate from one turbine to the next downstream turbine, is estimated by using a simplified wake model. Hereby, the Jensen-wake-model [12] is applied and by calculating the wind speed deficit in the wake of a turbine the wake propagation time is derived. New yaw angles are calculated at each expiration of the calculated wake propagation time. An influence is supposed only between neighbouring turbines in the wind farm layout.

The closed-loop controller determines new yaw angles on the basis of the difference between actual power production and desired power value defined by the operator. The desired power generation must consider the maximum limits of power gain according to the ambient conditions. Then the power difference is normalised by a reference wind farm power. The resulting value is multiplied by two control parameters. These allow an adaption to different flow conditions and magnitudes of desired additional power generation. The gradients at each wind turbine in the farm are also multiplied by the dimensionless error. This final value is added to the already applied yaw angles and is fed back to the wind turbines.

\[
\begin{bmatrix}
\alpha_1 \\
\vdots \\
\alpha_n \\
\end{bmatrix} = \begin{bmatrix}
\alpha_{1,\text{old}} \\
\vdots \\
\alpha_{n,\text{old}} \\
\end{bmatrix} + e_m \cdot \begin{bmatrix}
\frac{\partial P}{\partial \alpha_1} \\
\vdots \\
\frac{\partial P}{\partial \alpha_n} \\
\end{bmatrix} \tag{5}
\]

Equation (5) shows the calculation of new yaw angles \(\alpha\). It is based on the previous yaw angles and adds the multiplication of the control error \(e_m\) with the power gradients \(\frac{\partial P}{\partial \alpha_i}\).

\[
e_m = \frac{P_{\text{desired}} - P_{\text{actual}}}{P_{\text{baseline}}} \cdot f_{\text{const}} + I_{\text{state}} \tag{6}
\]

In equation (6) the control error is calculated from the normalised difference between the mean, desired power \(P_{\text{desired}}\) and the mean, actual power \(P_{\text{actual}}\) of the previous expired wake propagation time. The result is divided by a baseline power value \(P_{\text{baseline}}\) as reference power and is multiplied by a constant control factor \(f_{\text{const}}\). Then an integrator state \(I_{\text{state}}\) value is added. Both the control factor and the integrator state are parameters to tune the closed-loop control. The yaw angles change at each wake propagation time step, respectively. Power gradients \(\frac{\partial P}{\partial \alpha_i}\) are calculated by using FLORIS (see sections 3.4 and 4.3) in advance to prepare them as input lookup-tables to the closed-loop controller. Therefore, wind speed, flow direction, turbulence intensity, ambient density, wind turbine type and wind farm layout are considered. An exemplary power lookup table is provided in Figure 2. It shows the combined power output of three turbines in line for a wind speed of 9 m/s. The yaw angles of the first two turbines are varied while the third, most downwind turbine remains at a yaw angle of 0°. From this matrix the gradients are determined and are used in the closed-loop scheme.
Figure 2. Combined power output of a three turbine example case at a wind speed of $9 \text{ m/s}$. Turbines are placed in line; T1 is upstream, followed by T2 and T3.

3.3. Simulation tool: FAST.Farm
In order to evaluate the behaviour of the proposed tertiary control method an adequate simulation tool is required. The new FAST.Farm simulation tool developed by the US National Renewable Energy Laboratory (NREL) was considered to be suitable in resolving all relevant phenomena [13]. Wake modelling is based on the dynamic wake meandering (DWM) approach. The implementation in FAST.Farm includes modelling of wake deficits, advection, deflection, meandering and merging for wind farms. Individual turbine aerodynamics are calculated with blade element momentum (BEM) theory. The aerodynamic effects of yaw misalignment are taken into account by using the Pitt/Peters skewed wake correction model as implemented in Aerodyn v15 of the FAST code. Structural loads are accounted for via multi body simulation analogous to a single OpenFAST calculation. An advantage of FAST.Farm is the existing super controller interface for inter turbine communication. FAST.Farm accepts wind fields either generated in advance in a LES precursor simulation or by a spectral code such as Turbsim. FAST.Farm was tested and calibrated with LES and shows good agreement with this higher fidelity model [14]. This makes it a solid basis for this study.

3.4. Low order simulation tool: FLORIS
The FLORIS framework, initially developed as a wake model, was transferred to a platform of reduced-order wake models for wind farm control and layout optimisation [15]. FLORIS is built modular and includes a couple of existing steady-state wake models that offer predictions on the power production of wind farms at low computational costs. For this study, the zoned wake model was used to model the wake velocity [16]. For modelling the deflection of the wake, a wake center-line deflection model was used which assumes a strict distinction between the near and the far wake [17].
4. Application in a realistic scenario

4.1. Wind farm alpha ventus

The wind farm control concept for active power control was applied at the wind farm alpha ventus, which is located in the North sea; its layout is drawn in figure 3. Twelve turbines with each having a rated power of 5 MW are clustered in a staggered grid. For this study, the original turbines are replaced by the NREL 5 MW reference turbine to be able to adjust the turbine controllers for communicating with the farm controller. This is a fair replacement since the original turbines have very similar properties such as the rotor diameter of 126 m and the rotor speed range from 6.9 - 12.1 rpm. Site specific quantities such as hub height and distance between turbines are the same as in alpha ventus. The turbines are mounted on a monopile substructure.

![Wind farm layout of alpha ventus; North is at the top](image)

Figure 3. Wind farm layout of alpha ventus; North is at the top

![Wind statistics derived from Fino 1 met mast at hub height for years 2011-2018](image)

Figure 4. Wind statistics derived from Fino 1 met mast at hub height for years 2011-2018

Ambient conditions are taken from measurement data of the Fino 1 met mast, which is located close to the wind farm (see figure 3). The wind statistics of the years 2011-2018 are shown in Figure 4 and are used as reference. For the generation of wind fields neutral conditions with an average turbulence intensity of 6 % for all wind speeds are assumed. This assumption reflects the mean values recorded at Fino 1. Vertical shear of the wind profile is simulated by using a power law exponent of $\alpha = 0.14$.

4.2. Potential Analysis

In a pre-analysis it was evaluated what the highest possible power increase of the wind farm alpha ventus through adjusting the yaw angles is. The total power increase relates to the baseline power output, which is achieved for yaw angles equal to zero. FLORIS was used to calculate the total power output dependent on wind direction and wind speed. The results of the potential analysis are summarised in Figure 5. A horizontal line of 1 MW is drawn to reflect the minimum bid size according to the tender for the allocation of operating reserve by the four German transmission system operators [18]. Taking this into account there are only eight sectors of wind directions where the total power increase is high enough to provide reserve power to the electrical grid. Furthermore, it can be seen that there are pairs of wind direction sectors separated by 180° which have a very similar shape. This relates to the almost symmetrical layout of the wind farm. Therefore, it is concluded that only one of the pairing sectors must be
Figure 5. Total maximum power increase through adjusting the yaw angles compared to the baseline power output with yaw angles equal to zero.

simulated in a detailed simulation and the results can be transferred to the other sector. The four sectors are marked grey in Figure 5.

4.3. Lookup table generation
The proposed control method requires pre-calculated lookup tables where the power output of the wind farm is given in dependency on the yaw angles of the individual turbines. Although the number of wind directions to be evaluated was greatly reduced by the potential analysis, a complete permutation of the yaw angles of all 12 turbines is not possible. Hence, the turbines of the wind farm are divided into subgroups of up to 4 turbines depending on the wind direction. The subgroups are divided in a way that the power output of each group is independent of the other subgroups. This way the size of the lookup table becomes smaller and can be calculated more quickly.

Based on the potential analysis the identified wind direction sectors were discretised for creating the lookup table. For each wind direction wind speed was varied starting at 6 m/s to 14 m/s in steps of 0.5 m/s. The yaw angle of each turbine was changed from -30° up to 30° in steps of 5°.

5. Results
Within section 4.2 it was investigated at which wind directions an application of the wake steering method makes sense to increase the wind farm power output in below rated wind conditions. This knowledge was then used to decide which wind directions and wind speeds are simulated in FAST.Farm. Table 1 summarises the simulated scenarios. The simulation time was set to 1800 s. This consists of a start-up phase of 600 s, in which the flow and wakes develop; an initialisation phase of 300 s, in which wind speed is measured to derive initial yaw angles; and a performance phase of 15 min, in which minute reserve power is provided. Each scenario was simulated 6 times by using different turbulent wind field realisations. The wind fields were generated in advance by the use of TurbSim following recommendations given in [19].

5.1. Provision of positive minute reserve
In a first step, the general capability of the control method in connection with the wind farm alpha ventus for providing positive minute reserve was analysed. Figure 6 shows the power $\Delta P_{\text{farm}}$, which is the mean net power deviation from the non-controlled baseline case for all
Table 1. Simulated scenarios in FAST.Farm based on the potential analysis in Figure 5

| Sector | Wind direction [deg] | Wind speed [m/s] | Turbulence intensity [%] | Turbulent Seeds |
|--------|----------------------|------------------|-------------------------|-----------------|
| 1      | 176,180,185          | [7:1:12]         | 6                       | [1:1:6]         |
| 2      | 226                  | [10:1:12]        | 6                       | [1:1:6]         |
| 3      | 264,268,273          | [7:1:12]         | 6                       | [1:1:6]         |
| 4      | 313                  | [10:1:12]        | 6                       | [1:1:6]         |

simulated wind directions and wind speeds. The desired setpoint was 1 MW power increase in all cases. It is observed, that a positive net power value is mostly achieved for lower wind speeds up to 9 m/s. For wind speeds above 10 m/s the power output is only increased in the wind direction sector around 270° and for a wind direction of 185°. The other wind direction sectors show losses in total farm power up to -3 MW. The biggest spread in net power values can be seen in the sector around 180°, whereas a more homogeneous distribution is found around 270°. The sectors around 226° and 313° show a narrow band where a net farm power increase is achieved. This is compliant with the potential analysis in section 4.2.

Figure 6. $\Delta P_{farm}$ equals to mean values of the total wind farm power output subtracted by the baseline case with zero yaw angles. Error bars indicate combined standard deviation of the baseline and controlled cases.

5.2. Structural load distribution in alpha ventus
In order to evaluate the effects of the control concept on structural integrity of the turbines the fatigue loads at tower base, blade root and drivetrain are analysed. In Figure 7 the results are shown for a wind speed of 8 m/s and a wind direction of 185°. It can be seen that at tower base and low speed shaft the freestream turbines AV10-12 experience higher loads in the controlled scenario compared to the baseline. The results for the other turbines AV1-9 show similar or lower loads in the controlled scenario. In contrast, the trends for the loads at blade root show
the opposite behaviour meaning lower loads for the freestream turbines and higher loads for the other turbines in the controlled scenario.

![Figure 7. Case: wind speed 8 m/s, wind direction 185°. Top Left: Turbulence intensity at hub height. Top Right: Normalised DEL of the total bending moment at tower base. Bottom Left: Normalised DEL of the total bending moment at blade root. Bottom Right: Normalised DEL of the low speed shaft torque. The loads are normalised by their respective mean value of the baseline scenario. Error bars show standard deviation of turbulent seeds.](image)

In Figure 8 the fatigue loads for a wind direction of 273° and a wind speed of 9 m/s are given. It is observed that the loads at tower base, blade root and low speed shaft for basically all turbines are increased in the controlled scenario compared to the baseline case.

The two main drivers for creating the difference in loads between the baseline and controlled scenario are the yaw misalignment of certain turbines and the changing wake effects due to wake deflection. The influence of yaw misalignment on the loads can be identified best at freestream turbines. In the two picked cases yaw misalignment leads to increased loads for most of the components except the blade root. For more detailed explanations of yaw misalignment effects on turbine loads the reader is referred to [11].

In order to analyse wake effects on structural loads turbulence intensity is used as an indicator. Wind turbine wakes and especially wake meandering increase turbulence intensity which in turn leads often to higher loads at turbines. This can be observed in the two cases where in Figure 7 the turbulence intensity at the downstream turbines is reduced. This shows that the wakes are deflected past the downstream turbines leading to lower loads for most of the components. In the case presented in Figure 8 turbulence intensity at downstream turbines is slightly increased.
Figure 8. Case: wind speed 9 m/s, wind direction 273°. Top Left: Turbulence intensity at hub height. Top Right: Normalised DEL of the total bending moment at tower base. Bottom Left: Normalised DEL of the total bending moment at blade root. Bottom Right: Normalised DEL of the low speed shaft torque. The loads are normalised by their respective mean value of the baseline scenario. Error bars show standard deviation of turbulent seeds.

contributing to higher loads. However, differences in structural loads cannot be attributed to different turbulence intensities solely. For example, reducing wake effects by wake steering leads to different operational points of the wind turbines. This can be seen in Figure 7 where the blade root loads at downstream turbines are increased due to higher power production in the controlled scenario.

6. Conclusions
In this study we presented a control concept for the application in a wind farm with the objective of providing minute reserve power to the electrical grid. The control principle is based on the wake steering method where the total farm power output can be increased by intentionally changing turbine yaw angle set points. It was aimed for a simple concept which is based on a lookup table pre-calculated with the tool FLORIS, where farm power output is given based on turbine yaw angles. The lookup table is used to calculate power gradients which are eventually used to reduce the error of desired and actual farm power output. A desired power output value of 1MW higher than the baseline value was set in order to be compliant with grid code regulations.

The control concept was applied on the wind farm alpha ventus. In a simulation study with the tool FAST.Farm it was checked to what extent active power control can be provided and
what implications this has on the structural loads of the turbines. It was found that the provision of minute reserve power is dependent on the wind direction and wind speed. For a couple of cases the desired power increase of 1MW could be achieved quite accurately. However, for the majority of scenarios the desired power increase was not gained or even less power was generated compared to the baseline case.

In a second step the structural loads of the individual turbines were investigated. It was shown, that in general the control concept tends to increase the fatigue loads of the turbines compared to a greedy control scenario. On one hand, this can be seen as a result of additional periodic loads of the turbines operated under yaw misalignment. On the other hand, manipulating the wake path leads to different operating conditions of downstream turbines leading to different loads.

The simplistic control concept shows some promising results to be applicable for increasing power output of a wind farm. However, in the case of minute reserve power provision the uncertainty is still high and further work must be performed to achieve more reliable results. FAST.Farm turned out to be a useful tool to also include structural loads in the analysis of a new control concept for wind farms.

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