Design and Implementation of a Wind Farm Controller using Aerodynamics Estimated from LIDAR Scans of Wind Turbine Blades

Adam Stock, Lindsey Amos, Rui Alves and William Leithead

***Abstract*—A hierarchical Wind Farm Control (WFC) approach was previously developed that uses Power Adjusting Controllers (PACs) on each wind turbine in a wind farm. The PACs can be retrofitted to existing assets with no knowledge of, or change to, the wind turbine full envelope controller (FEC). However, knowledge of the wind turbine aerodynamics is required and is not usually directly available from the Original Equipment Manufacturer (OEM), necessitating estimation.**

In this work, estimated aerodynamic properties are obtained via a scanning LIDAR that directly measures the shape of a 2.5MW commercial wind turbine's blades. The impact of the resulting aerodynamic uncertainty on the PAC tuning and the accuracy of the change in power output from the PAC at a turbine level and at a wind farm level is assessed. It is shown that it is possible to tune a stable PAC using aerodynamic information estimated via blade scanning.

Although the requested turbine change in power suffers from some inaccuracy, the slow integral action at a WFC level causes the impact on the accuracy of the change in wind farm power output to be negligible. As such, the application of a WFC methodology utilising PACs without prior knowledge of the turbine aerodynamics is shown to be possible by using blade scanning to estimate the aerodynamic coefficients. Hence it is practical to retrofit the methodology to wind farms when aerodynamic information from the OEM is not available.

***Index Terms*—Energy Systems, Modelling, Uncertain systems**

I. Introduction

The global volume of wind energy connecting to electricity grids is increasing, creating an increasingly urgent requirement for flexibly operated assets to match supply and demand more easily in real time and to provide ancillary services from wind farms. Whilst some wind turbines and farms have some ability to alter their power output dynamically, most cannot. In particular, older assets often have very limited ability to vary power output over short time scales and the controllers of any commercial turbines that can do so are not in the public domain.

Adding the functionality required to dynamically alter a wind turbine's power output requires modification to the wind turbine's control system. The potential solutions in the literature (such as retrofitting the controllers in [1] or [2]) enable controllers to vary their power output somewhat, but require replacement of the original controller. OEMs are reluctant to allow any change to be made to their wind turbine's controllers, so a method that can be implemented as an augmentation to the existing controller and that does not alter the existing controller's performance is desirable. Such a controller has been designed, known as the Power Adjusting Controller (PAC) [3], the only controller in the literature to be designed as an augmentation to a FEC and hence suitable to be retrofitted without knowledge of the current FEC and without affecting the current FEC's efficacy.

Whilst the PAC does not require any knowledge of the wind turbine's controller, knowledge of the wind turbine aerodynamics is required; specifically the power and thrust coefficient tables, which are used in an internal model within the PAC. Prior work has always assumed the aerodynamic tables to be known, however, aerodynamic tables are rarely shared by the OEM. As such, the requirement for some method to estimate the aerodynamics of a wind turbine that provides sufficient accuracy to tune and operate the PAC and hence WFC is clear.

In the main, controllers and the linearised models used to design them presented in the literature either do not require knowledge of a wind turbine's aerodynamic coefficients or assume them to be known (e.g. [4], [5] or the linearised models generated directly from Bladed [6]). Whilst preliminary work utilising Gaussian processes to estimate wind turbine aerodynamic coefficients [7] has been conducted, it is at an early stage, and no other approaches for learning wind turbine aerodynamic coefficients are found in the literature, perhaps because controller designers typically assume the coefficients to be known. The task is non-trivial as the coefficients vary with both blade pitch angle and tip speed ratio in a non-linear manner. Methods based on data such as the aforementioned [7] have the disadvantage that, because the PAC necessitates operation away from the usual operating curve, data in some regions of operation is sparse at best. Also, many operators either do not have easy access to or do not collect the high frequency data required.

As such, in this work LIDAR scans of a commercial 2.5MW

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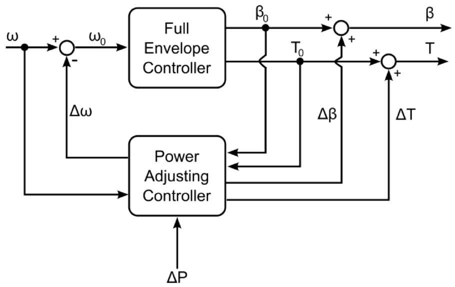


Fig. 1: The Power Adjusting Controller (PAC)

wind turbine's blades are used to estimate the geometry of the blades. Using the scanned geometry of the blades, estimates are made of the aerodynamic lift and drag coefficients for a series of aerofoil sections along the blade. The lift and drag coefficients for the aerofoil sections are then used to calculate an estimate of the power and thrust coefficients of the rotor. This method has the benefit that there is no requirement for large quantities of operational data and it can be quickly and cheaply implemented. Using these estimates the PAC is tuned for the turbine and the performance compared with the performance of a PAC tuned using known aerodynamics. The impact on both single turbine changes in power and WFC are assessed. As such, this paper gives a concise account of the innovative application of wind farm control using aerodynamics estimated from LIDAR scans of wind turbine blades.

In section II an overview of the PAC is presented. In section III the method used to scan the blades and estimate the aerodynamic coefficients is discussed. Sections IV and V discuss the impact of using aerodynamics estimated from blade scans on the accuracy of changes in turbine power and wind farm power respectively. In section VI the results of the study are discussed and conclusions drawn.

II. Overview of the Power Adjusting Controller

A short overview of the operation of the PAC is provided here, more detail can be found in [3]. The PAC (shown in Fig. 1) is designed to enable a wind turbine to flexibly alter its power output by an increment ΔP without alteration to, nor knowledge of, the wind turbine's FEC. The PAC adds a torque increment ΔT to the generator torque demand T in order to affect a change in power ΔP.

Without further alteration, if the turbine is operating in the torque control region, the increment in torque will be eliminated by an equal and opposite change in torque demand. To prevent the amelioration of the torque increment an estimate of the change in generator speed $\Delta\omega$ is calculated by the PAC and subtracted from the input to the FEC. If the torque increment and estimated change in generator speed are implemented as described then the change in power is accurate, however, the speed of the turbine changes as the aerodynamic and generator torques are not balanced. So, a change in the pitch, $\Delta\beta$ is calculated using a gain scheduled PI controller to minimise the estimated change in generator speed. Hence, the PAC makes use of the speed of torque actuation to provide fast and accurate changes in power whilst using the slower blade pitch actuators to control the slow induced change in generator speed. To correctly estimate the change in generator speed the PAC uses a simple internal model that is based on actuator disc theory and utilises power and thrust coefficient tables. It is these tables that must be estimated through blade scanning for turbines where the information is not directly available.

With power and thrust coefficients estimated, the PAC is designed in the same way as if the tables were known. Of course, any estimate of the power and thrust coefficients for the turbine will have some error that will, in turn, impact the accuracy of any change in power output.

A. *Wind Farm Control*

The PAC is designed to operate as part of a wind farm controller (WFC). The WFC is designed in a hierarchical manner whereby the wind farm power controller (WFPC) sets the desired wind farm change in power, which is sent to the wind farm distributed controller (WFDC). The WFDC uses knowledge of the operation of each wind turbine in the farm to distribute changes in power to PACs on the turbines such that the change in farm power is achieved. For many applications, such as curtailment, the WFPC includes a slow integrator within the control loop. It is hypothesised that errors in the change in power of individual wind turbines due to uncertainty in the aerodynamics will be ameliorated so that the total change in wind farm power is accurate, despite potentially inaccurate changes in power at each wind turbine.

B. *Test Methodology*

To test the hypothesis, two PACs are tuned for a wind turbine that has had its blades scanned and the aerodynamic properties estimated and for which the designed values for the aerodynamic tables are also known (referred to as the known values). The first PAC (PAC-1) is tuned using the known values. The second PAC (PAC-2) is tuned using tables estimated from blade scans. The performance of each PAC at turbine level is assessed via simulation of single turbines being requested to vary their power output. Additionally, a 10 wind turbine wind farm is simulated and the accuracy of changes in power at a wind farm level is assessed. All simulation models use the known aerodynamic values, only the aerodynamics modelled in the PAC are varied.

III. Blade Scanning Methodology

Whilst artificial errors could have been added to the known aerodynamics, the use of real data allows the validation of the blade scanning method and ensures a realistic magnitude and distribution of the errors. To obtain accurate scans of the blade geometry blade scans are completed with the turbine stopped and the blade to be scanned in the six o'clock position. All three blades are scanned from three locations to ensure good geometric overlap of the data. Each scan lasts approximately 10 to 15 minutes and collects approximately 1.2 million points per set up. The scanning device used is a Trimble SX10 that has a 3D position accuracy of 2.5mm at 100m scan distance.

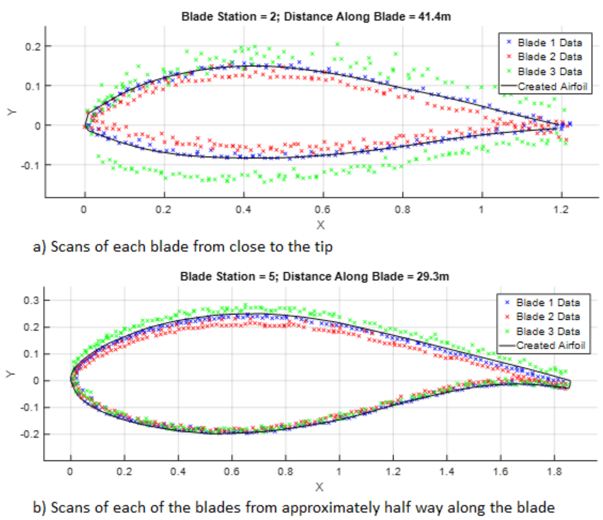


Fig. 2: Cross sections of the blade scans. Distance in units of length over chord length

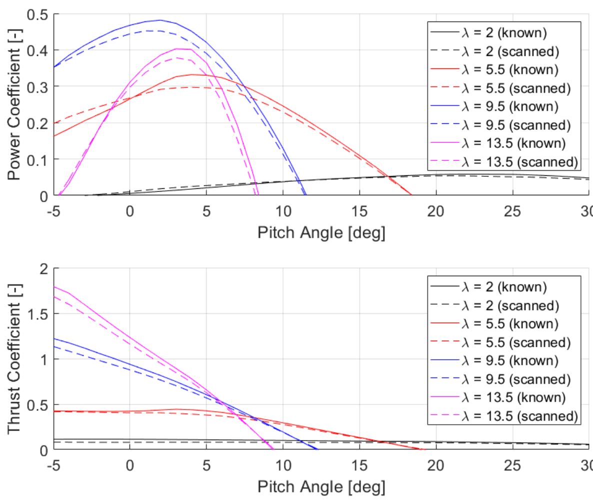


Fig. 3: Comparison between known values of the thrust and power coefficients and the values derived from blade scans

Note that the three stations are set 100 to 115m from the turbine, ensuring a good angle of incidence when collecting the data. The scanning accuracy is found to be sensitive to wind speed, as high winds cause the blade to oscillate. The scans are also sensitive to the distance along the blade, as the blade tip moves further than sections nearer the hub. Each 3D scan is ”sliced” into 12 aerofoil sections for analysis as this is a typical number of sections for an aerodynamic model to use. For example, it is same number of stations per metre as the NREL 5MW wind turbine [8]. The sensitivity of the scanning method to the number of aerofoil sections is outside the scope of this work but would be an interesting area for future work. Defining the blade stations at regular intervals is pragmatic given no prior knowledge of the blade design (i.e. the key aerofoil definition/sections of the blade). A better way of selecting the distribution of blade stations by further analysing the shape changes along the blade is outside the scope of this initial study. The reduction in accuracy with increasing wind speed and increasing distance from the hub can be seen in Fig. 2, which shows a cross section of the scans of the three blades, with the mean wind speed during the scan being 3m/s for blade 1, 6m/s for blade 2 and 8m/s for blade 3. Two sections are shown in Fig. 2. Initially, the X-Foil software package [9] is used with the section profiles directly taken from the LIDAR scans to generate lift and drag coefficients with power and thrust coefficients for the rotor hence derived. Unfortunately, using the X-Foil method results in very poor estimations of the power and thrust coefficients when compared to the known values (mean errors of the order of 25% to 35%). This could be due to a known X-Foil issue at low incident angles. Because of the poor result, the scanned aerofoil section shapes are instead compared to a set of known section shapes in a library and the lift and drag coefficients of the aerofoil that most closely matches the scanned shape are used as estimates. Note that the aerofoil sections actually used by the wind turbine are not included in the library. Fig. 3 shows a comparison of the power and thrust coefficients for the blades. In typical operating regions the power coefficient error is around 8% to 12%. Only a limited set of aerofoil sections with sufficient data regarding their lift and drag coefficients across a suitable range of inflow angles were available. A larger library of aerofoil sections, would be likely to give more accurate results.

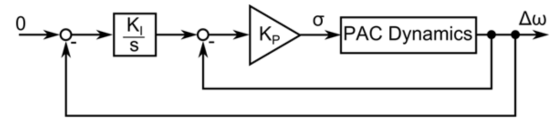


Fig. 4: Splitting of K_I and K_P for tuning

IV. Impact of Estimation Errors at Turbine Level

Whilst the PAC is designed for use as part of a wind farm controller it can also be used on a single wind turbine to adjust its power output. Using the estimates of the wind turbine’s aerodynamics introduces errors in the internal model used by the PAC and so reduces the accuracy of the change in power. In this section the impact of the induced aerodynamic uncertainty is quantified. Other turbine variables (such as rotor radius, rotor inertia, electrical losses) are also required to tune the PAC, however, these values are all either measurable or available for the majority of wind turbines and are therefore assumed to be known.

A. Tuning of the Power Adjusting Controller

The PAC must be tuned for the wind turbine it is used on. The PAC uses thrust coefficients to calculate an estimated wind speed $\hat{V}$, which is used alongside the power coefficient tables to derive an estimate of the change in aerodynamic torque caused by the PAC. Hence, the aerodynamic coefficient tables play a key part in the tuning of the PAC. Two PACs are tuned, one using known aerodynamics (PAC-1), and one using the PAC tuned with the estimated aerodynamics (PAC-2). The PAC is tuned using a linearised model of the PAC and wind turbine, detailed in [3]. The pitch controller, in the form of a gain scheduled PI controller, must be tuned in order to ensure the system is stable whilst minimising pitch actuator duty. The pitch controller is decomposed into integral and proportional gains in Fig. 4). In order to avoid feedback around the FEC, the closed loop system bandwidth must be kept low. In doing so, the duty on the pitch actuator will also be kept low. Typically the aim is to keep the rate of change of $\Delta\beta$ below 0.5 deg/s for most operating conditions but high enough to prevent large changes in rotor speed. Often this can be achieved with a bandwidth just above 1 rad/s. The PAC dynamics include the turbine aerodynamics and so the estimated tables must be used when tuning the PAC for PAC-2. In some operating conditions the open loop system is unstable, so two steps are used in the PI controller design, using an outer and inner feedback loop (see Fig. 4). First, closed loop stability is achieved through adjustment of the proportional gain to the minimum gain K_P that achieves stability. The inner feedback loop is then closed and the integral gain set. Whilst K_I is kept low to minimise pitch actuation, too low a value allows generator speed changes caused by the PAC, $\Delta\omega$, that are too high. Note that the bandwidth of the closed outer feedback loop is much less than the inner feedback loop. Because the relevant input to the system in Fig. 4 is zero, H(s) is simply,

$$K_P + (K_I K_P)/s \tag{1}$$

The Bode plot of the transfer functions for the open loop system for the wind turbine with known and scanned aerodynamic values are shown in Fig. 5a and Fig. 5b respectively. At lower wind speeds unstable poles are present, with the highest frequency for an unstable pole occurring at rated wind speed. Hence, the design of the controller is first conducted at rated wind speed. It is interesting to note that at 7m/s there is considerable difference in the phase for the known and uncertain aerodynamic cases as a pole in the system must have just crossed to the LHP, however at the important rated wind speed the difference is less. To achieve stability the proportional gain of the inner loop is set to 0.07 for PAC-1 and 0.10 for PAC-2. The integral gain in the outer loop is set to 0.10 for PAC-1 and 0.28 for PAC-2.

The system dynamics at rated wind speed whilst closed loop with proportional gain, and closed loop with proportional and integral gain are shown in Fig. 5c. The bandwidth of both systems is similar at 1.4rad/s. The proportional control loop stabilises the system whilst the integral gain is sufficiently high to limit the excursions in $\Delta\omega$ and low enough to keep the rate of change of $\Delta\beta$ low when the PAC is used. Both gains are higher for PAC-2. The higher proportional gain is partly due to both the difference in the modelled aerodynamics and a cautious approach to tuning to ensure stability. The same closed loop bandwidth is set for PACs for rated wind speed and so the larger integral gain is entirely due to the difference in aerodynamics. The bandwidth of the closed loop system varies with wind speed. To maintain a set bandwidth across all wind speeds, gain scheduling is required with the output of the controller multiplied by a gain K_{GS} where,

$$K_{GS} = \frac{k(\hat{V})\omega_{rated}^2}{\omega^2} \tag{2}$$

$k(\hat{V})$ is dependent on the estimated wind speed, which is calculated using the thrust coefficient tables. This, along with the difference in the linearised models used for tuning, makes the gain scheduling of PAC-1 and PAC-2 different.

Fig. 6a shows the closed loop system for a range of wind speeds using PAC-1 tuning and PAC-2 tuning. The bandwidth in both cases is similar for all wind speeds. In Fig. 6b, PAC-2 is applied to the PAC-1 model (with known aerodynamics). The bandwidth is larger than the designed bandwidth and the spread across different wind speeds is also larger. The PAC therefore uses more pitch actuation than designed and the speed of the pitch response will vary with wind speed.

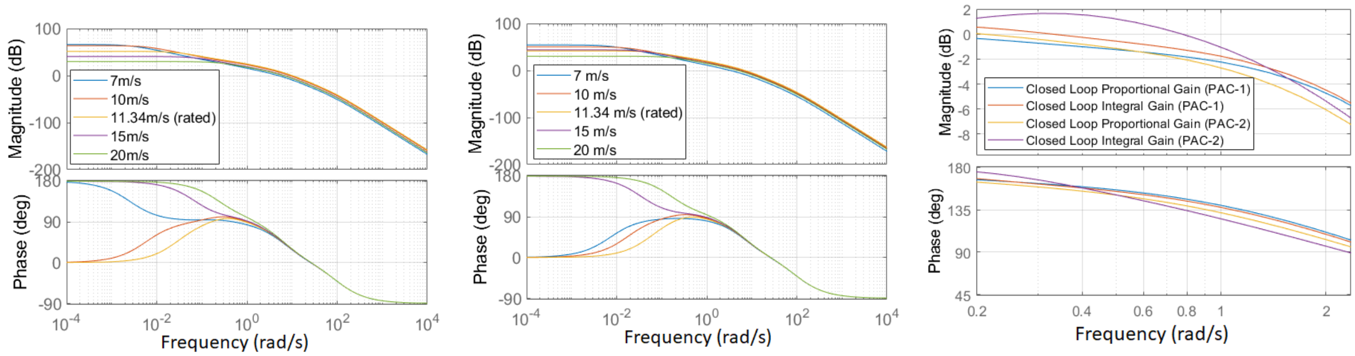
B. Comparing Results

DNV GL Bladed simulations are conducted to quantify the impact of aerodynamic uncertainty on performance. Simulations use constant wind speeds for clarity, with a series of step changes in power output requested using PAC-1 and PAC-2. Similar StrathTurb simulations are conducted. Table I shows a comparison of the steady state error in requested change in power. Both models use the same controller code for both the PAC and FEC (based on [10]) for easy comparison of performance. Note there is a small difference in power output for a given wind speed between Bladed and StrathTurb, as Bladed does not include losses due to damping in the drive-train. Whilst StrathTurb simulations produce a slightly lower maximum error, the magnitude of error in performance of each PAC tuning is clearly similar using both models. Hence, StrathFarm simulations, which use a StrathTurb turbine model for each turbine in the farm, are similarly valid. Fig 7 shows the StrathTurb results.

Wind Speed	8m/s		10m/s		11m/s		13m/s	
Simulation	ST	B	ST	B	ST	B	ST	B
PAC-1 (ΔP = 125kW)	1.2	3.4	0.0	0.2	0.2	0.5	0.2	1.4
PAC-2 (ΔP = 125kW)	6.0	10.5	5.6	7.0	-8.5	-8.3	0.2	1.4
PAC-1 (ΔP = 250kW)	1.5	1.6	0.9	0.7	0.8	1.1	0.1	0.7
PAC-2 (ΔP = 250kW)	5.2	6.4	4.9	4.7	-7.3	-7.3	0.1	0.7
PAC-1 (ΔP = 375kW)	1.8	1.1	1.0	0.5	1.0	1.4	0.1	0.5
PAC-2 (ΔP = 375kW)	4.0	4.3	4.1	3.6	-5.6	-5.4	0.1	0.5

TABLE I: % Steady state error of DNV GL Bladed (B) and StrathTurb (ST) Simulations for a range of wind speeds

PAC-1 performs well, the error in change in power is below 3% in steady state using Bladed and below 2% using StrathTurb. As expected, PAC-2 performs less well, with a steady state error between -8.5% and 6.0% with StrathTurb and between -8.3% and 10.5% with Bladed. In above rated wind speeds the error is closest to zero in both cases, as the FEC

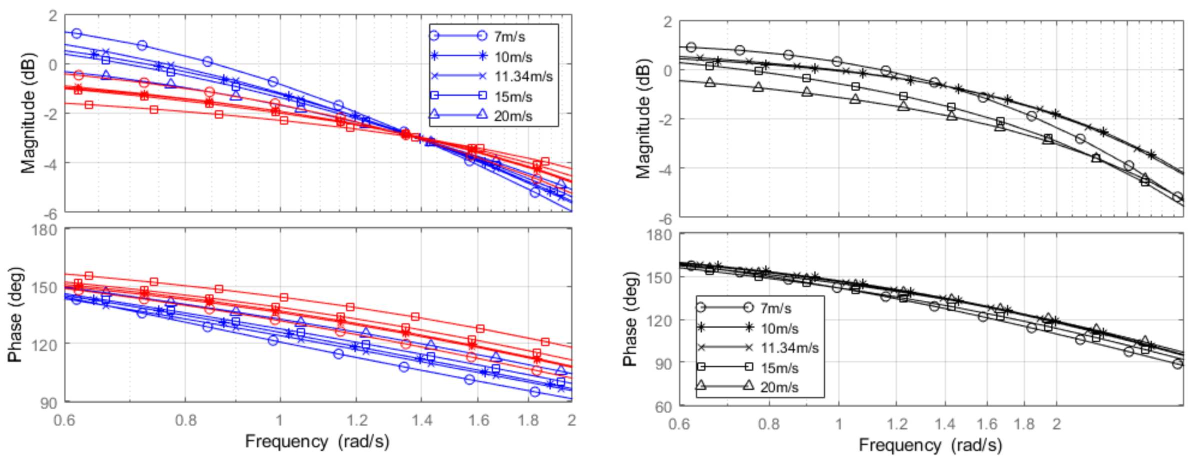


(a) Open loop plant Bode plot - known aerodynamics (PAC-1)

(b) Open loop plant Bode plot - uncertain aerodynamics (PAC-2)

(c) Closed loop Bode plots for PAC-1 and PAC-2 - Zoomed for detail

Fig. 5: Bode plots using both the known and uncertain aerodynamics for a range of linearised wind speeds



(a) PAC-1 in red and PAC-2 in blue for a variety of wind speeds

(b) PAC-2 applied to the known aerodynamics model

Fig. 6: Closed loop gain scheduled Bode plots using both the known and uncertain aerodynamics for a range of linearised wind speeds

operates using pitch angle control. Errors in $\Delta\omega$ are hence treated as disturbances to the system and ameliorated by FEC pitch action.

V. Impact of Estimation Errors at a Wind Farm Level

A. Modelling for Wind Farm Simulation

To model the wind farm, the University of Strathclyde StrathFarm model is used. StrathFarm uses StrathTurb wind turbine models that incorporate lumped parameter models of the drive-train and rotor, aerodynamic modelling (including induction lag) and coupled models of the blades and tower. StrathFarm is discussed in more detail in [11].

B. Simulations of Wind Farm Curtailment

10 wind turbines arranged in an offset grid are simulated. A simple WFPC is designed to curtail the wind farm power output to a set value. The WFPC calculates a change in farm power output ΔP_{Farm} using a simple PI controller, with proportional gain K_{pWf} and integral gain K_{iWf}, that minimises the error (ϵ) between the desired farm output (P_d) and the measured farm power (P_m),i.e.,

$$\epsilon = P_d - P_m \tag{3}$$

$$\Delta P_{Farm} = \epsilon(K_{pWf}s + K_{iWf})/s \tag{4}$$

$K_i = 0.15$ and $K_p = 0.80$. A simple WFDC distributes the changes in power equally between available turbines. Available turbines are those that are within a defined safe operational zone with estimated wind speeds above 6.5m/s.

C. Impact of Aerodynamic Uncertainty on Wind Farm Control Performance

Simulations are conducted with PAC-1, with PAC-2 and with no WFC. Mean wind speeds of 8m/s, 10m/s, and 16m/s with 10% turbulence intensity are used. The wind farm power output is curtailed to just below the minimum output of the non-curtailed simulation.

Fig. 8 shows that there is little difference in the performance of the WFC when using PAC-1 or PAC-2. The power output

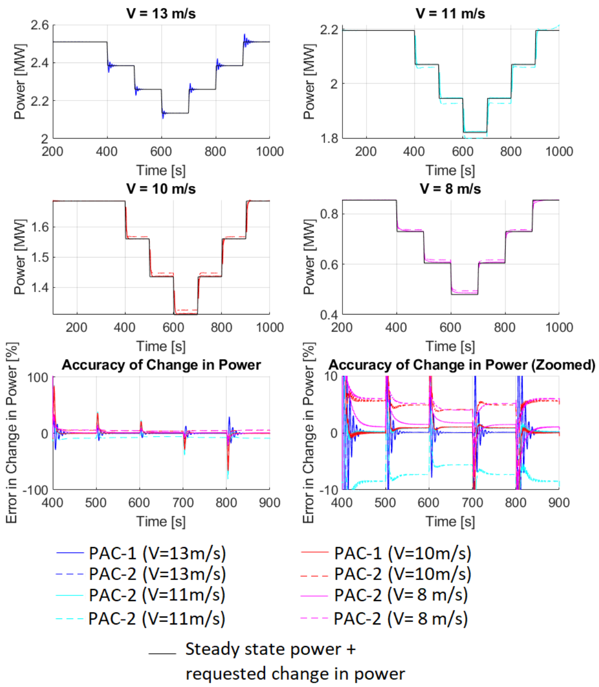


Fig. 7: Performance of the PAC-1 and PAC-2 for a series of step changes in power. Note PAC-2 (V=13) is almost identical to PAC-1 (V=13)

error at turbine level discussed in section IV is seen as a disturbance to the system by the WFPC and, due to the integral action, the error is minimised.

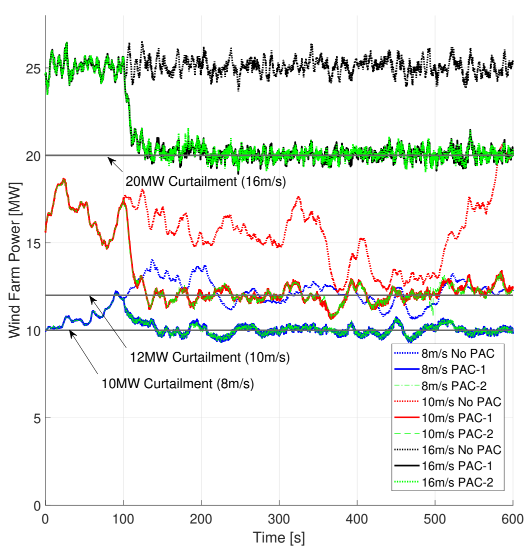


Fig. 8: Power outputs with no WFC and using WFC with PAC-1 and PAC-2 for wind speeds of 8m/s 10m/s and 16m/s

VI. Discussion and Conclusions

A wind turbine's blades were LIDAR scanned and hence aerodynamic tables were derived. The estimated power and thrust coefficients are approximately 10 to 12% inaccurate in the typical wind turbine operational regions. Using scanned aerodynamics during tuning does not prevent a stable PAC from being tuned, however, the PAC bandwidth and associated pitch actuator duty varies with wind speed. Once deployed on a wind turbine it may be possible to fine-tune the PAC gains to alleviate these issues. At wind turbine level, the aerodynamic uncertainty reduces the accuracy of the change in power compared to the requested change in power. Errors at turbine level can be up to 10.5% using the scanned aerodynamics compared to a maximum of 3.5% using known tables. However, when the PAC is used with a WFC with an integrator in the control loop, WFC performance is similar using both known and scanned aerodynamics. Scanning wind turbine blades using LIDAR in order to tune augmented controllers suitable for WFC clearly shows good potential, and the WFC produced is shown to operate well despite the aerodynamic uncertainties. Further work can build on this concise account of the innovative application of design and implementation of a WFC using aerodynamics estimated from LIDAR scans of wind turbine blades. In particular, the impact of uncertainty on PAC tuning safety margins, methods for greater accuracy of aerodynamic estimates and the impact on WFC strategies other than curtailment are areas of interest.

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