Cooperative Control Potential Between Offshore Wind Farms

Summary

A long-range wake recovery scenario between two large offshore wind arrays is investigated using an analytical model. Results are obtained for a wide range of wind speeds and separation distances, creating a map of conditions where cooperative control between the arrays may be beneficial. A modest net energy gain from cooperative control, i.e. aggregated across both arrays, is indicated for some of the parameter space.

In a large proportion of the parameter space, the impact of a cooperative control strategy on the combined energy yield is small, but the impact on the yield from the individual arrays is significant. This raises the prospect of using cooperative control for not only the purpose of increasing combined yield, but also to mitigate yield imbalance between arrays in so called 'wind-theft' scenarios.

Introduction

Cooperative control between large turbine arrays (or between clusters) offshore can result in an overall net energy gain. In the right conditions, if generation in an upwind array is purposefully reduced, the resulting increase in a downwind array's generation may more than compensate. An analytical model to explore this scenario [1] underlined the role played by atmospheric stability in moderating this increase in yield. Here the model is applied across a wide parameter space to investigate cooperative control further.

Modelling Approach

The top-down model used is based on the modelling approach of Smith [2]. A 1-dimensional, streamwise version of Smith's model, retaining only forcing and vertical mixing terms, can be written as:

$$U \frac{\partial u_B'}{\partial x} = F_x - C u_B' \qquad (1)$$

Here x is the streamwise distance, U is the depth-averaged wind speed, u_B' is the depth-averaged wind speed perturbation due to a forcing F_x from wind farm drag, and C is the combined Rayleigh friction coefficient. The direct analytical solution, for two arrays separated by a gap, with each array subject to constant forcing, was previously provided [1]. Here we require a more accurate version where the local forcing (from turbine thrust) varies with the local through-farm wind speed. This can be achieved with a finer-resolution piecewise (e.g. for streamwise segments of one turbine diameter length) implementation of the analytical solution. Alternatively, this can also be achieved using a downwind-stepping finite difference approximation to equation (1). Due to its simplicity, the latter approach was used here. This provides a direct means to explore wake interaction and cooperative control between upwind (subscript u) and downwind (d) turbine arrays, of lengths L_u and L_d respectively, separated by distance S. The model is one dimensional, therefore may be considered as representing 'infinitely wide' arrays.

Application Example

Two arrays were considered, each 15 turbines deep with a uniform inter-array separation between turbines of 8 rotor diameters. Power and thrust curves for a representative 5 MW wind turbine were used, see Figure 1. Both a 'Baseline' and a 'De-powered' controller configuration was used. A range of freestream wind speeds from 5 m/s to 14 m/s was modelled. A range of values for the separation distance S between the arrays was modelled, from a minimum of zero (i.e. a continuous array) up to 200 turbine diameters (approximately 25 km). Following [3], a value of C = 0.0001 s^{-1} was applied, representing a realistic low turbulence/high stability case. The upwind array was modelled with both the default/baseline and the de-powered control settings, and the downwind array with the default/baseline settings only, in this way exploring 'induction control' potential on a large wind farm scale.

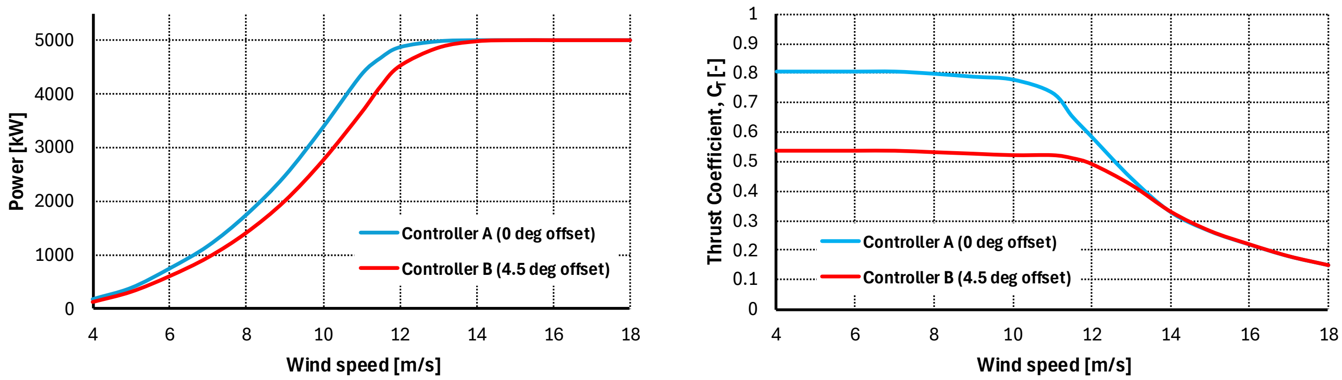

Figure 1: Wind Turbine Power (left) and thrust curves (right)

A 'heatmap' of the resulting increase or decrease in total energy yield (i.e. for both farms together), when using the de-powered upwind array strategy compared to the baseline strategy, is shown in Figure 2. These results were achieved in a few seconds on a commodity laptop computer running a spreadsheet application. The patterns of increased (blue) and decreased (red) yield areas of the speed/separation distance parameter space are sensitive to the specific thrust and power curves used.

Wind speed [m/s]	Recovery gap length between wind farms, *S* [multiples of wind turbine diameter]										
	0	20	40	60	80	100	120	140	160	180	200
5.0	0.7%	0.7%	0.5%	0.4%	0.2%	0.0%	-0.2%	-0.4%	-0.6%	-0.8%	-1.0%
5.5	1.8%	1.4%	1.1%	0.8%	0.5%	0.2%	-0.1%	-0.4%	-0.6%	-0.9%	-1.1%
6.0	1.8%	1.6%	1.4%	1.2%	1.1%	1.0%	0.9%	0.7%	0.6%	0.4%	0.3%
6.5	1.8%	1.6%	1.4%	1.3%	1.1%	0.9%	0.7%	0.5%	0.4%	0.2%	0.0%
7.0	1.7%	1.4%	1.2%	1.0%	0.8%	0.6%	0.4%	0.2%	0.0%	-0.2%	-0.4%
7.5	1.0%	0.8%	0.6%	0.4%	0.2%	0.1%	-0.1%	-0.3%	-0.5%	-0.6%	-0.8%
8.0	0.6%	0.4%	0.2%	0.1%	-0.1%	-0.3%	-0.5%	-0.6%	-0.8%	-0.9%	-1.0%
8.5	0.6%	0.5%	0.3%	0.2%	0.1%	-0.1%	-0.2%	-0.3%	-0.5%	-0.6%	-0.7%
9.0	0.5%	0.4%	0.2%	0.1%	0.0%	-0.2%	-0.3%	-0.5%	-0.6%	-0.7%	-0.9%
9.5	0.5%	0.4%	0.3%	0.2%	0.0%	-0.1%	-0.2%	-0.3%	-0.4%	-0.5%	-0.6%
10.0	0.7%	0.6%	0.5%	0.3%	0.2%	0.1%	0.0%	-0.1%	-0.2%	-0.3%	-0.5%
10.5	0.6%	0.5%	0.4%	0.3%	0.2%	0.0%	-0.1%	-0.2%	-0.3%	-0.4%	-0.5%
11.0	0.6%	0.5%	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%	-0.1%	-0.2%	-0.3%
11.5	0.7%	0.6%	0.5%	0.4%	0.3%	0.2%	0.1%	0.0%	-0.1%	-0.2%	-0.3%
12.0	0.6%	0.5%	0.4%	0.3%	0.2%	0.1%	0.0%	-0.1%	-0.2%	-0.2%	-0.3%
12.5	0.4%	0.3%	0.3%	0.2%	0.1%	0.0%	0.0%	-0.1%	-0.2%	-0.2%	-0.3%
13.0	0.3%	0.2%	0.1%	0.0%	0.0%	-0.1%	-0.2%	-0.2%	-0.3%	-0.3%	-0.4%
13.5	-0.1%	-0.2%	-0.2%	-0.2%	-0.3%	-0.3%	-0.4%	-0.4%	-0.5%	-0.5%	-0.6%
14.0	-0.4%	-0.4%	-0.4%	-0.4%	-0.5%	-0.5%	-0.5%	-0.5%	-0.6%	-0.6%	-0.6%

Figure 2: Total energy yield increase (blue) or decrease (red) using a cooperative control strategy, relative to the baseline.

An increase in yield of more than 1% is indicated for some cases, even with ~10 km (80 diameters) separation distance. The variation across the parameter space for the set-up selected is fairly modest. (For different conditions, the results vary significantly. For example, the gains/losses are much more dramatic for more closely packed arrays). An optimisation algorithm, selecting different controller settings for each upwind turbine, rather than the same for all, would increase the 'beneficial' spread and magnitude.

Figures 3 and 4 show longitudinal profiles of wind speed and turbine power respectively, for the case with a wind speed of 9 m/s and a ~10 km (80 diameters) separation distance. In this case the energy decrease in the upwind array is almost exactly matching the energy increase in the downwind array, so the net effect on total yield is effectively zero. This case, and others like it, may appear to be uninteresting. However, the cooperative control strategy has increased the yield at the downwind wind farm by 8%, thus significantly reducing the influence of the upwind wind farm. The yield of the upwind wind farm is reduced by a corresponding amount. This indicates that cooperative control may be an effective means to mitigate yield imbalance between upwind and downwind arrays, without decreasing net yield.

In our modelled parameter space (with stable conditions), see Figure 2, 70% of the cases show a total yield impact of -0.25% or better. This takes -0.25%, arbitrarily, as a threshold beyond which total yield reduction would not be acceptable to improve yield imbalance. The model results therefore indicate that although significant yield increases (say >1%) are indicated in relatively few cases, the objective of yield imbalance mitigation is served much more broadly by a cooperative control strategy.

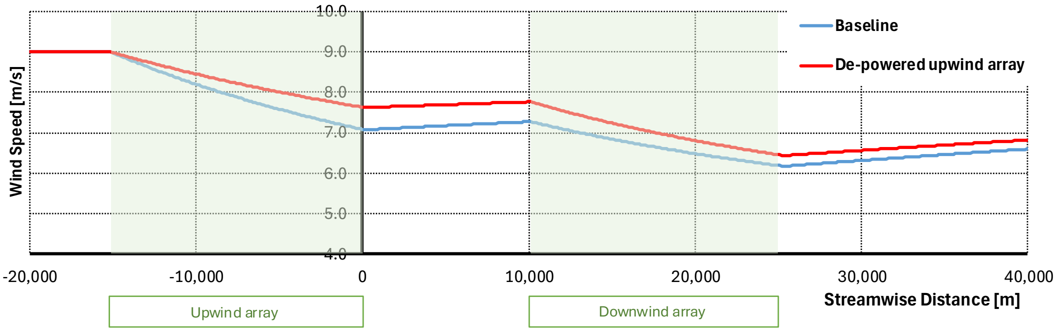

Figure 3: Wind Speed Through Wind Farm – Longitudinal

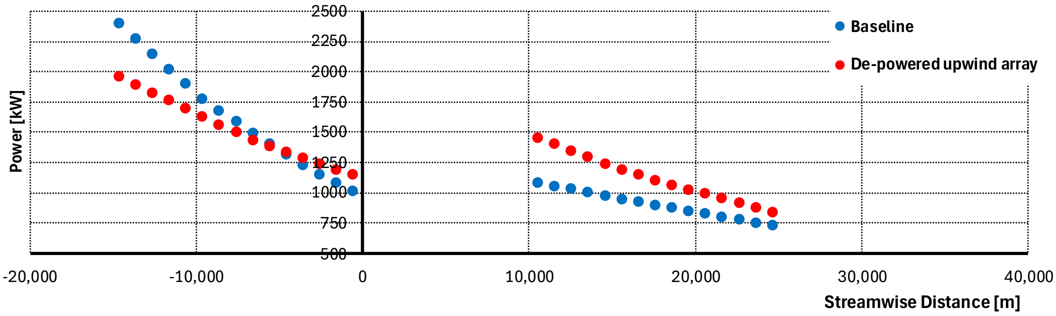

Figure 4: Wind Turbine Powers Through Wind Farm - Longitudinal

Conclusion

The impact of a cooperative control strategy on combined energy yield is often small, i.e. less than 0.25%, but the impact on the yield from the individual arrays is significant. This raises the prospect of using cooperative control to mitigate yield imbalance between arrays in so called 'wind-theft' scenarios, at least for stable atmospheric conditions. Using this model, favourable conditions for this objective appear far broader than favourable conditions for combined energy yield.

The model allows exploration of wind farm cooperative control scenarios very simply, as an additional option alongside comprehensive versions of the Smith model (see e.g. [3]) and/or higher-fidelity modelling.

References

[1] 'A model for long range wind farm wakes, sensitive to stability', Technical Note, 4 August 2026, NewSky Consulting.
[2] Smith, R.B. Gravity wave effects on wind farm efficiency. *Wind Energ.*, 13: 449-458, 2009.
[3] Smith, R. B. and Gribben, B. J.: Coriolis recovery of wind farm wakes, *Wind Energ. Sci.*, 11: 233–249, 2026.