Optimising yaw control at wind farm level

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Abstract. The wind turbines in a wind farm must turn to face the wind to achieve maximum power production. Until now, each turbine achieves this individually: the nacelle-mounted wind vane measures the yaw misalignment, from which the turbine controller decides when to make a yaw correction by using a combination of heavy filtering and counters or dead-band hysteresis. In a wind farm context, each turbine could make use of information from its neighbours, and therefore, in principle, it should be possible to achieve better yaw control by using a centralised farm-level yaw control algorithm which uses input measurements from all the turbines, and then tells each turbine how to yaw. “Better” yaw control will always be a compromise between maximising energy production and minimising yaw actuator duty. Using a realistic dynamic simulation model of a wind farm which uses actual measured wind data as input, different possible yaw strategies are tested, and compared in terms of energy production and yaw actuator duty. The results indicate that centralised yaw control is likely to achieve a better compromise. There also is much current interest in the use of wake steering, where yaw setpoints are optimised to steer the wakes of some turbines away from others. Centralised yaw control may offer a better way to implement these setpoints, rather than sending yaw offsets to be acted on by the normal turbine yaw controllers with their own filtering, dead-band logic, etc.

1. Introduction
Conventional, a wind vane on top of the nacelle measures yaw misalignment at a point which is poorly representative of the rotor-average wind direction and is also situated in highly disturbed flow, affected by flow around the nacelle and by the blade roots passing just upstream as the rotor rotates. Therefore, the wind vane signal is passed through a heavy low-pass filter, both to smooth out the short-term variations and to make the resulting signal more representative of rotor-average variations. To prevent frequent yaw manoeuvres which would cause unnecessary yaw system wear, a hysteresis dead-band is introduced. All this means that the yaw response is considerably delayed. Forward-pointing LiDAR can be used both to obtain a signal more representative of the rotor as a whole, and can also provide a small amount of preview, but it represents a considerable extra cost.

Yaw control is relatively slow and simple, and has rarely been studied in detail. Control algorithms typically use a low-pass filter and a hysteresis dead-band or a combination of counters and timers, generating discrete yaw manoeuvres from time to time. The parameters determining the yaw control are usually obtained by a combination of trial and error and field experience. The resulting yaw action depends on relatively low-frequency changes in wind direction, although they are measured at high frequency by the small wind vane. The wind plant simulator LongSim has been developed specifically to investigate control aspects of this sort, by allowing simulations with a short time-step (suitable for
representing the wind vane measurements) which can run for long enough for the effects of low-frequency wind field variations to be experienced. The potential of this model to optimise single-turbine yaw control algorithms has been described previously [1]. Since then, the model has been extended to allow it to simulate a whole wind farm, accounting also for the correlations in wind field variations [2] between the turbines across the farm, and also for wake effects [3], [4], [5], including wake meandering [6] and wake deflection caused by any yaw misalignments [7]. This extended model is ideal for testing wind farm controllers, and its use to test active wake control algorithms such as induction (power set-point) control and wake steering has been presented in [8]. A more detailed description of the model can be found in [9].

In this paper, the model is used to test different wind farm yaw control algorithms and compare them against individual turbine yaw control. The results demonstrate a potential for significant reductions in yaw actuator duty and/or increased energy production for the whole wind farm.

If wake steering is to be used, part of the benefit is lost if the deliberate yaw misalignments, calculated by the wind farm controller, are applied simply as offsets and subjected to the yaw errors inherent in the individual turbine yaw control algorithms. Central yaw control as presented in this paper should be a better basis for adding wake steering control, to gain further energy capture benefits.

2. Methodology
Using the LongSim model, a time-domain simulation based on the Horns Rev 1 offshore wind farm (off the west coast of Denmark) has been set up. The turbine layout is shown in Figure 1. The 80 turbines are 80m in diameter, with a rated power of 2MW. The turbine power curve is known from public-domain information, but information about the turbine yaw behaviour is not readily available, and so realistic assumptions have been made, which may not match the actual reality for this site but are reasonable for this conceptual study. This includes modification of the power curve and rotor thrust for different yaw angles, and the actual yaw control strategy of the turbines. These assumptions are detailed in Section 2.1.

The wind conditions for the simulation are taken from publicly-available 10-minute data measured at the FINO-1 meteorological mast in the German North Sea. Although this is not the same as the Horns Rev site, it is probably reasonably representative and is certainly suitable for this conceptual study. Using a selected part of this wind record, a correlated wind field covering the entire farm has been generated, using synthetic turbulence for the higher frequencies. A half-hour simulation was used initially, and repeated with different yaw control philosophies, which are described in Section 2.2. A simulation time-step of 1 second was used. Results are presented in Section 3.

2.1. Assumptions about turbine yaw
The simple assumption that power decreases as $\cos^p(\text{yaw})$ seems not to be valid, and a number of cases have demonstrated a factor of $\cos^p(\text{yaw})$ with the exponent $p$ being much less than 3, typically more like 1.4 – 2.0 (e.g. $p=1.43$ in [10]). Here the value $p=1.4$ has been used as a basis; however, this cannot simply be used to scale the entire power curve, as it would result in less than rated power in high winds where, in reality, pitch control would compensate for yaw to bring the power back to rated. Therefore, a factor $\cos^p(\text{yaw})$ has instead been applied to the wind speed used for the power curve look-up. For example, if $\cos^p(\text{yaw}) = 0.95$ the power at 10 m/s would be obtained from the power curve value for 9.5 m/s; and above rated, say at 20 m/s, the power would be calculated for 19 m/s, which is still rated power. For this turbine, $w = 0.5$ has been used as it gives a very similar result to $p=1.4$ in below-rated wind speeds while allowing the power curve still to reach rated, albeit at a higher wind speed than at zero yaw. The resulting power curves are illustrated in Figure 2 and Figure 3. For the turbine thrust look-up, the same factor $w$ is assumed to apply to the effective wind speed.

For the yaw control logic, a 30-second first-order low-pass filter is applied to the wind direction, obtained as the sum of the nacelle position and the wind vane signal, and the nacelle position is subtracted from this to get the filtered yaw error (this avoids the problem of nacelle motion interfering
with the filtering if it’s applied directly to the wind vane signal). Then when the yaw error exceeds $\pm 8^\circ$, the turbine yaws at $\pm 0.3^\circ/s$ until the filtered yaw error crosses zero.

**Figure 1**: Turbine layout at Horns Rev 1 (axes in metres), with an illustration of central yaw control strategy. Purple arrow: approximately estimated wind direction, Red circle: controlled turbine, Green circles: equal-weighting contours, showing an upwind preview distance. The demanded nacelle direction of the controlled turbine is a weighted sum of directions at other turbines, weighted inversely with distance from the centre of the green circles.

**Figure 2**: Assumed power curve at $15^\circ$ yaw

**Figure 3**: Assumed power curve at $30^\circ$ yaw

2.2. **Yaw control philosophies**

The following yaw control philosophies have been simulated:

- ‘Ideal’: the turbine yaws continuously to maintain zero yaw misalignment. This is infeasible in practice but gives an upper limit on the possible energy capture.
• Turbine-based yaw control based on typical standard yaw control logic, using a 30-second first-order filter on the wind vane signal and various hysteresis dead-bands.
• Central yaw control, where the wind farm controller uses an exponentially-weighted average of turbine wind direction estimates to derive a demanded nacelle position for each turbine (illustrated schematically in Figure 1). Offsetting the point of highest weighting to a position upstream of the controlled turbine gives a preview effect. The direction estimates consist of the same 30-second filtered wind direction as in the turbine-based yaw control. A dead-band is still applied to prevent continuous yawing, but it can be smaller than in the turbine-based case, because the spatial averaging over adjacent turbines results in further smoothing. For the same reason, the filter time constant for the wind directions could perhaps also be reduced.

The strategies and the parameters used are detailed further in Table 1.

**Table 1:** Details of yaw control strategies

| Strategy name | Description | Parameters |
|---------------|-------------|------------|
| Ideal | "Ideal” yaw control (immediate, continuous response to true rotor-average wind speed) |
| T1 (base case) | Typical turbine-based yaw control | 8° dead-band, 30-second average |
| T2 | 5° dead-band, 30-second average |
| T3 | 2° dead-band, 30-second average |
| C1 | Central yaw control with weighting factor exponential decay distance D and preview distance P | D=1000m, P=700m, 8° dead-band, 30-second average |
| C2 | D=1000m, P=700m, 2° dead-band, 30-second average |
| C3 | D=500m, P=500m, 5° dead-band, 30-second average |
| C4 | D=300m, P=300m, 2° dead-band, 30-second average |
| C5 | D=300m, P=300m, 8° dead-band, 30-second average |

**3. Results**

The same half-hour simulation was repeated with each of the yaw control strategies defined above, and the total wind farm power was recorded along with the total yaw travel of all the turbines, and the total number of yawing events (in the ‘Ideal’ case the latter is effectively infinite because yawing is continuous). The wind speed and direction for the simulations are shown in Figure 4; this is the data from the met mast, after smoothing, which was used as a basis for the generation of the wind farm wind field.

![Figure 4: Wind conditions for the simulation (met mast data, smoothed)](image-url)
Typical yaw time histories are shown in Figure 5, for an upstream turbine and a downstream one. The base case (T1) is compared against one of the central control cases (C3). The upstream turbine cannot benefit from any preview, because there are no turbines further upstream, but the benefit of preview is clear for the downstream one.

For all the cases, the trade-off between energy capture and yaw duty is shown in Figure 6. It is clear that the central yaw control strategies can both increase the energy capture and reduce the yaw duty, especially when measured in terms of yaw travel. The results are tabulated in Table 2.
Table 2: Summary of results

| Case         | Mean power, MW | Yaw travel, degrees | No. of yaw events |
|--------------|----------------|---------------------|------------------|
| Ideal        | 77.72          | 36897.0             | ∞                |
| T1 (base case)| 72.71          | 4321.8              | 393              |
| T2           | 72.80          | 5566.5              | 762              |
| T3           | 72.85          | 7050.0              | 2163             |
| C1           | 72.80          | 2397.3              | 250              |
| C2           | 72.81          | 3381.9              | 1393             |
| C3           | 72.86          | 3296.4              | 525              |
| C4           | 72.86          | 4424.7              | 1752             |
| C5           | 72.80          | 3077.7              | 302              |

4. Discussion

By combining wind direction estimates from other nearby turbines, a smoother, spatially-averaged measure of wind direction is available to each turbine, which may be used to improve the yaw control compared to the conventional case where each turbine uses only its own wind vane. Furthermore, most of the turbines can benefit from preview information from any turbines which are situated further upstream. This leads to a better trade-off between energy output and yaw actuator duty, simultaneously increasing energy output while reducing total yaw travel significantly, and also reducing the number of yaw events.

The technique does rely on communication between the turbines, but this can be readily achieved through the wind farm SCADA system. It would clearly be advantageous for the yaw calculations to be carried out in a central wind farm controller, rather than at each turbine, and this is consistent with the increasing interest in using active wake control, such as induction control and/or wake steering [8]. Especially in the case of wake steering, the individual turbine yaw control can significantly detract from the implementation of the yaw setpoints which are calculated to optimise the total wind farm performance. Wake steering studies underway in the CL-Windcon project [11] are already demonstrating an improvement in wake steering performance when implemented using central yaw control. Results will be published in the near future.

Central yaw control also relies on the accurate measurement of nacelle position (also a requirement for wake steering). Currently, many turbines pay little attention to this; since the yaw control relies only on the wind vane, very crude nacelle position sensors are sufficient, and are often not even calibrated, as this is important, even for cable unwinding. Better sensors are readily available, however, such as GPS-based sensors.

The central direction estimates may have a secondary use as a way to detect yaw sensor errors on individual turbines, by detecting any large discrepancies between these direction estimates and the turbine’s own measurements.

The simulations in this paper are considered reasonably realistic, and are able to use site-specific wind data to ensure that results are representative for a particular project. The simulations run reasonably fast on a single processor, which is useful for evaluating different strategies and tuning parameters, as this paper demonstrates, but it also means that longer simulations could then be run to test out a selected strategy over a longer run of data, e.g. several days or more. As ever, there are some aspects to the modelling which are not proven. For example, while the simulations are based on real met mast data, and this is used to generate representative wind fields over the whole wind farm, the met mast still only gives point data, so some assumptions are necessary. Standard models of spatial
coherence are assumed to apply, and the way in which low-frequency changes in conditions propagate through the farm also have to be assumed. In this case, the propagation of changes in direction through the wind farm is linked to the current wind speed and direction, which may not always be valid, and even this simple assumption needs further assumptions because those quantities are, by definition, not uniform across the farm in these cases. The assumptions are probably reasonable most of the time, but unusual events like thunderstorm fronts may be quite different in character.

5. Conclusions
In a wind farm context (even before considering any wake steering), centralised control of turbine yaw can lead to increased energy production and reduced yaw actuator duty when compared to conventional individual turbine yaw control. The example in this paper showed a very modest 0.2% increase in power production, compared to a more dramatic 24% decrease in yaw travel – in financial terms it is difficult to say which effect is the more significant, but it is a win-win situation. The technique benefits from spatial averaging, and a significant preview effect is also beneficial. These benefits are available for no additional cost, apart from the need for more accurate and properly calibrated nacelle position sensors. The paper presents a realistic dynamic simulation model which is appropriate for tuning and evaluating the performance of different yaw controllers, using site-specific wind conditions is available.

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