Abstract:

When the installed capacity of wind power becomes high, the power generated by wind farms can no longer simply be that dictated by the wind speed. With sufficiently high penetration, it will be necessary for wind farms to provide assistance with supply-demand matching. The work presented here introduces a wind farm controller that regulates the power generated by the wind farm to match the grid requirements by causing the power generated by each turbine to be adjusted. Further benefits include fast response to reach the wind farm power demanded, high accuracy, little variability in the wind farm power output and provision of synthetic inertia.

Keywords: Wind farm power control, wind turbine control, flexible turbine operation.

1 Introduction

When the installed capacity of wind power becomes high, the power generated by wind farms can no longer simply be that dictated by the wind speed. Already, the operation of some wind turbines is being curtailed. With sufficiently high penetration, it will be necessary for wind farms to provide services to the grid including spinning reserve, frequency support and assistance with supply-demand matching. In these circumstances, to regulate the power generated by the wind farm to match the grid requirements, a wind farm controller, causing the power generated by each turbine to be adjusted, is required.

The structure of the wind farm controller discussed here is shown in Figure 1. It has two elements, the Network Wind Farm Controller (NWFC) and the Turbine Wind Farm Controller (TWFC). The NWFC acts on information regarding the state of the power network to determine the required power output from the wind farm and so the adjustment ($\Delta P$) relative to $P$, the wind speed dictated output that would arise with no adjustment. The TWFC acts on information regarding the state of the wind farm and the turbines therein to allocate adjustments to each turbine, $\Delta P_i$ (for $i = 1, ..., N$, where $N$ is the number of turbines in the farm) relative to $P_i$, the wind speed dictated output of turbine $i$.

Each wind turbine in the farm has its own full operational envelope controller [1] that ensures the wind turbine follows its required operating strategy and remains in a safe operating condition through regulating rotor speed, torque and some loads. Since the wind farm controller requires each turbine to adjust its power output on request, the full envelope controller is modified by addition of a Power Adjusting Controller (PAC) [2]. The PAC causes the turbine to adjust its generated power by a demanded amount relative to that dictated by the wind speed. As the PAC is essentially a feed forward controller, jacketing the full envelope controller, it does not compromise the operation of the full envelope controller, hence redesigning or retuning of the existing full envelope controller is not necessary. Furthermore, the PAC contains safeguards to prevent the turbine being driven into unsafe operating regions. The PAC is sufficiently fast acting to provide the turbine with a synthetic inertia response [3].

To prevent the introduction of feedback loops between the wind farm controller and the individual turbines as depicted in Figure 1, the only communication regarding the state of each turbine to the wind farm controller is through flags, $f_i$. Furthermore, since the wind farm consists of a large number of turbines, the wind farm controller feedback acting on the total power output from the farm only introduces very weak feedback on each turbine. In other words, as the number of turbines that share the adjustments to the wind farm power output increases, the feedback effect decreases. Hence, the wind farm controller acts independently to the controllers of the wind turbines.

The purpose of this paper is to investigate the design and performance of the wind farm controller in Figure 1 with the objective of operating the wind farm at some specified output power. The controller not only adjusts the total power generated but allocates the individual adjustments to each turbine.
The design of the wind farm controller is presented in Section 2. Its performance is presented in Section 3 by being applied to curtail the power output of a 10 turbine wind farm. The wind farm is modelled using both Matlab/SIMULINK and BLADED. The turbines are the SuperGen (Sustainable Power Generation and Supply) Wind 5MW wind turbine. Conclusions are drawn in Section 4.

2 Wind Farm Control

The wind farm controller requires that each variable-speed pitch-regulated wind turbine be equipped with an existing central (full envelope) controller and PAC. The central controller causes the turbine to track its design operating curve as depicted in Figure 2; that is, a constant generator speed (i.e., 70 rad/s) is maintained in the lowest wind speeds (mode 1); the $C_{p\text{max}}$ curve is tracked to maximise the aerodynamic efficiency in intermediate wind speeds (mode 2); constant generator speed (i.e., 120 rad/s) is again maintained in higher wind speeds (mode 3); and above rated wind speed, the rated power of SMW is maintained by active pitching (mode 4) [4], [5].

![Figure 1: Structure of the wind farm controller.](image)

The PAC provides fully flexible operation adjusting the power output from each turbine, more specifically, reducing the power or increasing the power for a limited time if required. However, if an increase or decrease in the power output is sustained, the turbine operating state could move away from the design operating curve.

The wind farm controller regulates the wind farm power output ensuring, at the same time, that each turbine (with the central controller and PAC) operates within the safe operating region defined by the thresholds in Figure 2. In below rated wind speed, the turbines operating inside the inner thresholds could be allocated greater adjustments in power than the turbines operating outside the inner thresholds. The turbines operating outside the outer thresholds will be allocated zero adjustment in power to bring them back onto the design operating curve. The same strategy is applied in modes 3 and 4 except that there are no inner bounds since the deviation from the design operating curve caused by the PAC in above rated wind speed is smaller than the deviation in below rated wind speed.

In this paper, it is assumed that every turbine has the same status except that they operate in different wind speeds. The wind is stochastically varying with time and continuously interacting with the rotor. The effective wind speed is wind speed averaged over the rotor area such that the spectrum of aerodynamic torque remains unchanged. It is obtained by filtering the point wind speed [6] through the filter introduced in [7]. The point wind speeds that take into account the correlation of layout of the cluster is obtained from BLADED.

Different wind speeds cause the turbines to operate on different parts of the design operating curve (Figure 2). The wind farm controller adjusts the power for each turbine based on its status with reference to the inner and outer thresholds. The thresholds are determined on the generator torque ($T_g$) vs generator speed ($\omega_g$) plane since the central controller is designed to follow the design strategy curve on the $T_g$ vs $\omega_g$ plane although some other existing controllers are designed to follow the design strategy curve on the aerodynamic torque ($T_e$) vs rotor speed ($\Omega$) plane [8], in which case the thresholds would be determined on the $T_e$ vs $\Omega$ plane. Each threshold is defined as

$$ y_T = T_e - k_T\omega_g^2 $$

(1)
where \( k_T \) is a constant, unique for each threshold. For instance, for the outer threshold above the \( C_{\text{max}} \) curve, \( y_T \) becoming positive indicates that the threshold has been crossed. Hysteresis loops are incorporated into the thresholds to avoid chattering. The hysteresis limit in the direction outwards from the \( C_{\text{max}} \) curve is set to \( 10^3 \), while the limit in the direction towards the \( C_{\text{max}} \) curve is set 5 times larger since it tends to move more rapidly when moving towards the \( C_{\text{max}} \) curve.

In mathematical terms, \( \Delta P \) is computed as

\[
\Delta P(t) = k_i \int P_d(t) - P_d(t) \, dt
\]

where \( \Delta P(t) \) and \( P_d(t) \) denote adjusted power and the demanded power, respectively, and \( k_i \) is a tuning parameter.

Consequently, unadjusted power, \( P_m \) (the wind speed dictated wind farm power output that would arise with no adjustment) would be

\[
P_m = P - \Delta P
\]

When \( \Delta P \) is negative, the TWFC distributes \( \Delta P \) to each turbine as \( \Delta P_i \) based on flags, \( f_i \) (status of each turbine) and \( \bar{f}_i \) (wind farm status as depicted in Figure 1) as follows

\[
\Delta P_i = \frac{\Delta P \min (f_i - \bar{f}_i)}{\sum_{i=1}^{N_T} \min (f_i - \bar{f}_i)}
\]

for \( i = 0, 1, \ldots, N_T \). The implication is that

\[
\sum_{i=1}^{N_T} \Delta P_i = \Delta P
\]

where \( N_T \) denotes the number of turbines in the wind farm.

In mode 2, flags are returned as 0, 1 or \( f_m \), which is 3 in this paper. If a turbine is operating within the inner threshold (Figure 2), a flag of \( f_m \) would be returned. If a turbine is operating within the outer threshold but outside the inner threshold, a flag of 1 would be returned. Finally, if a turbine is operating outside the outer threshold, a flag of 0 would be returned. \( \Delta P \) with a flag of 0 would be zero, and \( \Delta P \) with a flag of 3 would be 3 times larger than \( \Delta P_i \) with a flag of 1. These numbers are design parameters that can be altered appropriately. In modes 3 and 4, only the outer thresholds exist and, thus, only flags of 0 and \( f_m \) are present.

The wind farm status could be determined by a number of factors including the health, age and location of the turbines. For instance, reduction in generated power may be made to only half the wind turbines in the farm, those on the up-wind side of the farm [2]. The wind farm status, \( \bar{f}_i \) (for \( i = 0, 1, \ldots, N_T \)) is also returned as 0, 1 or \( f_m \) in mode 2 and 0 or \( f_m \) in modes 3 and 4. In turn, \( \bar{f}_i \) and \( f_i \) are compared and the minimum is utilised in (4). However, as previously mentioned, it is assumed that every turbine has the same status in this paper; that is, \( \bar{f}_i = f_m \) (for all \( i \)).

When \( \Delta P \) is positive, the change in \( \Delta P_i \) impacts on the turbine operating state much more significantly, causing turbines to cross the outer threshold more readily. Thus, (4) and (5) need to be modified as follow. More detailed justification for the following modification is presented with a simulation example in Section 3.2.

\[
\Delta P_i = Q_i \frac{\Delta P \min (f_i - \bar{f}_i)}{\sum_{i=1}^{N_T} \min (f_i - \bar{f}_i)}
\]

where

\[
Q_i = \frac{\sum_{i=1}^{N_T} f_i}{N_T f_m}
\]

and (5) is subsequently replaced with

\[
\sum_{i=1}^{N_T} \Delta P_i \neq \Delta P
\]

only if \( \Delta P \) is positive.

The allocation and reallocation of the power adjustment should take place in a smooth manner, which avoids the introduction of large transients, discontinuities and steps in the wind farm power output. It is achieved by filtering \( f_i \) (for \( i = 0, 1, \ldots, N_T \)) to ensure that the smoothing occurs only when the switching takes place; that is, filtering \( f_i \) is equivalent to filtering \( \Delta P_i \) only when the switching takes place. A low pass filter, with time constant of 3 s, is exploited although it could be larger in real life.

The central controller ensures that the switching between the various modes (Figure 2) also takes place in a smooth manner. In mode 1, the PAC is not activated.

### 3 Simulation results

Matlab/Simulink and BLADED models of the Supergen 5MW exemplar turbine are used. The rated wind speed is approximately 11.5 m/s. The BLADED model provides greater details for the structural loads, while the Matlab/Simulink model enables many turbines to be included in a wind farm model. The wind farm model thus consists of 9 Matlab/Simulink models and 1 BLADED model. The two software packages are connected using StrathControl Gateway, a commercial software package that fully integrates the simulation. Due to the high computational demand, it is assumed that the wind farm contains only 10 turbines.

A number of simulations have been conducted to demonstrate how the wind farm control strategy performs, and three of these simulations are reported in this section. In Simulation 1, \( \Delta P \) is always negative in below rated wind speed. In Simulation 2, \( \Delta P \) alternates between negative and positive in below rated wind speed. In Simulation 3, \( \Delta P \) is always negative in just below rated wind speed that requires the central controllers to switch between modes 2 and 3.

The frequency analysis for examining the feedback (as depicted in Figure 1) effect that could adversely affect the performance of the full envelope controllers is also discussed for Simulation 3.
### 3.1 Simulation 1

In Simulation 1, the wind farm is required to produce a constant power of 12 MW at a mean wind speed of 8 m/s. Adjusted power in blue is depicted against unadjusted power in red in Figure 3. The PAC is switched on at 120 s past the transient response, and $\Delta P$ always remains negative.

In the same situation, if the turbines were curtailed individually to 1.2 MW (subsequently adding the individual power outputs together to yield the wind farm power output), the individual power outputs would be reduced below 1.2 MW when some turbines experience lower wind speeds as depicted in Figure 5. Consequently, as depicted in Figure 6, the output from the wind farm would, for much of the time, be less than 12 MW as depicted in red against the adjusted power by the wind farm controller.

In summary, with the wind farm control strategy introduced here, by curtailing the wind farm power output in place of the individual wind turbine power outputs, the turbines seeing higher wind speeds compensate those seeing lower wind speeds, producing an improved result as depicted in Figure 6. Another benefit of curtailing the wind farm power output rather than the individual power outputs is that it does not necessitate redesigning or retuning of the existing central controllers; that is, incorporating PAC into the existing central controller does not alter the dynamics of the central controller as discussed in more detail in Section 3.3.
The behaviour of each turbine on the $T_e$ vs $\omega_g$ plane and the $T_i$ vs $\Omega$ plane [8] is also depicted in Figure 7. As reported in Section 2, the strategy is based on the $T_e$ vs $\omega_g$ plane; that is, thresholds are designed on this plane. The results demonstrate that the turbines operate within the inner thresholds, allowing for the hysteresis loops. In more detail, when a turbine crosses the inner threshold, the turbine is allocated smaller adjustment in power, as the flag changes from 3 to 1, thereby causing the turbine either to slow down in moving outwards from the design operating curve or to move towards the design operating curve. In this example, setting the flags to 1 from 3 diverts the turbine towards the design operating curve, and the outer threshold is never reached.

Despite all the allocation and reallocation of $\Delta P$ to each turbine as illustrated in Figures 4 and 7, a constant power of 12 MW is still maintained with little variability as depicted in Figure 3.

### 3.2 Simulation 2

In Simulation 2, the wind farm is required to produce a constant power of 18MW at a mean wind speed of 8 m/s. Adjusted power in blue is depicted against unadjusted power in red in Figure 8. The PAC is switched on at 120 s past the transient response. It depicts that $\Delta P$ alternates between positive and negative. Though $P$ can be held smaller than $P_m$ ($\Delta P < 0$) persistently, $P$ cannot be held larger than $P_m$ ($\Delta P > 0$) indefinitely. Moreover, positive $\Delta P$ must be compensated afterwards [2]. Consequently, $P$ drops at around 270s, and $\Delta P$ remains negative from around 270 until it is fully compensated.

The behaviour of each turbine on the $T_e$ vs $\omega_g$ plane and the $T_i$ vs $\Omega$ plane is also depicted in Figure 9. When turbines cross the inner threshold, the turbines are allocated smaller $\Delta P_i$ (as the flags change from 3 to 1). It diverts some turbines towards the design operating curve, but some turbines still move towards the outer threshold, but more slowly now, in contrast to Simulation 1, where changing the flags from 3 to 1 diverts each turbine towards the design operating curve. When the turbines eventually cross the outer threshold, the flags change from 1 to 0, finally redirecting them towards the design operating curve as illustrated in Figure 9. During this so-called recovery process, the previous positive $\Delta P_i$ is compensated.

In this simulation, where $\Delta P$ is positive, if (4) were still exploited instead of (6), the remaining turbines would compensate for the turbines that have crossed the outer threshold, thereby satisfying (5). For instance, when turbine 1 crosses the outer threshold above the design operating curve, $\Delta P_1$ would become zero to bring turbine 1 back to the design operating curve (leaving the turbine in the recovery process), and $\Delta P_i$ of the remaining turbines would increase to compensate and, thus, satisfying (5). As mentioned earlier, the turbine operating
state becomes much more sensitive when $\Delta P$ is positive, and as such, the remaining turbines would speed up moving towards the outer threshold (due to the increase in $\Delta P$). This process would repeat causing every turbine to cascade towards the outer threshold as depicted in Figure 10.

It consequently leaves a large dip in $P$ as depicted in Figure 11 (just after 270s). As such a large dip would not satisfy the grid operation, (6) replaces (4). As a result, when one turbine crosses the outer threshold in the same example, the remaining turbines do not attempt to compensate as depicted in Figure 9 (i.e., $\Delta P_i$ of the remaining turbines would not increase), no longer cascading towards the outer threshold. However, (5) is no more satisfied in return, but the undesired dip is removed as depicted in Figure 8 in comparison to Figure 11.

When $\Delta P$ is negative such as in Sections 3.1 and 3.3, the turbine operating state is not as sensitive to the change in $\Delta P_i$. Moreover, negative $\Delta P$ does not necessitate any compensation afterwards, and therefore, (4) can safely be exploited, hence satisfying (5).

### 3.3 Simulation 3

In Simulation 3, the wind farm is required to produce a constant power of 25 MW at a mean wind speed of 10 m/s. At this mean wind speed, the controller causes the turbines to switch between the $C_{p_{\text{max}}}$ tracking (mode 2) and the constant speed (mode 3) operations.
thresholds and Turbines 6 and 7 cross the inner threshold. Consequently, Turbines 6 and 7 should be reallocated a reduced power adjustment in comparison to Turbines 1 and 2. Figure 15 (just before 400 s) demonstrates that the reallocation takes place as expected at the switching region.

Figure 13: Simulation 3: behaviour of each turbine on the generator torque and generator speed; upper subfigure: turbines 1 to 5, lower subfigure: turbines 6 to 10.

Despite the allocation of reallocation of $\Delta P$ to each turbine, adjusted power is still smooth, avoiding the introduction of large transients, discontinuities and steps in the wind farm power output, as depicted (in blue) in Figure 12.

Figure 14: Simulation 3: behaviour of each turbine on the aerodynamic torque and rotor speed plane.

Figure 15: Simulation 3: adjustment in power; upper subfigure: turbines 1 to 5, lower subfigure: turbines 6 to 10.

As reported in Section 2, the change in wind farm power output is determined as the difference between the unadjusted wind farm power output and the wind farm power demand as depicted in Figure 1. This could create a feedback effect and alter the dynamics of the central controllers. However, as the number of turbines in the wind farm increases, the number of turbines that share the adjustments to the wind farm power output ($\Delta P$) increases and the feedback effect decreases. Nonetheless, since there are only 10 turbines in the wind
farm, it is important to ensure that the wind farm controller does not create a significant feedback effect.

It is not practical to utilise time-series plots for analysing the feedback effect. The long term effect of the feedback on the structural loads on the tower and blades would not be visible in time-series plots but would clearly be visible in power spectra. Also, the feedback effect could affect the power spectrum at high frequencies but might not appear in time-series plots. Therefore, power spectra are exploited for analysing the feedback effect as follows.

For Simulation 3, the power spectra of fore-aft tower bending moment (TBM), fore-aft blade bending moment (BBM) and side-to-side BBM are depicted in Figures 16, 17 and 18, respectively. The spectra for the situations with (red) and without (blue) a feedback effect are also depicted for comparison purposes. To simulate the situation with a feedback effect, the wind farm controller is applied to a single turbine model, and to simulate the situation without a feedback effect, a constant $\Delta P$ is applied with no feedback loop.

![Figure 17: Spectrum of fore-aft blade bending moment (black) in comparison to the situations with (red) and without (blue) a feedback effect.]

![Figure 18: Spectrum of side-to-side blade bending moment (black) in comparison to the situations with (red) and without (blue) a feedback effect.]

The results demonstrate that the power spectra for the situation with the wind farm controller and the power spectra for the situation with no feedback loop are analogous. It is, therefore, evident that the wind farm produces a constant power of 25 MW at a mean wind speed of 10 m/s, avoiding creating a significant feedback effect even for a wind farm with only 10 turbines. The feedback effect is even weaker for a wind farm with a larger number of turbines. Almost identical results have been obtained for Simulations 1 and 2.

4 Conclusions

The wind farm controller introduced in this work exploits an existing full envelope controller and the PAC, which has been developed to provide fully flexible operation of each turbine. The wind farm power output meets the wind farm power demand as determined by the grid side operation requirements for the wind farm, taking into account the status and the operating state of each turbine.

The simulation results demonstrate that the wind farm power demand is rapidly achieved while keeping each turbine in a safe operating region. The allocation and reallocation of the power adjustments between the turbines takes place in a smooth manner, which avoids the introduction of large transients, discontinuities and steps in the wind farm power output. By curtailing the wind farm power output as opposed to individual turbine power outputs, improved results are attained by allowing those turbines seeing higher wind speeds to compensate for those turbines seeing lower wind speeds. The wind farm controller could also be utilised for increasing the power output as opposed to curtailing. However, the increase in power can only be sustained for a limited time, and the algorithm is modified not to allow those turbines seeing higher wind speeds to compensate for those turbines seeing lower wind speeds for improved results.

The wind farm controller does not cause any significant feedback that could reduce the effectiveness of the turbines’ full envelope controllers even for a wind farm with 10 turbines. The feedback effect is even weaker for a wind farm with a larger number of turbines.

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References


