

Using rotor inertia as stored energy in below rated wind farms to provide primary frequency response

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Abstract. The objective of this work is to present a method for providing ancillary services to the grid with minimal reduction in power output from the turbines in a wind farm by utilising the stored energy in the turbine rotors. By first demonstrating an approach of extracting energy from a single turbine's rotor, it can be shown that this could lead to increased energy yields while still being able to provide primary response provision compared to curtailing each turbine by 10%. Following this, when this approach is tested at the wind farm level there is considerable evidence that considering the energy stored in the turbine rotors across a wind farm can lead to increases in energy capture while not significantly increasing damage equivalent loads for either towers or blades.

1. Introduction

As wind power increases its share of grid penetration in power grids around the world, there is an increased requirement for wind power to not just generate as the wind speed dictates, but also to provide additional services such as frequency response. While primary and secondary frequency response are not currently mandatory for wind farms in the UK, wind farm operators can bid for provision of firm frequency response, which requires them to provide both primary and secondary responses. This may change in the future as the number of synchronous generators is reduced as the grid is decarbonised. The aim of this paper is to investigate a number of options for control strategies to provide primary response using the rotational stored energy in the rotors of a wind farm for solely primary response provision.

The requirement for primary response in Great Britain is to increase power output from a plant for 30 seconds to increase the grid frequency. The grid code states that at least a "frequency response of 10% of Registered Capacity achievable" [3] [4]. A reserve to enable this increase is normally held by derating the wind turbines, but the machines have some stored energy in the kinetic inertia of their rotors which is not normally considered.

Strathfarm, the University of Strathclyde's in-house wind farm modeling software, is used to simulate the wind farm and assess the performance of various farm level control strategies. The main advantage of Strathfarm is that it can be run on a standard desktop PC, simulating up to 100 wind turbines in real time. The control strategies are implemented in Strathfarm by means of a farm level controller the architecture of which allows each turbine to have a high level of operational autonomy.



This autonomy is provided by the addition of a Power Adjusting Controller (PAC) [8] to each wind turbine controller. The PAC acts as an augmentation to the control structure which allows a turbine's generated power to be adjusted continuously through a combination of changes to both the torque and pitch demand, without compromising the wind turbine's full envelope controller. The feedback action of the turbine's full envelope controller is unaffected by the presence of the PAC. The PAC jackets the full envelope controller as can be seen in Figure 1. In addition, the PAC provides operational information to the wind farm controller (WFC), generally in the form of binary flags, e.g. providing information regarding the displacement of the turbine from its normal operational strategy, but sometimes in the form of a numeric value such as an estimate of wind speed.

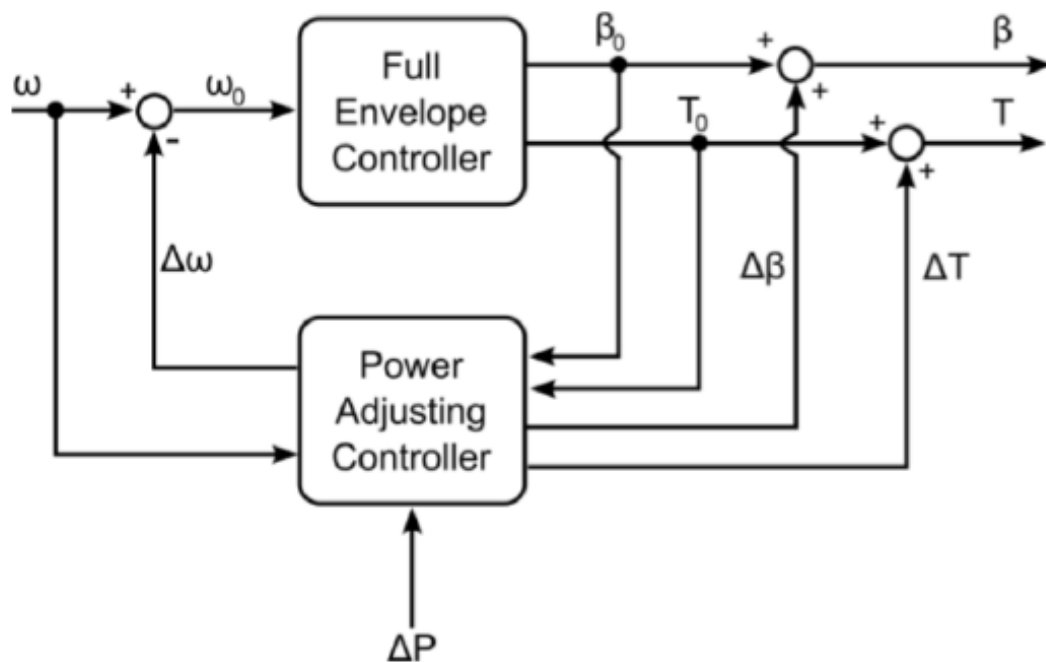


Figure 1: The general form of the Power Adjusting Controller (PAC) [8]

The purpose of this work is to explore the provision of primary ancillary services to the grid. The first requirement is to minimise the reduction in power output from the turbines in a wind farm by utilising the stored energy in the turbine rotors. By beginning with a turbine level proof of concept and explanation of the control strategy for extracting energy from the turbine's rotor, a cost analysis demonstrates that this approach for holding spinning reserve is worth pursuing further. Subsequently, a farm level strategy can be compared to two turbine level approaches, comparing damage equivalent loads (DELs) of both turbine towers and blades and energy capture over a range of mean wind speeds, wind directions and turbulence intensities. Previous research has been done before in this area, particularly at the wind turbine level [2] [8] and for providing droop control [9], but the work presented here is focused more in the impact on DELs than the actual delivering of primary response.

2. Methodology

2.1. Wind Turbine level Approach

The first step in the development of this approach is to explore the limits of how much energy can be extracted from a turbine's rotor in the 30 second period when primary response is provided. The

amount of stored energy in the rotor is given by:

$$E = \frac{1}{2}J(\omega_0^2 - \omega^2) \tag{1}$$

Where:

- E is the energy stored in the rotor,
- J is the inertia of the rotor and drivetrain,
- ω_0 is the initial rotational speed of the generator.
- ω is the new rotational speed of the generator.

Equation 1 shows that the amount of energy which can be extracted from a turbine’s rotor is not strictly governed by the wind speed, but instead by the difference in the square of the rotor speeds.

The PAC ensures safe operation of the turbine either by setting limits to any requested change to generated power from the farm level controller or by setting mandatory limits on the operating state of the turbine. The former limits are referred to as soft limits, as the turbine state can still cross them. The latter are referred to as hard limits, as the PAC acts to prevent the turbine state from crossing them. Information regarding which soft and hard limits apply at any given time is communicated to the farm level controller by binary flags. Examples of soft limits are traffic light boundaries, the green, amber and red boundaries in Figure 2, and an example of a hard limit is the black boundary, depicted on Figure 2. Within the green boundary, the turbine operating state is furthest from the unsafe region and the limits on requested changes to generated power are most relaxed.

By using steady state wind fields in the turbine model, the amount of energy which can be extracted for 30 seconds while remaining inside the PAC’s green flag boundary has been found for wind speeds between 7 and 11 m/s. Following this, energy extraction from the rotor, the turbine enters a recovery mode which returns the turbine to its uncurtailed operational strategy.

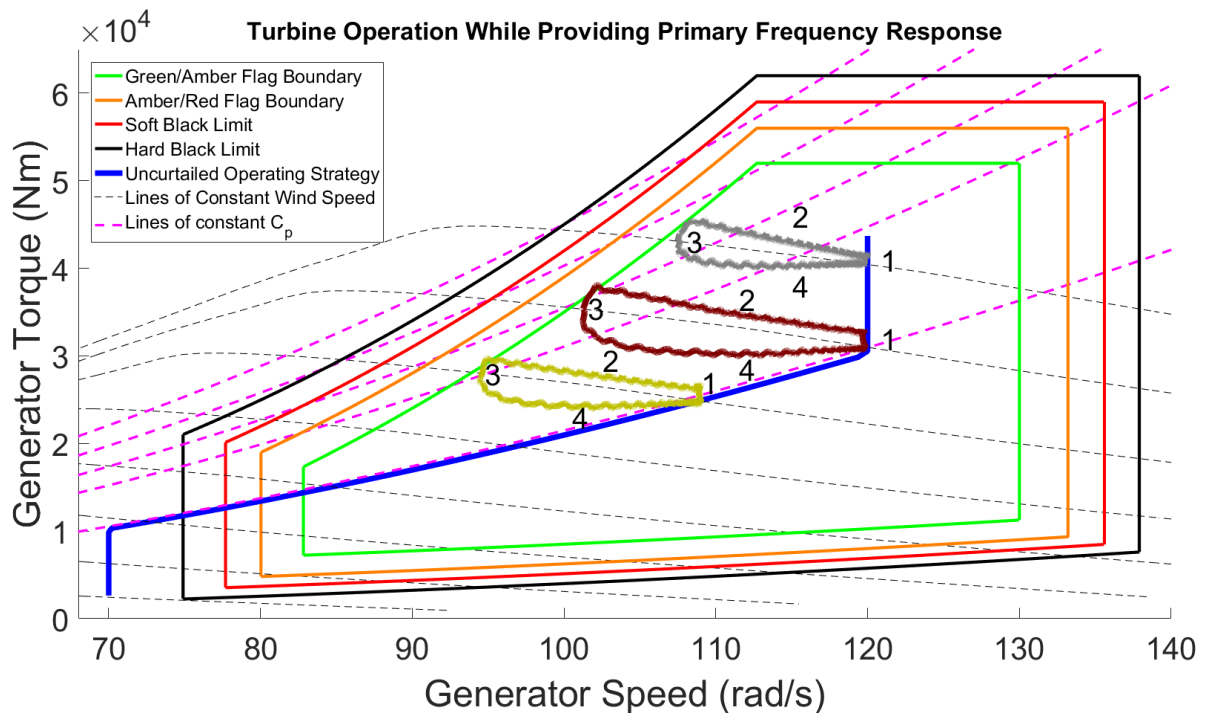


Figure 2: A torque-speed diagram of a wind turbine extracting energy from its rotor for 30 seconds at 9, 10 and 11 m/s.

Figure 2 shows the operation of the turbine in the torque-speed plane of the turbine as energy is extracted from the rotor with the PAC's traffic light flag boundaries, the turbine's lines of constant wind speed between 4m/s and 11m/s and the turbine's lines of constant C_p from 100% to 92% at 2% intervals all shown. The extraction process has been numbered for clarity, with 1 showing the initial position, 2 showing the 30 second extraction period, 3 showing the switching from extraction to recovery and 4 showing the recovery of the turbine to its normal operational strategy. The magenta dashed lines show efficiency curves at 2% intervals beginning at 100% of the maximum C_p .

For the three simulations shown the increase in power output for the 30 second period is 180kW, 240 kW and 100kW for the constant wind speeds of 9 m/s, 10m/s and 11 m/s respectively. When this approach is used the wind turbines operate in a less aerodynamically efficient location of the torque-speed plane; that is, there is a reduction in C_p and so energy capture. This reduction in C_p is particularly noticeable at 11 m/s, as is shown in Figure 3 and 4. Even though the 11 m/s plot indicates a smaller reduction in tip speed ratio (λ) it has the largest relative reduction in its C_p value.

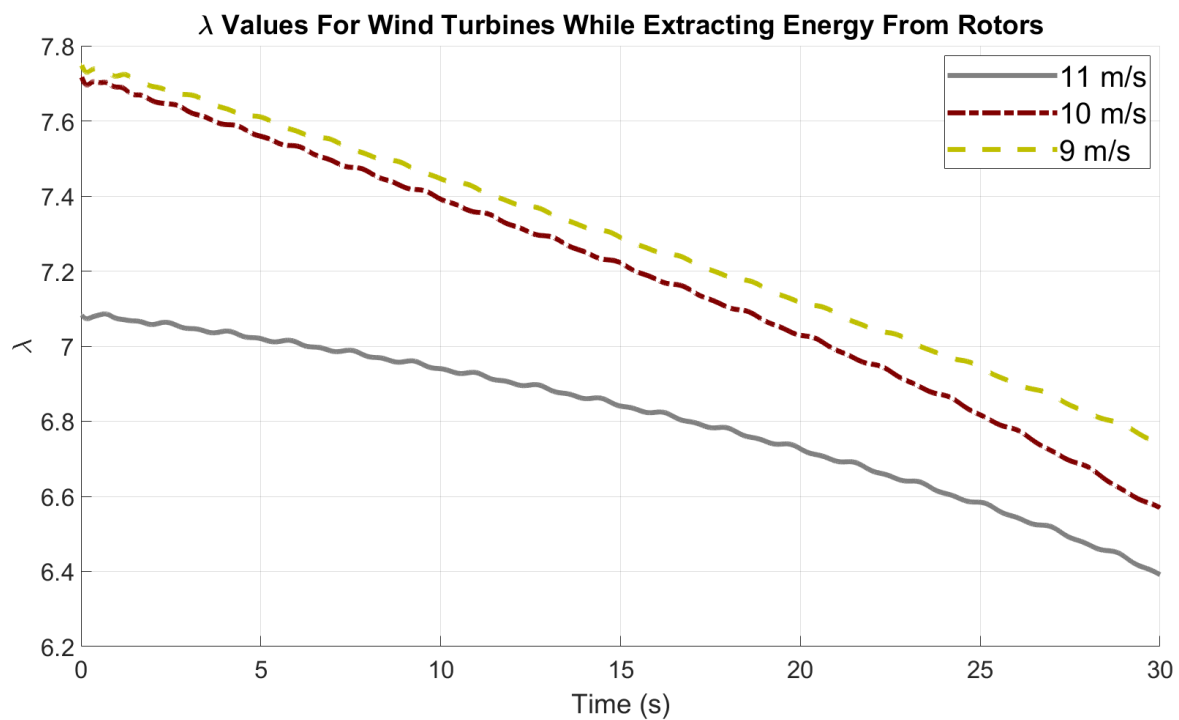


Figure 3: The tip speed ratio of a wind turbine which is extracting energy from its rotor for 30 seconds at 9, 10 and 11 m/s.

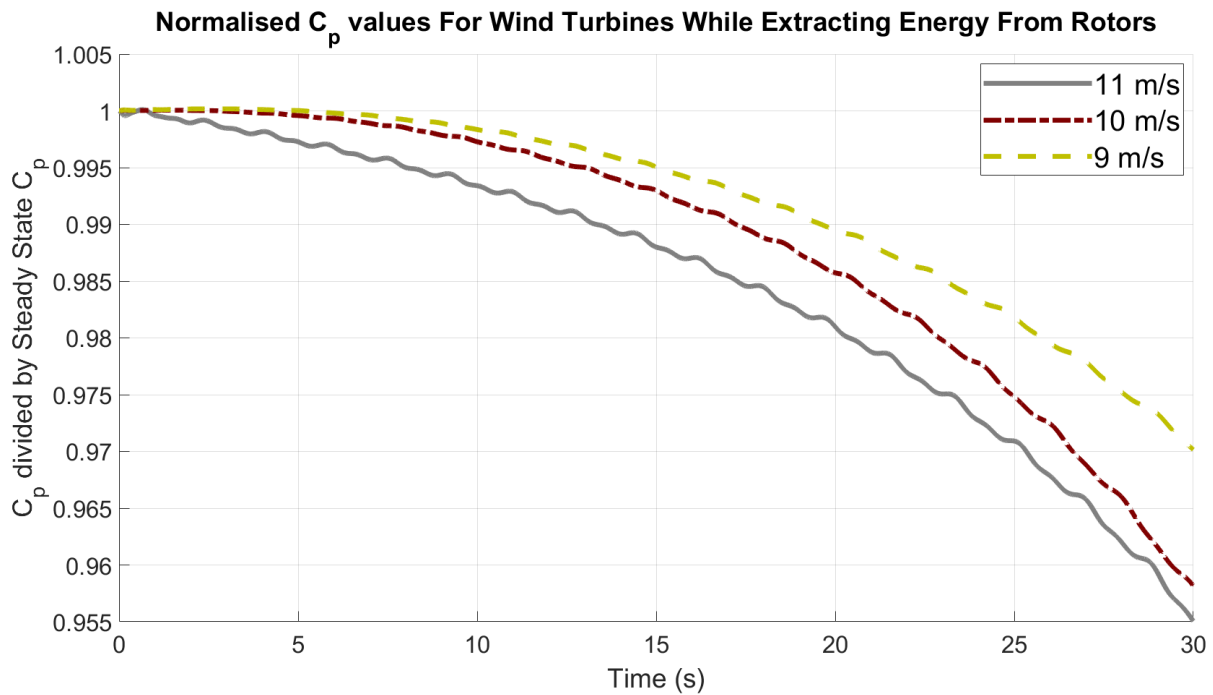


Figure 4: The ratio of the turbine level C_P divided by the steady state C_p as energy is extracted from the turbine’s rotor.

Figure 4 shows the normalised C_p of the turbine as energy is extracted from its rotor. Due to the flatness of the peak of the $C_p - \lambda$ curve near its peak there is very little change in the C_p values initially at 9 or 10 m/s. This flatness can be seen in the efficiency curves shown in Figure (2) as the gap between the 100% and 98% curves is significantly larger than that of the other curves.

Wind Speed (m/s)	Rotor Inertia Reserve [kW]	Percent of Uncurtailed Power	Additional Curtailment Allocation [kW]	Total requested Reserve Power for Farm Level Approach [kW]
7	25	2.1%	0	25
7.5	75	5%	0	75
8	100	5.6%	0	100
8.5	140	6.5%	0	140
9	180	7.2%	0	180
9.5	220	7.3%	0	220
10	240	6.9%	120	360
10.5	170	3.8%	280	450
11	100	2.2%	370	470

Table 1: Maximum sustainable power extraction from the rotor for 30 seconds and allocated turbine level curtailment by wind speed.

Table 1 shows the increase in turbine power output which can be sustained for 30 seconds by wind speed while staying within safe operational limits. When a farm level approach is considered an additional curtailment through pitching is added to the curtailment total as a way to avoid higher tower loads near to the rated wind speed and to allocate the power reduction to turbines which are

more likely to be able to provide the curtailment request without crossing a flag boundary in the PAC.

By considering the costings of this strategy on an individual turbine level it can be seen that there is a possible case for this new approach. If the approach shown in Table 1 is compared to curtailing a turbine by 10% of its power output on an annualised basis using a Weibull distributed wind speed, with a mean wind speed of 10 m/s, it will have an energy capture 402438 kWh higher than curtailing a turbine by 10% if this strategy were to be used at all times of operation. If a constant energy price of £50 per MWh is assumed this will mean that a turbine using this proposed approach will increase revenue by £20122 each year.

2.2. Farm Level implementation

Three strategies for holding a level of reserve power are tested here, two turbine level approaches and one farm level approach.

The reduction in power allocated to each turbine for the three strategies are given by:

$$\Delta p_i = -0.1 \times P_i \quad (2)$$

for always curtailing by 10%,

$$\Delta p_i = -0.1 \times P_i + R_{WT}(v)_i \quad (3)$$

for implementing the use of stored energy at the turbine level and

$$\Delta p_i = R_{WF}(v)_i + \frac{\sum_{i=1}^n (-0.1 \times P_i + R_{WF}(v)_i)}{n} \quad (4)$$

for implementing the use of stored energy at the farm level, where:

- Δp_i - is the requested reduction of power for the i th turbine,
- P_i - is the uncurtailed power of the i th turbine,
- $R_{WT}(v)_i$ - is the turbine level curtailment from Table 1 of the i th turbine as a function of the estimated wind speed v ,
- $R_{WF}(v)_i$ - is the total curtailment from both the energy in the rotors and additional curtailment from pitching shown in column 2 and 4 respectively in Table 1 of the i th turbine as a function of the estimated wind speed v ,
- n - is the total number of turbines in the farm.

To investigate the effectiveness of these approaches 240 wind fields have been created which each last 900 seconds, the strategies were implemented from 150 seconds to allow for the dissipation of transients in the turbine models. The DELs and energy capture were calculated from 350 seconds to allow for the propagation of wakes through the wind farm. The DELs were calculated using the approach described by [5].

For the simulations mean wind speeds of 8.5, 9, 9.5, 10 and 10.5 m/s were used, wind directions of 0, 15, 30 and 45 degrees and turbulence intensities (TI) of 5% and 10%. In addition to these each combination of parameters were used to generate wind fields six times.

The wind farm layout used can be seen in Figure 5, the turbines are spaced 1000 meters (8 diameters apart) in a 4 by 4 square of 16 turbines. The wind angles of 0, 15, 30 and 45 degrees were chosen as the square layout means that one eighth of a rotation is sufficient due to a square having eight symmetries.

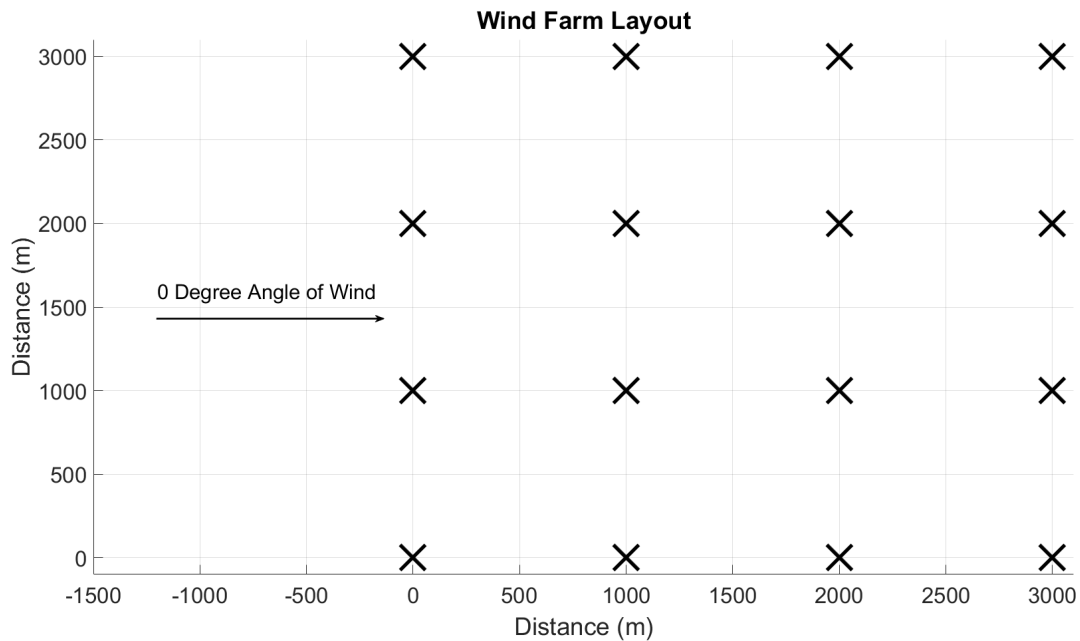


Figure 5: The layout of the wind farm used for the simulations presented here.

3. Results

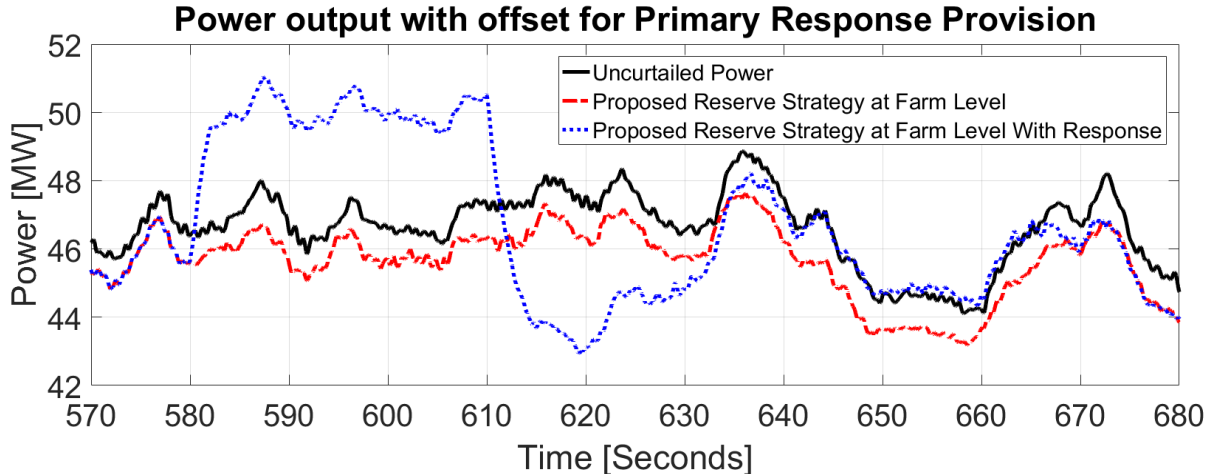


Figure 6: An example of the Reserve Curtailment strategy in a 9.5 m/s windfield with 10% turbulence intensity in a 16 turbine wind farm.

Figure 6 shows the farm level power with and without activation of the primary frequency response. The response rate is faster than is required by the grid code [4] as wind turbines can change their power outputs very quickly. This fast response has been demonstrated as a possible method of providing synthetic inertia [6]. Figure 6 shows a large drop in power when the turbines enter into the PAC's recovery process to bring them back to their normal operational strategy. This large dip can be mitigated by staggering when the turbines enter into recovery [8]. Further research on implementing this is planned as part of the development of a power system model in Strathfarm which will be able to use information on a grid's frequency to decide when to begin the recovery process for each turbine to reduce the impact on grid stability.

For the results where the reserve power is held there is a significant difference between when there is a 5% TI and when there is a 10% TI so each will be discussed in turn. There is no statistically significant difference in the totals for energy capture, tower or blade DELs for when the angle of the wind field to the farm is varied. 5% and 10% TI are around the level of turbulence which would be expected in typical operation of an offshore wind farm as [1] shows with data from the Greater Gabbard wind farm.

The results presented here show the average changes of all 24 simulations performed at each wind speed-turbulence combination. While some of the changes are significant the number of simulations needed to prove a statistical improvement in Strathfarm is currently being investigated. As a result of this, definitive conclusions cannot currently be made for which strategy performs the best.

In the results presented here: 10% Curtailment refers to the strategy shown in Equation 2, Turbine Level Curtailment refers to the strategy shown in Equation 3 and Reserve Curtailment refers to the strategy shown in Equation 4.

3.1. 5% Turbulence Intensity

Tower DELs					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	0.87%	2.45%	6.13%	4.64%	0.74%
Turbine Level Curtailment	-2.16%	-1.31%	2.82%	5.26%	4.82%
10% Curtailment	8.12 %	7.96%	8.43%	8.27%	8.17%

Table 2: The average reduction in tower DELs of each of the three strategies by wind speed when compared to not curtailing the turbines at 5% TI.

Table 2 shows that there are mixed results for the Reserve Curtailment and Turbine Level Curtailment approaches, peaking at 10 m/s and 9.5 m/s respectively but also with some results showing that the approaches are detrimental to tower DEL reductions. In contrast to this the 10% Curtailment approach shows a consistent reduction in tower DELs of approximately 8%.

Blade DELs					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	2.95%	5.35%	13.48%	16.51%	13.91%
Turbine Level Curtailment	-1.22%	-0.26%	5.53%	10.48%	12.37%
10% Curtailment	11.97%	11.61%	11.76%	10.86%	9.26%

Table 3: The average reduction in blade DELs of each of the three strategies by wind speed when compared to not curtailing the turbines at 5% TI.

Table 3 shows the reduction in blade DELs compared with not curtailing the wind farm. The Reserve Curtailment and the Turbine Level Curtailment approaches both show very small improvements over not curtailing at lower wind speed but have very large reductions at 10 and 10.5 m/s. The 10% Curtailment approach shows improvements which vary much less with wind speed.

Energy Capture					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	1.48%	1.20%	1.37%	2.29%	3.61%
Turbine Level Curtailment	1.46%	1.19%	1.38%	2.29%	3.62%
10% Curtailment	7.26%	7.24%	7.34 %	7.45%	7.59%

Table 4: The average reduction in energy capture of each of the three strategies by wind speed when compared to not curtailing the turbines.

Table 4 shows that the 10% Curtailment approach has a reduction in energy capture of between 7.24 and 7.59%, rather than the 10% that would be intuitively predicted. This higher energy capture is due to the wake effects within the farm. As the wind turbines are curtailed the strength of the wakes which propagate through the farm is reduced. This reduction leads to a small change in wind speed but due to the cubic relationship between wind speed and energy in the wind leads to a much larger increase in power generation. Approaches which use the effect are common in the literature but are normally researched in quasi-steady state models rather than the dynamic model used here [6] [7].

3.2. 10% Turbulence Intensity

The simulations run at 10% turbulence intensity show larger improvements in tower and blade DELs. This is to be expected as when the turbulence intensity increases the DELs will become larger as they are caused by variation in bending moments so more variation in operation will make them increase.

Tower DELs					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	1.35%	7.33%	10.00%	11.20%	13.49%
Turbine Level Curtailment	-3.63%	1.46%	4.61%	8.23%	10.31%
10% Curtailment	5.27%	9.05%	9.71%	10.55%	12.50%

Table 5: The average reduction in tower DELs of each of the three strategies by wind speed when compared to not curtailing the turbines at 10% TI.

Table 5 shows that the Reserve Curtailment strategy shows a much greater reduction than not only the Individual Turbine approach but also than the 10% Curtailment approach at wind speeds above 9 m/s.

Blade DELs					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	7.03%	12.13%	14.83%	15.11%	14.08%
Turbine Level Curtailment	0.50%	4.60%	7.63%	10.50%	10.76%
10% Curtailment	10.93%	11.40%	11.35%	10.58%	9.86%

Table 6: The average reduction in blade DELs of each of the three strategies by wind speed when compared to not curtailing the turbines at 10% TI.

Table 6 shows that the improvements for the blade DELs show a similar pattern to the tower DELs with the Reserve Curtailment approach having larger reductions in DELs over both of the other strategies even though it has a higher energy capture.

Energy Capture					
Approach	8.5 m/s	9 m/s	9.5 m/s	10 m/s	10.5 m/s
Reserve Curtailment	1.54%	1.76%	2.17 %	3.27%	4.21%
Turbine Level Curtailment	1.46%	1.72%	2.13%	3.28%	4.27%
10% Curtailment	6.79%	7.33%	7.45%	7.69%	7.94%

Table 7: The average reduction in energy capture of each of the three strategies by wind speed when compared to not curtailing the turbines at 10% TI.

Table 7 shows that the Reserve Curtailment and the Individual Turbine approach have higher energy capture than the 10% Curtailment approach with the differences reducing as the wind speed increases.

4. Conclusions

By considering the stored rotational energy in each wind turbine's rotor and by curtailing turbines where this cannot be efficiently utilised, a more sophisticated method of holding reserve power than simply reducing turbine power by 10% is shown. The Reserve Curtailment control strategy has a higher energy capture than curtailing each turbine by 10% while not resulting in significantly higher DELs to the towers or the blades in the wind farm.

While the lower tower DELs for the 10% Curtailment strategy is possibly offset by the higher energy capture and lower blade DELs of the Reserve Curtailment approach it is most likely not enough to overcome the fact that the Reserve Curtailment approach not only cannot provide a complete secondary response but also requires a reduction in power output to return each of the wind turbines to their normal operational generator speed. Currently the UK Grid Code requires both primary and secondary response, so if this approach were to be implemented it may be worth considering in the future if, for example a wind farm were to provide a primary and inertial response and could create an arrangement with a slower acting generator to provide the secondary response a joint bid could be submitted in the market.

Another possible approach would be to extract less energy from the wind turbines' rotors, as Figure 4 shows that 9 and 10 m/s the change in C_p is initially very small so by only extracting a small amount of energy there will be a smaller reduction in C_p so the turbine can be returned to its normal operational strategy over a longer time frame as it will not have to overcome as large of a deficit in efficiency.

Future work in this area would be to simulate the proposed strategies over more more wind speeds, particularly above rated so that the changes in DELs can be validated. Additional further research will be to test these approaches in Strathfarm using a power system model, which is currently under development. Using the grid frequency as an input to the WFC would allow it to stagger the start of the recovery periods across the farm, mitigating the dip in power output.

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