15th EAWE PhD Seminar on Wind Energy
29–31 October 2019
Centrale Nantes, France

Optimising Wind Farm Power Output to Deliver the Maximum Requested Power Under Future Grid Constraints

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Abstract

This paper investigates the maximum output and minimum variation in power that can be reliably provided by wind farms performing voluntary curtailment. Two wind farm sizes, three mean wind speeds and two controller strategies are considered. Simulations using the StrathFarm wind farm modelling software show that higher mean wind speeds can produce greater mean power output and reduced 95% power confidence band widths. Proportional-integral (PI) control offers higher mean power output and tighter power control than a simple curtailment (SC) strategy under all conditions. At near-rated wind speeds, the choice of control strategy is shown to have a very significant effect on tower base damage-equivalent loading (DELs); PI control can reduce tower base DELs by up to 36%, whilst SC control can *increase* these loads by up to 20%.

Keywords: Wind farm control, curtailment, tower loading

1 Introduction

Traditionally, each wind turbine in a farm has operated solely to maximise its own power output (known as a 'greedy' control strategy). However, this approach is unlikely to be optimal for overall wind farm performance [1],[2]. In addition, as penetration of wind energy into the electricity grid increases, periods of enforced wind farm curtailment are becoming more frequent as the network operator seeks to maintain the balance of the network [3]. Indeed, over the past year there have been multiple days on which the wholesale electricity prices have become *negative* for significant periods of time as high production from wind leads to significant excess of supply [4]. In the future, new market structures will likely mean that wind farms will bid in short time-scale markets, offering a precise power output which must be met within a given margin. The wind farm operator will wish to produce the maximum power possible to increase profitability, but must not exceed the agreed power bid. This requires control of the wind farm's power output to a fairly thin band, regardless of the variation in the wind. For this purpose, turbines may sometimes be required to over-produce for limited periods, extracting energy temporarily from the rotor rotation. At other times they will be required to curtail output so as not to exceed the agreed bid. Individual curtailment of turbines will generally lead to under-production and doesn't allow for customised alleviation of the structural loads on specific turbines within the farm [5]. However, if a global control strategy is applied across the whole wind farm, both the overall power output and the individual turbine loads may be controlled much more tightly. The goal of this work is therefore to quantify the maximum power output and minimum variation in power that can be reliably delivered under a range of wind farm conditions. Simulations are performed to investigate the effect of mean wind speed, wind farm size and wind farm control strategy on curtailment; the effect of this curtailment on tower base damage equivalent loads (DELs) is also quantified.

2 StrathFarm Modelling Software

All simulations for this work have been performed using the 'StrathFarm' wind farm modelling software developed at the University of Strathclyde [6]. StrathFarm is an aero-elastic wind farm model based in MATLAB/Simulink and incorporating temporally and spatially correlated turbulence wind models and wake interaction modelling (See Fig. 1). Farm layout, choice of turbines and controllers, mean wind speed, wind direction and turbulence intensity are flexible for wind farms of up to 20 turbines. A generic wind farm controller has been developed for StrathFarm with the hierarchical structure shown in Fig. 2.

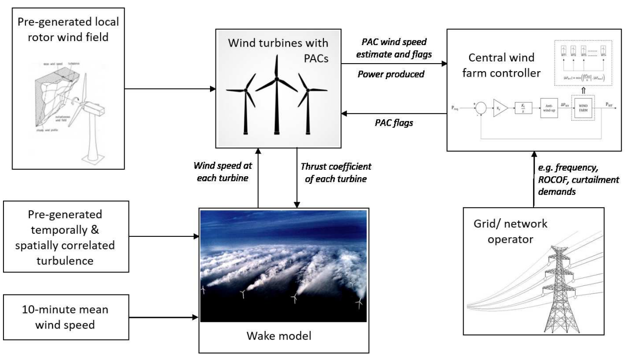

Figure 1: Overview of StrathFarm model

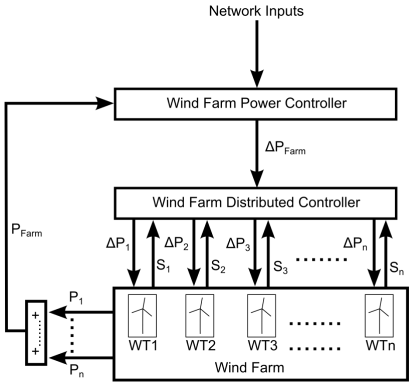

Figure 2: Hierarchical structure of the wind farm controller implemented in StrathFarm

Each turbine in the StrathFarm model is equipped with a Power Adjusting Controller (PAC) [7]. The PAC allows dynamic adjustments to the power set-point of each turbine within certain operating limits (determined by the controller design and individual turbine status) without interfering with the full envelope controller. Outputs from the PAC as status flags (see [7]) and wind speed estimates are used as inputs to the overall wind farm controller. For this study, all wind turbines were modelled using the 'StrathTurb' model, which is based on the 5 MW Supergen variable-speed, pitch-regulated exemplar turbine. Two wind farm layouts were modelled for this research; a 4-row, 10-turbine farm (referred to as 10WT) with the offset grid layout shown in Fig. 3 and a 10-row, 20-turbine farm (referred to as 20WT) with the offset grid layout shown in Fig. 4.

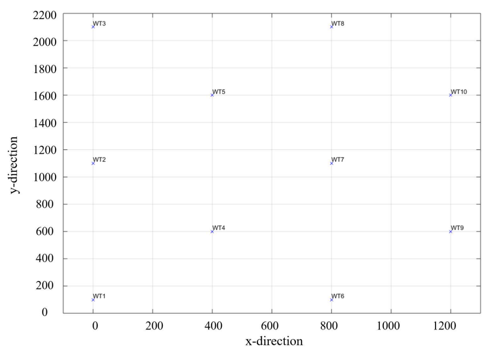

Figure 3: Offset grid layout for 10-turbine wind farm

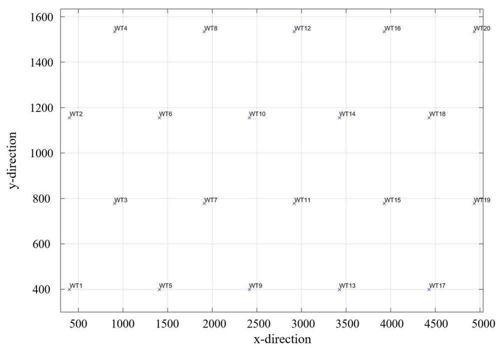

Figure 4: Offset grid layout for 20-turbine wind farm

3 Wind Farm Controllers

3.1 Simple Curtailment

The simple curtailment (SC) controller strategy implemented in this paper limits the power output of each turbine to $\frac{P_{req}}{n}$ where P_{req} is the requested (curtailed) wind farm power and n is the total number of wind turbines in the farm (i.e. open-loop control). No account is taken of the PAC flag status of individual turbines. This is the easiest curtailment strategy to implement and is thus the current default approach for a wind farm forced to curtail to comply with network management. A block diagram of the SC controller is shown in Fig. 5.

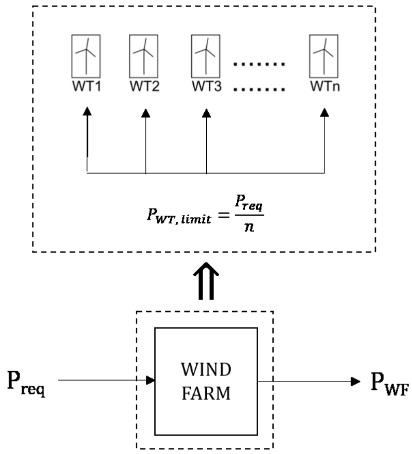

Figure 5: Block diagram of the simple curtailment controller strategy

3.2 PI Control

The second controller modelled in this paper employs proportional-integral (PI) control with anti-wind-up, implemented in discrete time. As before, the input to the controller is P_{req}, the requested (curtailed) wind farm power. The output from the PI controller is a demanded change in power for the wind farm (ΔP_{WF}) which is split equally between all turbines with 'Green' and 'Amber' PAC flags (see appendix [7]), unless this value exceeds the maximum power change that can be performed by the respective turbine. A block diagram of the controller is shown in Fig. 6. Values for K_p and K_i were 0.8 and 0.05 respectively for all simulations. The anti-wind-up process is required to prevent values of ΔP_{WF} being requested that cannot be achieved. In this instance, we set $\Delta P_{WF} = \Delta P_{WFlimit}$ and calculate the input, U, that would have produced this output; this is used as an input to the controller at the current time step.

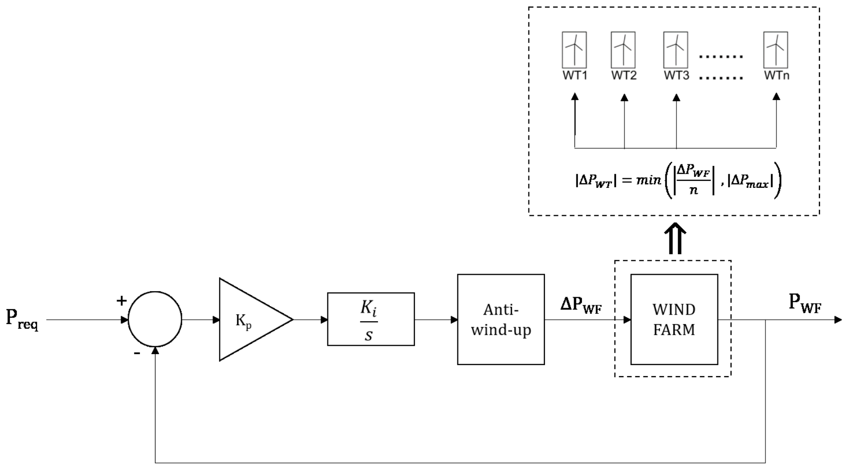

Figure 6: Block diagram of the PI controller with anti-wind-up

4 Results

The goal of this research was to quantify the maximum output (and minimum variation in) power that can be achieved when curtailing wind farm power under a variety of wind and farm conditions. Simulations were run on the 10WT and 20WT farms under 2 different controller strategies and at 3 values of 10-minute mean wind speed. The effect of wind speed on curtailment is presented in section 4.1; the effect of wind farm size is presented in section 4.2. The effect of this curtailment on in-plane damage equivalent loads (DELs) at the tower base is presented in section 4.3. The implications of these results for power control and tower loading is discussed in section 5

4.1 Effect of Wind Speed on Curtailment

Simulations were performed on the 10WT farm at 10 m/s, 12 m/s and 14 m/s values of 10-minute mean wind speed. Turbulence intensity was constant at 5% for all simulations. Fig. 7 to Fig. 9 show the mean power time-series and 95% confidence bands, averaged over 10 simulations, for each control strategy and at each wind speed. All simulations were run for 900 seconds, with the SC or PI controller switching on at 150 seconds if present. Mean powers and power bands are calculated for the last 10 minutes of the simulation (300 - 900 s) to ensure that the wind field and turbine wakes have propagated through the farm and that transients created by controller switch-on have abated.

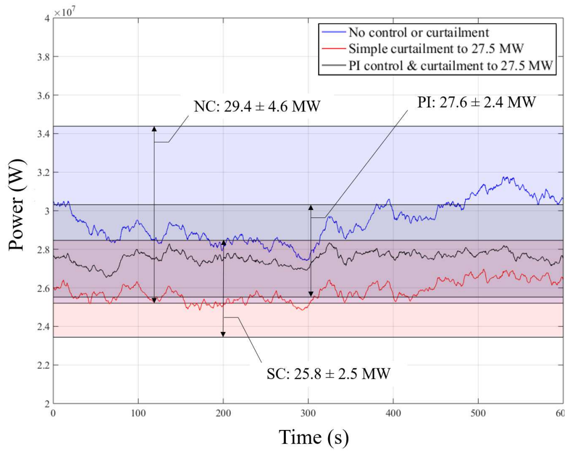

Figure 7: Mean power time-series and 95% bands for all controller strategies on a 10-turbine wind farm at 10 m/s 10-minute mean wind speed

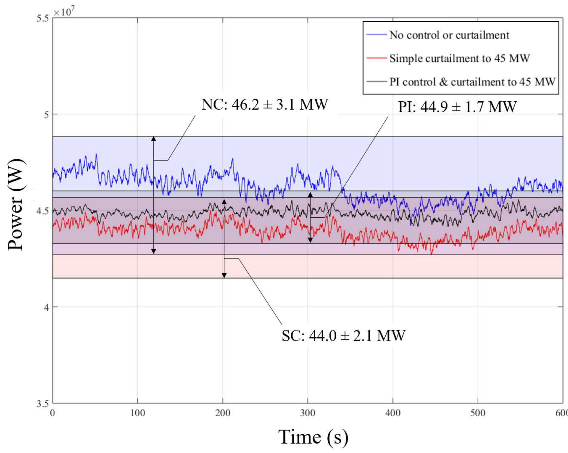

Figure 8: Mean power time-series and 95% bands for all controller strategies on a 10-turbine wind farm at 12 m/s 10-minute mean wind speed

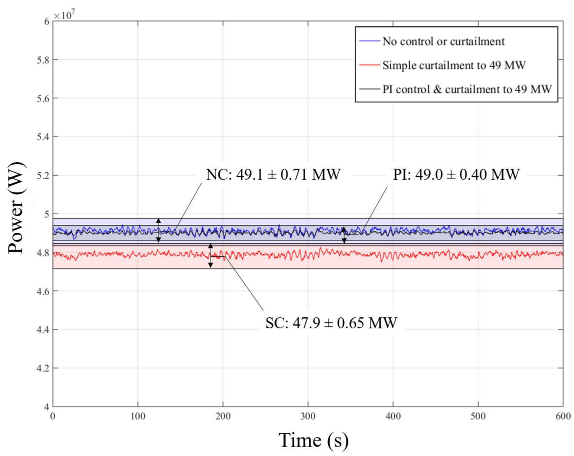

Figure 9: Mean power time-series and 95% bands for all controller strategies on a 10-turbine wind farm at 14 m/s 10-minute mean wind speed

4.2 Effect of Wind Farm Size on Curtailment

The above analysis was repeated on the 20WT farm shown in Fig. 4. Fig. 10 to Fig. 12 compare the mean power time-series and 95% confidence bands, averaged over 10 simulations, for each size of wind farm under the PI control strategy. Tables 1 and 2 summarise these results for both wind farm sizes.

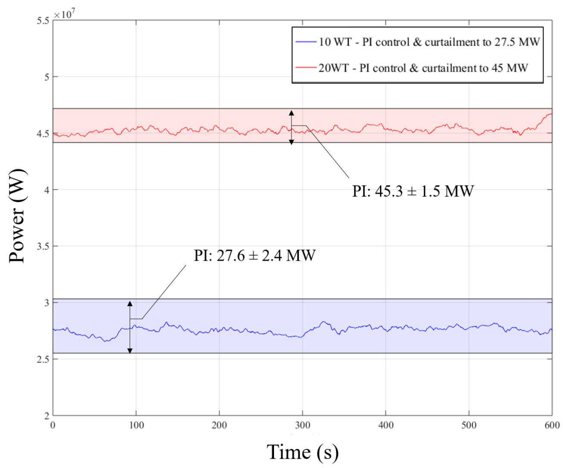

Figure 10: Mean power time-series and 95% bands for 10- and 20-turbine wind farms at 10 m/s 10-minute mean wind speed

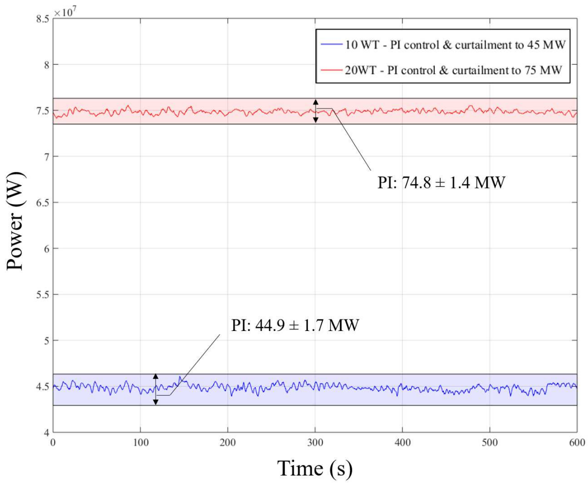

Figure 11: Mean power time-series and 95% bands for 10- and 20-turbine wind farms at 12 m/s 10-minute mean wind speed

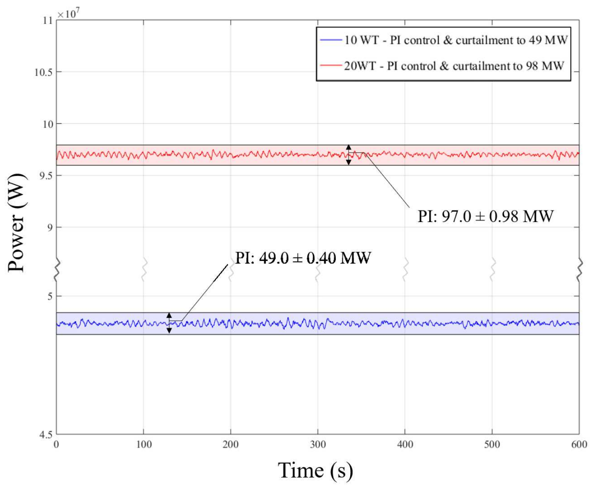

Figure 12: Mean power time-series and 95% bands for 10- and 20-turbine wind farms at 14 m/s 10-minute mean wind speed (truncated y-axis scale)

Table 1: Summary of power output and controllability for the 10WT wind farm

10WT	No Control			Simple Curtailment			PI Control + Curtailment		
	10 m/s	12 m/s	14 m/s	10 m/s	12 m/s	14 m/s	10 m/s	12 m/s	14 m/s
Requested power (MW)	-	-	-	27.5	45	49	27.5	45	49
Mean power (MW)	29.44	46.21	49.1	25.83	43.95	47.88	27.56	44.85	49.00
Power band (MW)	± 4.59	± 3.07	± 0.714	± 2.51	± 2.10	± 0.652	± 2.40	± 1.703	± 0.395
Lost energy (MWh/h)	-	-	-	3.61	2.27	1.22	1.88	1.36	0.102

Table 2: Summary of power output and controllability for the 20WT wind farm

20WT	No Control			Simple Curtailment			PI Control + Curtailment		
	10 m/s	12 m/s	14 m/s	10 m/s	12 m/s	14 m/s	10 m/s	12 m/s	14 m/s
Requested power (MW)	-	-	-	45	75	98	45	75	98
Mean power (MW)	49.38	82.07	97.91	43.43	73.03	93.82	45.28	74.84	97.00
Power band (MW)	± 4.924	± 7.336	± 1.479	± 1.701	± 2.567	± 1.525	± 1.504	± 1.405	± 0.977
Lost energy (MWh/h)	-	-	-	3.61	2.27	1.22	1.88	1.36	0.102

4.3 Effect of Curtailment on Tower DELs

Controller strategies can significantly affect the bending moments at the tower base; this impacts the rate of tower fatigue and overall turbine lifetime. Tower damage equivalent loads (DELs) have been calculated for each turbine in the 10WT and 20WT farms under each control strategy and at each mean wind speed used in sections 4.1 and 4.2. Fig. 13 shows the tower DELs for the 10WT farm; Fig. 14 shows the mean tower DELs for the 20WT farm. Error bars represent ± one standard deviation.

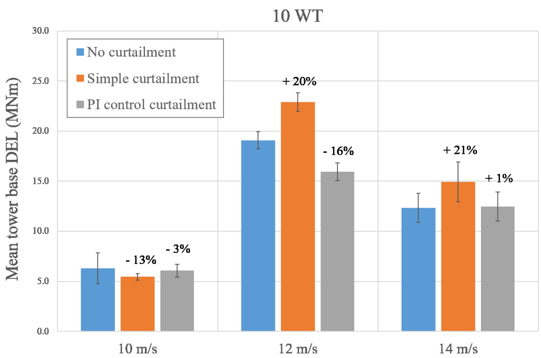

Figure 13: Mean in-plane DELs at the tower base under each control strategy for the 10-turbine farm at 10 m/s, 12/ms and 14 m/s

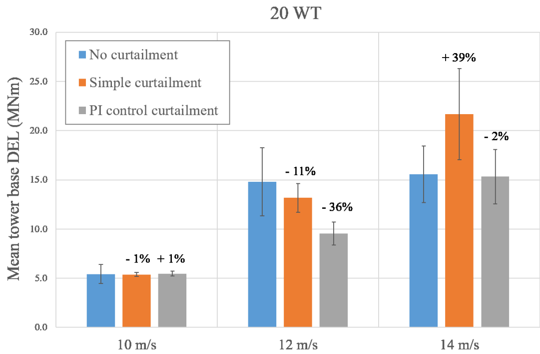

Figure 14: Mean in-plane DELs at the tower base under each control strategy for the 20-turbine farm at 10 m/s, 12/ms and 14 m/s

5 Discussion

5.1 Effect of Wind Speed on Curtailment

As would be intuitively expected, section 4.1 shows that the maximum (curtailed) power output that can be produced increases with mean wind speed, whilst variation (i.e. the width of the 95% power band) decreases. This trend with increasing wind speed holds for uncontrolled and SC and PI control strategies. With the same requested curtailment, the PI strategy produces 2-3% higher mean power output than the SC strategy and up to a 39% narrower power band on the 10WT farm. The effectiveness of the PI strategy is greatest at higher mean wind speeds. At all wind speeds, PI control produces 95%-confidence bands of around half the magnitude of those seen with no control. However, at below-rated wind speeds, this band is still relatively large (± 2.40 MW for the 10WT farm and ± 1.50 MW for the 20WT farm, both at 10 m/s). This bandwidth cannot be improved (with this controller) by lowering the curtailed power request because of the individual turbine limits on ΔP and $\frac{\Delta P}{dt}$, which are set by the PAC. Improvements on controller design would therefore be required in order to further tighten this power band in low wind-speed conditions. However, curtailment of wind power is only required when electricity supply exceeds demand; this is most likely to occur when the renewable sources are producing large power outputs, i.e. when mean wind speeds are high. As such, the performance of curtailment is most important during periods of high mean wind speed. These simulations have demonstrated that power can be very tightly controlled at above-rated (14 m/s) wind speeds and so it is likely that a similar form of PI control would be sufficient to meet future grid constraints whilst still maximising farm output and operator revenue.

5.2 Effect of Wind Farm Size on Curtailment

Both the 10WT and 20WT farms show increasing power output and decreasing width of the controlled power band with increasing mean wind speed. However, the curtailed power that can be reliably extracted from the 20WT farm is *lower* than could be extracted from 2 x 10WT farms in the 10 m/s and 12 m/s mean wind speed cases, i.e. the power per turbine is lower. This is unsurprising given that the 20WT farm contains more turbine rows; as such, wind conditions at the rear of the farm will be heavily contaminated by upstream wakes and it would be expected that power output from these turbines would be correspondingly diminished. At 14 m/s (above-rated), the 20WT *can* match the 10WT farm in terms of power output per turbine, but at the cost of a wider power band. Again, this wider band is likely due to the higher turbulence wind conditions seen by some turbines in the 20WT farm as they are impacted by wakes produced upstream. Additional simulations would be required with many more combinations of wind farm size and layout to satisfactorily separate the effects of wind farm size and layout on the ability of a wind farm operator to tightly control power output whilst maximising profits.

5.3 Effect of Curtailment on Tower DELs

Curtailing power is inherently unattractive for wind farm operators due to the revenue that is lost when under-producing. However, voluntary curtailment may seem more attractive if there are proven benefits for turbine loading, O&M demand and overall lifetime. Fig. 13 and Fig. 14 show the change in tower base DELs for both sizes of wind farm at all three wind speeds. At above-rated wind speeds (14 m/s), the SC control strategy *increases* tower base DELs for both sizes of wind farm tested; the PI controller has no significant effect on DELs. At below-rated wind speeds (10 m/s), the PI controller again has negligible effect on the tower base loads; the SC controller appears to offer some load reduction in the 10WT farm, but this is within one standard deviation of the uncontrolled loading and so is unlikely to be significant. Tower base loads are highest around rated wind speed and curtailment has the biggest effect on this loading around this operating point [8]. Wind turbines are also designed and sited such that the rated wind speed for the turbine is close to the peak of the wind speed probability distribution for that site; as such, turbines spend a large proportion of time operating in near-rated conditions. Controller switching, large changes in power output and higher turbulence are also features of near-rated operation. Optimising performance and minimising tower loads in near-rated conditions is therefore of vital importance and the choice of control strategy is likely to have a significant impact on turbine loading at these operating points. This hypothesis is very clearly supported by the results in section 4.3; at 12 m/s mean wind speed, the PI control strategy produces a 16% reduction in tower DELs for the 10WT farm and a 36% reduction in tower DELs for the 20WT farm. In contrast, the SC strategy significantly increases tower loads within the 10WT farm and produces only an 11% reduction within the 20WT farm.

5.4 Limitations

One of the greatest challenges surrounding the optimisation of wind farm control is the number of variables that can be adjusted. This work has considered only three mean wind speeds and one level of turbulence intensity; simulations over a much wider range of wind field conditions would be required to validate these results for the full range of real-world wind conditions that a farm would be likely to experience over its lifetime. The size and layout of a wind farm also has a significant impact on its controllability and the loading on individual turbines; the two sizes of farm modelled here do not fully explore this

6 Conclusions and Future Work

6.1 Conclusions

A high penetration of renewable energy in the future electricity grids, both in the UK and worldwide, will likely mean that wind farms (and indeed other renewable energy sources) will, at times, be required to curtail power output in order to balance the grid. Wind farm operators wish to produce the maximum possible power output in order to maximise revenue, but the network operator will require inputs to the grid to be controlled to within a fine margin of the agreed bids. Simulations performed using the StrathFarm model have demonstrated that the implementation of PI control at a wind farm level, in conjunction with individual power-adjusting controllers on each turbine, can provide this combination of curtailment and control. The 20WT farm can achieve curtailment to within ± 1.5% of the rated wind farm power across the full range of mean wind speeds tested. The 10WT farm performs less well at lower wind speeds, with power bands of 0.8 - 4.8% of the rated power of the farm at the three mean wind speed values tested. However, the reduced wake contamination in the 10WT farm leads to a higher mean power output per turbine during curtailment. The impact of control on tower DELs is most significant at near-rated wind speeds. Intelligent PI control can reduce turbine loads by 16-36% at 12 m/s mean wind speed. At below- and above-rated wind speeds this PI controller has negligible effect on tower loading. In contrast, employing simple curtailment strategy could be exceptionally damaging to turbines - in the worst case, this blunt curtailment strategy actually *increased* tower DELs by 20-40%. This result emphasises the importance of considered approaches to curtailment; whilst an intelligent approach can reduce loads and offer some compensation to operators for lost energy revenue, blunt curtailment could in fact cause serious extra loading and reduce the remaining useful life of individual turbines.

6.2 Future Work

As discussed in section 5.4, simulations across a much wider range of wind field conditions and farm sizes/layouts would be required to fully quantify realistic curtailment and control limits for wind farms under future constraints. A key next step would be to perform simulations at a range of turbulence intensities and to model wind farm layouts for farms already operational or under construction. There is also much greater scope for reducing tower base loading by employing dispatch strategies which customize the curtailment of each turbine according to the local wind speed. These more complex control strategies would also need to be implemented over a wide range of wind and farm variables as discussed above.

Acknowledgements

This work was undertaken at the University of Strathclyde as part of the CDT in Wind & Marine Energy Systems, funded by the EPSRC.

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