On wind turbine control for participation in grid frequency regulation

To cite this article: Iker Elorza et al 2019 J. Phys.: Conf. Ser. 1222 012024

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Abstract. An energy mix with a large contribution from wind power requires wind farm participation in frequency regulation. To do this effectively, it is necessary for wind turbines to curtail their power production by a certain amount, or 'delta', which serves as a reserve. Although it is relatively straightforward to achieve this in certain conditions, doing so consistently normally requires wind speed observers to estimate available power. A delta control method is proposed here, which does not rely on said observers and naturally extends popular torque and pitch control algorithms.

1. Introduction

The concept of frequency support with wind turbines is not new, and proportional de-loading for that purpose is relatively simple to achieve [1]. The idea is simple - operate turbines at a constant fraction, e.g. 75%, of the maximum power available, for any given wind conditions. Implementation is also simple, at least in certain wind conditions - modify the generator speed-torque curve or the minimum pitch, or both, for operation with a power coefficient that is a fraction, e.g. 75%, of the optimum power coefficient. In practice, ensuring proportional de-rating at all wind speeds is slightly more subtle, and some implementation choices are to be made - e.g. Loukarakis et al. [2] use two look-up tables, one 1D for pitch and another 2D for power, whereas two 1D tables are enough and no considerations are made about constant speed operating regions.

It is also arguable that delta control has a role to play in wind farm participation in grid frequency regulation [3] [4] [5] [6] [7] [8]. The idea is, again, simple - operate a turbine at a constant power delta, e.g. 1MW, below the maximum power available, for any given wind conditions. Implementation is not as simple, however - different wind speeds require operation at different power coefficient values and, as far as we have been able to review the literature, all reported constant delta methods require wind speed estimation (see, for example, [9]), with one exception (discussed below).

Kristoffersen described a Danish offshore farm’s operational experience with 'Delta Control', which keeps a constant spinning reserve power [10]. However, no description is given of how said control was implemented.

Wang et al. [11] mention that proportional curtailment strategies have been demonstrated in a workshop paper by the same authors. However, they simply suppose it is technically possible to do constant curtailment 'as it is part of the regulation capacities required by the Danish [authorities for some] wind farm'.
Baccino et al. [12] use local wind estimations, without further discussion, as do Aho et al. [13].

Hansen et al. [14] also use a wind estimator, and they estimate available power based on the difference between the optimal speed-power curve and current power. This overestimates available power, because increasing generator torque to increase power output results in the rotor slowing down, which in turn results in generator power decreasing along the optimal speed-power curve.

A delta control scheme not based on wind speed estimation is briefly described in [15], where they use a 2D look-up table, giving the generator power setpoint from generator speed and power delta. This allows overspeed-based delta control. The problem with this strategy is that generator speed quickly increases with power delta, and it does therefore not work at wind speeds high enough to result in operating points near or at the maximum generator speed, since no further over-speed is possible then. We will show that this can be done with a 1D look-up table, as well as extend it to all wind speeds.

In this paper, we take Kristoffersen’s classification [10] of active power control functions as a basis for our discussion. Said classification is as follows (quotes taken from [10]):

- **Absolute power limitation**: ‘the wind farm is able to operate at reduced levels with all turbines running’.
- **Balance control**: ‘the wind farm is able to participate in the regional secondary control’.
- **Power rate limitation**: ‘when the wind speed increases, the wind farm is able to impose a positive rate of change (dP/dt) limitation’.
- **Delta control**: ‘the wind farm is controlled so the power production is an adjustable number of MWs below the possible power’. Here, we make the following further distinction:
  - **Proportional delta control**: the power production is proportional to available power, and their ratio is adjusted externally, e.g. to 85%.
  - **Constant delta control**: the difference between available power and power production is adjusted externally, e.g. to 10 MW.

We assume that all active power control functions above, although they are formally defined only at farm level, are also performed identically at turbine level, while we make the provision that setpoints may vary from one turbine to another and are decided by the farm controller. As already discussed, although the literature presents several approaches to turbine-level control functions of this sort, it is not trivial to extract from it a readily industrializable set of algorithms. Said extraction, and the addition of our own contributions, is the purpose of this paper.

2. Torque and pitch control

Following [16], we consider a base turbine controller with two generator speed regulators, e.g. PI controllers, one of which modifies the blades’ collective pitch angle, $\beta$, while the other one modifies the generator torque $Q_e$.

The generator speed setpoint for the pitch controller, $\omega_\beta$, is always the maximum operating speed, $\omega_{\text{max}}$. The lower pitch angle saturation limit is as follows:

$$\beta_{\text{min}} = \beta_\delta (Q_e)$$

where $\beta_\delta (Q_e)$ is a function of generator torque $Q_e$ which is chosen to maximize the power coefficient – we use subscript $\delta$, rather than the more usual ‘opt’ because we will use this torque for delta control in section 6.

On the contrary, the generator speed setpoint for the torque controller, $\omega_q$, is switched between $\omega_{\text{max}}$ and the minimum operating speed, $\omega_{\text{min}}$. The choice between the two is made
based on proximity to the actual generator speed, $\omega$, and the generator torque saturation limits are chosen so that:

\[
Q_{\text{max}} = \begin{cases} 
\frac{P_n}{\omega_{\text{max}}}, & \text{if } \omega_q = \omega_{\text{max}} \\
Q_\delta(\omega), & \text{if } \omega_q = \omega_{\text{min}} 
\end{cases}
\]

(2)

\[
Q_{\text{min}} = \begin{cases} 
Q_\delta(\omega), & \text{if } \omega_q = \omega_{\text{max}} \\
0, & \text{if } \omega_q = \omega_{\text{min}} 
\end{cases}
\]

(3)

where $P_n$ is the rated power, while $Q_\delta(\omega)$ is a function of $\omega$ which is chosen to make the tip-speed ratio converge to its optimal value – we use subscript $\delta$, rather than the more usual 'opt' because we will use this torque for delta control in section 6. Figure 1a shows the resulting speed-torque curve.

3. Operation at optimal tip-speed ratio

The method for the choice of $Q_\delta(\omega)$ is well established, e.g. in [17]. It is based on the following simple turbine model:

\[
J \frac{\dot{\omega}}{\dot{\beta}} = Q_a - b (Q_e + Q_l)
\]

(4)

where $J$ is the rotor inertia, $b$ is the gearbox ratio, $Q_a$ is the aerodynamic torque and $Q_l$ is the torque due to mechanical losses.

The available aerodynamic power is:

\[
P_{av} = \frac{1}{2} \rho \pi R^2 U^3 C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})
\]

(5)

where $\rho$, $R$ and $U$ are the air density, rotor radius and wind speed, respectively, while $\lambda_{\text{opt}}$ and $\beta_{\text{opt}}$ are the tip-speed ratio and blade pitch angle, respectively, for which the power coefficient $C_p$ is the greatest. Operating at $\beta = \beta_{\text{opt}}$ is trivial - one need only choose $\beta_\delta = \beta_{\text{opt}}$. However, $\lambda$ cannot be directly manipulated, or indeed measured, since it is defined as follows:

\[
\lambda = \frac{R \omega}{b U}
\]

(6)

When operating at $\beta = \beta_{\text{opt}}$ but, in general, $\lambda \neq \lambda_{\text{opt}}$, the aerodynamic torque is:

\[
Q_a = \frac{1}{2} \rho b \pi R^5 \frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} \frac{\omega^2}{b^2}
\]

(7)

Using (6), we may rewrite (7) thus:

\[
Q_a = \frac{1}{2} \rho \pi R^5 \frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} \frac{\omega^2}{b^2}
\]

(8)

Note from (4) and (8) that $\lambda = \lambda_{\text{opt}}$ becomes a fixed point if we choose:

\[
Q_e = \frac{1}{2} \rho \pi R^5 \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})}{\lambda_{\text{opt}}^3} \frac{\omega^2}{b^2} - Q_l
\]

(9)

It is also interesting to know whether (4), (8) and (9) lead to $\lambda = \lambda_{\text{opt}}$ being asymptotically stable. To find out, we use (6) to rewrite (4), (8) and (9) thus:
\[
\dot{\lambda} = \frac{1}{2} \rho \pi R^4 U J^{-1} \lambda^2 \left[ \frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} - \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})}{\lambda_{\text{opt}}^3} \right]
\]  

We then choose the following Lyapunov function candidate:

\[ L = (\lambda - \lambda_{\text{opt}})^2 \]  

Derivation of (11) w.r.t. time and substitution of (10) yield:

\[
\dot{L} = \rho \pi R^4 U J^{-1} \lambda^2 (\lambda - \lambda_{\text{opt}}) \left[ \frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} - \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})}{\lambda_{\text{opt}}^3} \right]
\]  

From (12), the fixed point \( \lambda = \lambda_{\text{opt}} \) is asymptotically stable if:

\[
\begin{cases}
\frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} > \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})}{\lambda_{\text{opt}}^3}, & \text{for } \lambda < \lambda_{\text{opt}} \\
\frac{C_p(\lambda, \beta_{\text{opt}})}{\lambda^3} < \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})}{\lambda_{\text{opt}}^3}, & \text{for } \lambda > \lambda_{\text{opt}}
\end{cases}
\]  

The fulfillment of these conditions may easily be verified from a turbine’s power coefficient curve.

The choice of \( Q_\delta(\omega) \) is therefore based on (9), i.e.:

\[ Q_\delta = \frac{1}{2} \rho b \pi R^5 \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) \omega^2}{b^3} - Q_l \]  

Note from (2), (3) and (14) that (9) is fulfilled as long as \( \lambda = \lambda_{\text{opt}} \) lies within \( \omega \in (\omega_{\text{min}}, \omega_{\text{max}}) \), because \( Q_e \) saturates at \( Q_\delta \).

4. Operation at constant rotor speed

Once \( \omega_{\text{min}} \) or \( \omega_{\text{max}} \) is reached, it is no longer possible to operate the turbine at \( \lambda = \lambda_{\text{opt}} \). The tip-speed ratio at which we must now operate the turbine, \( \lambda_n \), is determined by wind speed, \( U \), thus:

\[ \lambda_n = \frac{R \omega_n}{b U} \]  

where \( \omega_n \) is either \( \omega_{\text{min}} \) or \( \omega_{\text{max}} \).

It is still possible, however, to choose the pitch angle, \( \beta \), which also influences efficiency. We are therefore interested in finding \( \beta_{\text{opt}}|_{\lambda_n} \), the optimal pitch angle for the tip-speed ratio we are forced to operate at.

When operating at \( \lambda = \lambda_n \), the aerodynamic torque is:

\[ Q_a = \frac{1}{2} \rho b \pi R^3 \frac{C_p(\lambda_n, \beta)}{\omega_n} \]  

In steady state, (4) and (16) become

\[ Q_e = \frac{1}{2} \rho b \pi R^3 \frac{C_p(\lambda_n, \beta)}{\omega_n} - Q_l \]  

From (17), it is possible to numerically calculate a look-up table giving \( \beta_{\text{opt}}|_{\lambda_n} \) as a function of \( Q_e \), to be applied when \( Q_e \notin (Q_\delta(\omega_{\text{min}}), Q_\delta(\omega_{\text{max}})) \). The choice of \( \beta_\delta(Q_e) \) is, therefore, made as follows:

\[ \beta_\delta(Q_e) = \begin{cases} 
\beta_{\text{opt}}|_{\lambda_n}(Q_e), & \text{if } Q_e \notin (Q_\delta(\omega_{\text{min}}), Q_\delta(\omega_{\text{max}})) \\
\beta_{\text{opt}}, & \text{otherwise}
\end{cases} \]  

(18)
5. Absolute power limitation, balance control and power rate limitation

Absolute power limitation at rated power is often part of the torque and pitch control described in section 2. It is simply implemented by modifying (2) thus:

\[ Q_{\text{max}} = \begin{cases} P_n/\omega, & \text{if } \omega_q = \omega_{\text{max}} \\ Q_\delta(\omega), & \text{if } \omega_q = \omega_{\text{min}} \end{cases} \tag{19} \]

We may generalize (19) to any power setting \( P_r \) thus:

\[ Q_{\text{max}} = \begin{cases} P_r/\omega, & \text{if } \omega_q = \omega_{\text{max}} \\ \min(Q_\delta(\omega), P_r/\omega), & \text{if } \omega_q = \omega_{\text{min}} \end{cases} \tag{20} \]

This of course requires the upper torque limit to supersede the lower one, so that situations in which \( P_r/\omega < Q_\delta(\omega) \) are appropriately handled. We therefore modify (3) thus:

\[ Q_{\text{min}} = \begin{cases} \min(Q_\delta(\omega), P_r/\omega), & \text{if } \omega_q = \omega_{\text{max}} \\ 0, & \text{if } \omega_q = \omega_{\text{min}} \end{cases} \tag{21} \]

Note that dynamics are the same as in section 2 for \( Q_\delta(\omega) < P_r/\omega \), i.e. at wind speeds insufficient to reach the power setting. However, at higher wind speeds we have, instead of (9):

\[ Q_e = P_r/\omega \tag{22} \]

From (4), (6), (7) and (22):

\[ \frac{J}{b^2}\omega = 2\frac{1}{2}\rho\pi R^2 U^3 \frac{C_p(\lambda, \beta_{\text{opt}})}{\omega} - P_r/\omega - Q_l \tag{23} \]

Equation (23) has a fixed point at \( \omega = \omega_0 \) and \( \lambda = \lambda_0 = R\omega_0/bU \), which satisfies

\[ \frac{1}{2}\rho\pi R^2 U^3 C_p(\lambda_0, \beta_{\text{opt}}) - \omega_0 Q_l = P_t \tag{24} \]

We are, again, interested in the stability of the fixed point at \( \omega = \omega_0 \), so we choose the following Lyapunov function candidate:

\[ L = (\omega - \omega_0)^2 \tag{25} \]

Derivation of (25) w.r.t. time and substitution of (23) yield:

\[ \dot{L} = 2\frac{\omega - \omega_0}{\omega} b^2 \left[ \frac{1}{2}\rho\pi R^2 U^3 C_p(\lambda, \beta_{\text{opt}}) - P_t - Q_l \right] \tag{26} \]

From (26), the fixed point \( \omega = \omega_0 \) is asymptotically stable if:

\[ C_p(\lambda, \beta_{\text{opt}}) > C_p(\lambda_0, \beta_{\text{opt}}), \quad \text{for } \lambda < \lambda_0 \]

\[ C_p(\lambda, \beta_{\text{opt}}) < C_p(\lambda_0, \beta_{\text{opt}}), \quad \text{for } \lambda > \lambda_0 \tag{27} \]

and

\[ Q_1(\omega) < Q_1(\omega_0) \quad \text{for } \omega < \omega_0 \]

\[ Q_1(\omega) > Q_1(\omega_0) \quad \text{for } \omega > \omega_0 \tag{28} \]

The fulfillment of these conditions may easily be verified from a turbine’s power coefficient curve and mechanical loss model.

Balance control is essentially the same as absolute power limitation, but with a \( Pr \) that changes, while power rate limitation may be achieved by maintaining a secondary power limit which is perpetually a small increment above current power, said increment being the maximum power rate times the time step.
6. Proportional delta control

Proportional delta control at low wind speeds may easily be accomplished by modifying (14) thus:

\[ Q_\delta = \frac{1}{2} \rho \pi R^5 k_\delta \frac{\omega^2}{b^3} - Q_l \]  \hspace{1cm} (29)

where

\[ k_\delta = \frac{C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} \]  \hspace{1cm} (30)

Here \( \lambda_\delta \) and \( \beta_\delta \) are such that

\[ \frac{C_p(\lambda_\delta, \beta_\delta)}{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}})} = 1 - \delta \]  \hspace{1cm} (31)

\( \delta \) being the proportion of the available power to be kept as a reserve. This is implemented via two look-up tables, giving \( k_\delta \) and \( \beta_\delta \), respectively, as a function of \( \delta \).

Note that solutions of (31) are generally non-unique, which leaves one degree of freedom for the choice of \( \lambda_\delta \) and \( \beta_\delta \) on the basis of criteria other than those discussed here (see, for example, [18]).

It is possible to prove that (29) leads to operation at \( \lambda = \lambda_\delta \) the same way that it has been proven that (14) leads to operation at \( \lambda = \lambda_{\text{opt}} \).

When, at higher or lower wind speeds, we are constrained to operation at \( \lambda = \lambda_n \), the available aerodynamic power is

\[ P_{\text{av}} = \frac{1}{2} \rho \pi R^2 U^3 C_p(\lambda_n, \beta_{\text{opt}}|\lambda_n) \]  \hspace{1cm} (32)

We may choose \( \beta_\delta \) such that

\[ \frac{C_p(\lambda_n, \beta_\delta)}{C_p(\lambda_n, \beta_{\text{opt}}|\lambda_n)} = 1 - \delta \]  \hspace{1cm} (33)

It is again possible to use (17) and (33) to produce a two-dimensional look-up table giving \( \beta_\delta \) as a function of \( Q_e \) and \( \delta \).

Lastly, for wind speeds above rated, it is necessary to limit \( P_t \) to \( P_n (1 - \delta) \).

From the definition of \( \delta \), it is easy to estimate the reserve power as \( \delta P_c/(1 - \delta) \), with \( P_c \) the current power.

7. Constant delta control

If we want to keep a constant power, \( P_\delta \), as a reserve, the choice of \( \lambda_\delta \) and \( \beta_\delta \) may appear less obvious than in section 6, because \( \delta \) depends on \( P_{\text{av}} \), which is not directly known:

\[ \delta = \frac{P_\delta}{P_{\text{av}}} \]  \hspace{1cm} (34)

However, we need simply substitute (5) and (34) into (31) to get

\[ C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) - C_p(\lambda_\delta, \beta_\delta) = \frac{2P_\delta}{\rho \pi R^2 U^3} \]  \hspace{1cm} (35)

Because (35) makes explicit reference to \( U \), it is not directly usable without a measurement or estimation of the wind speed. We therefore rewrite (35) thus:

\[ \frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) - C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} = \frac{2b^3 P_\delta}{\rho \pi R^2 \omega^3} \]  \hspace{1cm} (36)
From (36), we pick our strategy. We shall choose $\lambda_\delta$ and $\beta_\delta$ so that
\[
\frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) - C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} = \frac{2b^3 P_\delta}{\rho \pi R^5 \omega^3}
\] (37)

It is easy to implement (37) as two look-up tables, giving $k_\delta$ and $\beta_\delta$, respectively, as functions of $2b^3 P_\delta/\rho \pi R^5 \omega^3$. We may then use $\beta_\delta$ in (1) and $k_\delta$ in (29). However, we must have $Q_\delta \geq 0$ so, from (29), there is a limit to our choice of $k_\delta$ at:
\[
\frac{1}{2} \rho \pi R^5 k_\delta \frac{\omega^2}{b^3} - Q_\delta = 0 \quad (38)
\]

This, in turn, means that the actual power reserve is $\hat{P}_\delta \leq P_\delta$ when (38) is reached. It can be calculated thus:
\[
\frac{C_p(\lambda_{\text{opt}}, \beta_{\text{opt}}) - C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} = \frac{2b^3 \hat{P}_\delta}{\rho \pi R^5 \omega^3}
\] (39)

The limit (38) can be implemented as two look-up tables giving limit values for $k_\delta$ and $\beta_\delta$ as a function of $\omega$. A third look-up table giving the value of $\lambda_\delta$ corresponding to (38) allows us to use (39) to report actual power reserve $\hat{P}_\delta$.

We are, of course, interested in the dynamic characteristics of (4), (29) and (37), from which we now get, instead of (10):
\[
\dot{\lambda} = \frac{1}{2} \rho \pi R^4 U J^{-1} \lambda^2 \left[ \frac{C_p(\lambda, \beta_\delta)}{\lambda^3} - \frac{C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} \right] \quad (40)
\]

There always exist $\lambda_0 \geq \lambda_{\text{opt}}$ and $\beta_0 \geq \beta_{\text{opt}}$ such that either (37) or (38) be satisfied for $\lambda_\delta = \lambda_0$ and $\beta_\delta = \beta_0$, so there is a fixed point of (40) at $\lambda = \lambda_\delta = \lambda_0$ and $\beta = \beta_\delta = \beta_0$. We therefore choose the following Lyapunov function candidate:
\[
L = (\lambda - \lambda_0)^2 \quad (41)
\]

Derivation w.r.t. and substitution of (40) yield:
\[
\dot{L} = \rho \pi R^4 U J^{-1} \lambda^2 (\lambda - \lambda_0) \left[ \frac{C_p(\lambda, \beta_\delta)}{\lambda^3} - \frac{C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3} \right] \quad (42)
\]

From (42), the fixed point is asymptotically stable if:
\[
\begin{cases}
\frac{C_p(\lambda, \beta_\delta)}{\lambda^3} > \frac{C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3}, & \text{for } \lambda < \lambda_0 \\
\frac{C_p(\lambda, \beta_\delta)}{\lambda^3} < \frac{C_p(\lambda_\delta, \beta_\delta)}{\lambda_\delta^3}, & \text{for } \lambda > \lambda_0
\end{cases} \quad (43)
\]

Whether or not these conditions are satisfied is determined by the nature of $C_p$.

When, at higher or lower wind speeds, we are constrained to operation at $\lambda = \lambda_n$, choose $\beta_\delta$ so that, instead of (37):
\[
\frac{C_p(\lambda_n, \beta_{\text{opt}}|\lambda_n)}{\lambda_n^3} - \frac{C_p(\lambda_n, \beta_\delta)}{\lambda_n^3} = \frac{2b^3 \hat{P}_\delta}{\rho \pi R^5 \omega_n^3} \quad (44)
\]

It is again possible to use (17) and (44) to produce a two-dimensional look-up table giving $\beta_\delta$ as a function of $Q_\epsilon$ and $P_\delta$.

Lastly, for wind speeds above rated, it is necessary to limit $P_t$ to $P_n - P_\delta$. 


8. Example: NREL 5MW

Figure 1b shows the contour plot of the power coefficient of NREL’s 5MW reference turbine model [19], as a function of tip-speed ratio and pitch angle. The lines of optimum pitch angle, given the tip-speed ratio, and optimum tip-speed ratio, given the pitch angle, are also shown, together with an arbitrary \( \{ \beta, \lambda \} \) trajectory, along which the operating point moves, via modification of \( \beta \) and \( k \), up and down the \( C_p \) 'hill'.

For proportional delta control within the variable speed range, only \( k \) and \( \beta \) need be modified, in order to impose a fixed point, along the chosen \( \{ \beta, \lambda \} \) trajectory, which corresponds to the correct power coefficient, as dictated by (31). The look-up tables for this are shown by figure 2.

At the limits of the variable speed range, i.e. for constant-speed operation, \( \beta \) need also change with generator torque, as dictated by (17) and (33). The two-dimensional look-up table for this is shown by figure 3a. Note that the values of \( \beta \) on the flat sections of the lines on figure 3a correspond to the values given by figure 2b, and that said flat sections quickly shrink as \( \delta \) grows. Figure 3b shows the resulting operating points.

For constant delta control within the variable speed range, again, only \( k \) and \( \beta \) need be modified, in order to impose a fixed point, along the chosen \( \{ \beta, \lambda \} \) trajectory, which corresponds to the correct power coefficient, as dictated by (35). The look-up tables for this are calculated from (37), and are the same as those shown by figure 2, only they are entered with \( 2b^2 P_b / \rho \pi R^5 \omega^3 \), rather than \( \delta \).

At the limits of the variable speed range, i.e. for constant-speed operation, \( \beta \) need also change with generator torque, as dictated by (17) and (44). The two-dimensional look-up table for this is shown by figure 4a. Note that the flat sections seen on the lines on figure 3a do not appear on figure 4a, since the power coefficient is now variable even within the variable speed range. Figure 4b shows the resulting operating points.

9. Conclusions

Wind farm participation in grid frequency regulation is necessary for deep wind energy penetration. Delta control will play a role there, and a seemingly viable method for that is discussed here. The distinguishing feature of our method is that it does not use wind speed measurements or estimators, and it extends a control scheme that is popular in industrial practice. Further study will evidently follow regarding the choice of the \( \{ \beta, \lambda \} \) trajectory and its effects on the pitch and torque look-up tables, as well as on turbine dynamics and loads.
Figure 2: Torque gain (a) and pitch angle (b) variation with derating ratio

Figure 3: Minimum pitch variation with torque and derating ratio (a) and operating torque at different derating ratios (b)

Figure 4: Minimum pitch variation with torque and reserve power (a) and operating torque at different reserve power levels (b)
Further research is also necessary regarding the fact that, at farm level, there is in fact double accounting when wakes are ignored [20]. This is due to a turbine’s power reserve being here referred to power available from incident wind, which may be in turn affected by the wakes of upwind turbines. If said upwind turbines also have power reserves, their wakes will reduce available power for the downwind turbine when the reserves are used to increase the farm’s power output, i.e. the farm’s reserve is less than the aggregate reserves of its constituent turbines. Some authors are already trying to fix this with farm control [21, 22].

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 727477

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