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Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions

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Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions

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Abstract. With increasing levels of electrical energy generated by intermittent sources such as wind turbines, their participation in grid ancillary services is becoming a necessity. Typically, all generated energy from variable generators is absorbed by the electric grid and balancing is left to traditional generators. Wind turbine technology has matured to the level where a large wind generator is capable of providing ancillary services such as up- and down- active power regulation (secondary frequency regulation). The up-regulation capacity of a variable generator is constrained primarily by external factors such as the prevailing wind speed in the case of a wind turbine. This work uses the Wind Energy Institute of Canada's (WEICan) 10 MW Wind R&D Park (Type 5 generators) in Prince Edward Island, Canada, to test and evaluate a simple algorithm to provide up- and down-regulation services from a wind park. The developed algorithm uses a 10-minute averaged wind speed to estimate the available park generation potential. A fixed power curtailment is applied to provide room for up-regulation. An historical, external AGC signal is then applied to the wind park's active power set-point and the resulting park performance is evaluated. Results of the 4.5 hour test prove the technical capability of the wind farm in participating in the regulation market. A performance score of 64 % was calculated according to the PJM method, averaged across the test duration.

1. Introduction

Wind energy and other intermittent renewable sources (such as solar PV) are increasingly being used throughout the world to generate electricity. Electrical energy production from wind in some jurisdictions has increased to supply a significant percentage of their annual consumption. For example, in 2017 Spain, Germany, and Denmark produced 18%, 21%, and 43% of their annual electrical demand from wind power [1], [2], respectively. In Spain wind power supplied 60.7% of the demand at one specific moment [1].

The operation of any power system involves balancing generation and load, which has traditionally been done with conventional, synchronous generators. Traditional generators have been used for energy production as well as providing additional grid functions such as regulation of grid frequency or voltage [3]. Collectively, these services are referred to as ancillary services [4]. Providing ancillary services such as regulation from intermittent renewable energy sources is uncommon. As wind and solar displace traditional generators they, or other sources such as storage, will be required to provide ancillary services. The grid rules in high wind penetration regions require that turbines accept active and reactive power set-points as well as active power



ramp rate limits. Wind turbines are capable of changing their active power output in response to several factors. One set of factors is meteorological and includes changes in wind speed. This is not strictly a controlled response as the maximum power production is limited by the prevailing wind speed. A second set of factors is grid conditions such as grid frequency changes. Turbines respond through means such as power-frequency response curves [5]. This is typically done to satisfy grid requirements. A third set of conditions are in response to external set-points such as network operator limits or automatic generation control (AGC) signals. Often, network operators enforce maximum power export limitations on wind farms. As an example of wind generation being limited, in 2016 in Ireland, 2.9% of the available wind energy production was curtailed [6] in response to local transmission constraints and bulk system limitations. Although all new wind farms in Ireland (and several other jurisdictions) are required to respond to external power set points, few, if any, use this capability to provide secondary frequency regulation (AGC).

Frequency changes on the grid are a good representation of the balance between supply and demand. The response of the grid frequency to events such as load or generation changes can be divided into regions such as primary, secondary and tertiary response as shown in Figure 1 which is based on [7]. AGC is a means of secondary frequency regulation and is achieved by temporary increases (regulation-up) or decreases (regulation-down) in generator active power output. Regulation-up and regulation-down services are sometimes collectively referred to as regulation services (Reg-services for short) [8]. Regulation is done on a time scale faster than the fastest market clearing schedule and is used by system operators to meet performance standards (e.g. NERC). These standards are typically based on time averages of a balancing areas' Area Control Error (ACE). Area Control Error is the difference between the scheduled and actual electrical generation within a control area on the grid while accounting for frequency bias and power exchanges [9]. AGC is one method of providing Reg-services using generators that can respond to fluctuations in the MW/min range [7]. The dispatch centre monitors and controls generators across the power system to balance generation and load thereby maintaining a constant system frequency [9]. The AGC signal is derived from the ACE signal and is sent as a regulation signal to Market Participants' or Qualified Schedule Entities' AGC controllers. In essence, if system frequency falls below the target value (60 Hz), the AGC system sends a Reg-Up signal, calling for an increase in active power generation. Conversely, if system frequency increases above the target value, the AGC system sends a Reg-down signal to reduce generation.

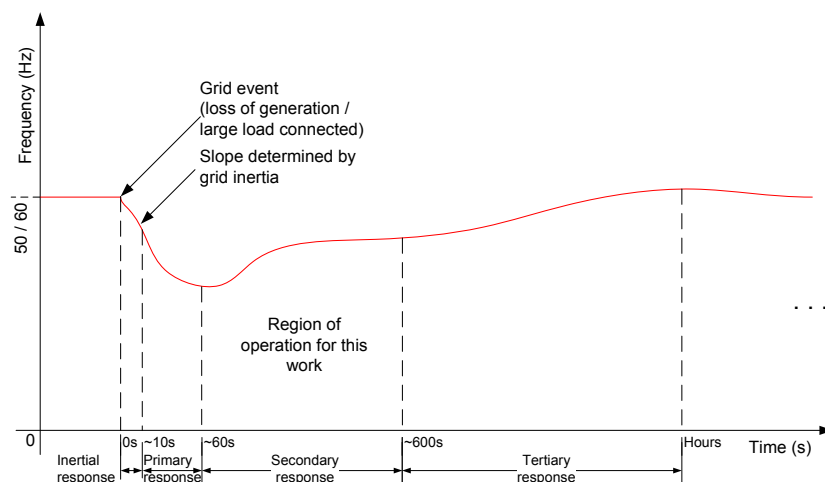


Figure 1: Types of frequency control [7]

Providing AGC through a wind turbine has been investigated on an NREL CART3 600 kW

turbine in [10] where reasonable accuracy is shown between the produced power and the target. As discussed in [11] either a delta strategy (% of available power) or a fixed reserve can be used as to provide the base power upon which to add the system operators AGC signal. In this investigation a fixed reserve of 1 MW was used while the wind park was generating between 1 MW and 10 MW (rated farm power). The fixed reserve of 1 MW represents 10% of rated farm power and is chosen to be consistent with previous tests performed with the same turbines [12].

1.1. Technical Objective

The objective of this investigation is to test the ability of a wind farm to provide secondary frequency regulation in order to understand the technical challenges and limitations of providing this service from a wind farm. This work demonstrates the potential of a wind farm to provide AGC in a manner similar to a conventional generator. We use a power set-point update frequency of 4 seconds. This contrasts with typical wind turbine curtailments which do not change for minutes or hours. This work builds upon [12] and examines providing AGC in the region between cut-in and rated wind speed (see Figure 5).

1.2. Test Site Information

This test is performed at the Wind Energy Institute of Canada's 10 MW Wind R&D Park located in Prince Edward Island, Canada. It has 5 DeWind D9.2 turbines, each of which have a 2 MW rating, 93 m rotor diameter and a hub height of 80 m. They are unique turbines in that they have a synchronous generator that is directly grid connected. The generator is connected to the variable speed rotor through a hydraulic torque converter (Voith WinDrive) and a two-stage gearbox [13]. It is considered a Type 5 wind generator [14]. The generators generate at 13.8 kV, which is stepped-up to 69 kV to tie into the local network. The wind park has an active power set-point target and a voltage set-point target, both of which are controlled by the local utility. During the testing period, the voltage set-point target was constant at 71.0 kV and the active power set-point target was varied. The active power set-point was disconnected from utility control and was updated every 4 seconds.

2. Algorithm Methodology and Formulation

2.1. Algorithm

An overview of the implemented algorithm is presented in Figure 2. We begin by using a 10 min rolling average of the hub height wind speed measured at each turbine. The averaging is done by the turbine's control system. The averaged values are read on a SEL RTAC 3530 controller via DNP3. Here, these are used to estimate the power available at each turbine. The theoretical power is the power that each turbine is capable of generating at any instant of time based on the prevailing wind speed. The estimation is done using a power curve. A power curve for each wind turbine is determined based on the historical nacelle wind speed and power production data. This is done to avoid errors when using the manufacturer's design power curve (free-field wind speed versus measurements down wind of the rotor). Between cut-in and rated wind speeds, the power curve is modeled by a second order polynomial fit to data from December 2017 and January 2018. The averaged wind speed value is used with each turbine's power curve to estimate the power production. The sum of these powers across the wind park produces the "theoretical power" value (Figure 3 (b)).

To accommodate the regulation bid (1 MW), half the regulation bid value is subtracted from the calculated theoretical power. This creates room for 0.5 MW of up-regulation. This produces the baseline power value (See Figure 2 and Figure 3). We provide regulation in the range of 1 MW to 10 MW of net park power. Below net park power levels of 1 MW, the AGC signal is ignored. In the regulation range of 1 MW to 10 MW, we provide 1 MW of AGC room, i.e. 500 kW of up-regulation and 500 kW of down-regulation.

The historical AGC signal data is read from a CSV file by a simple LabVIEW script. This script runs on an independent computer that acts as a MODBUS server. The AGC signal is sent to the RTAC via MODBUS. This AGC value is summed with the baseline power value to produce the park MW set-point value (Equation 1). The AGC signal acts as a bias value for the baseline power value. This value is sent from the RTAC to the DeWind park control system via DNP3. A closed loop power controller is implemented in the DeWind park controller, which distributes the park power set-point across the turbines. We do not control the active power setpoints for individual wind turbines.

$$\text{Park power target} = \text{Theoretical power} - 500 \text{ kW} + \text{AGC Local} \quad (1)$$

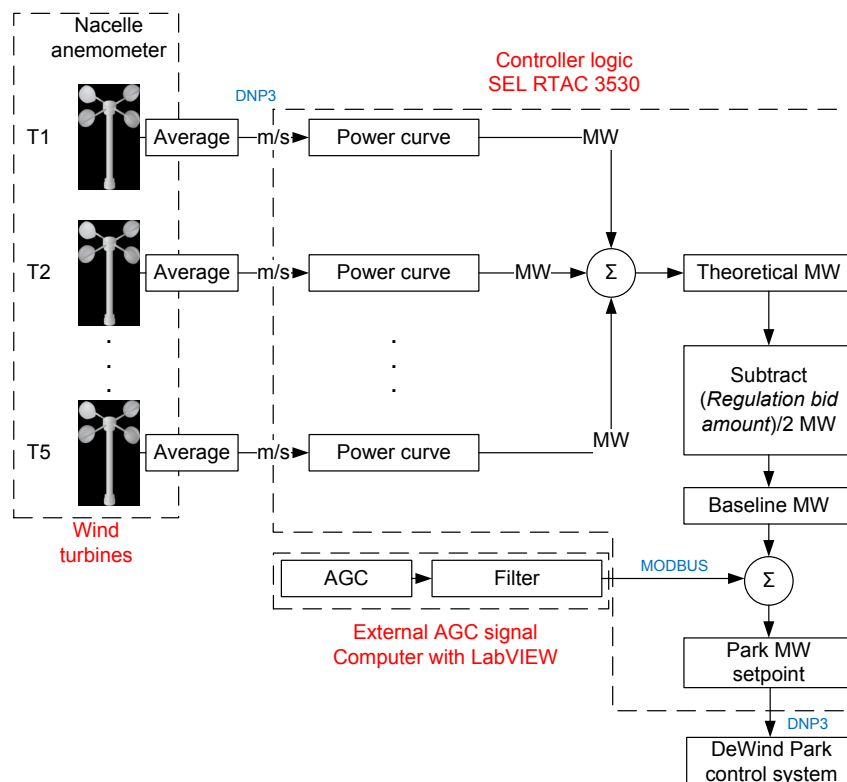


Figure 2: Developed curtailment algorithm

2.2. Historical AGC Signal and regulation room

This work uses a 4.5 hour (270 minute) AGC signal (in MW) extracted from historical data provided by the Alberta Electric System Operator (AESO). A new AGC set-point is calculated and generated every 4 seconds. It is important to emphasise that this AGC signal did not have any correlation with prevailing meteorological or grid conditions during the test. AESO send a time-varying AGC signal to generators over and above an energy dispatch value (MW). The energy dispatch value is relatively constant. As illustrated in Figure 3, the key difference in the interpretation of the regulation room in the case of variable generators is in the changing energy dispatch level—the dashed red line in Figure 3 (a). This figure illustrates how the energy dispatch level translates to this work. This variation is a consequence of the power output of a wind farm being dependent on a variable input (wind speed).

This work uses a 1 MW regulation market offer. This translates to a maximum power change of 0.5 MW above or below the calculated “baseline power” at any given time (See Figure 3).

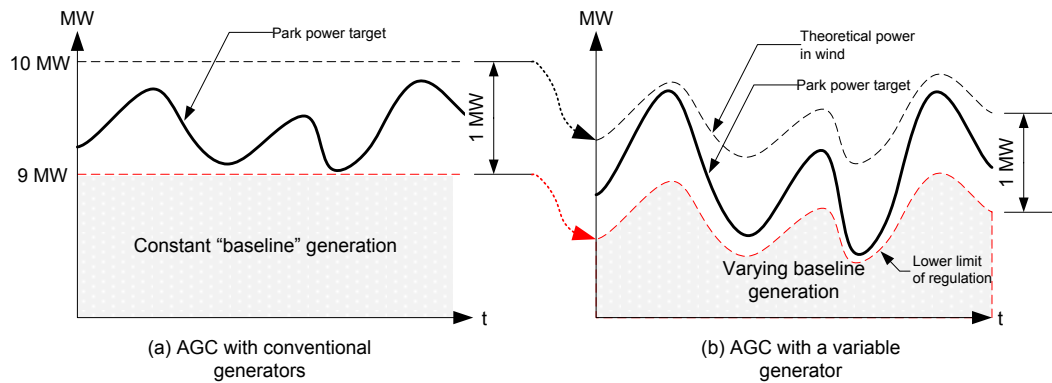


Figure 3: Difference in the appearance of AGC regulation room in a conventional generator (a) versus a variable generator (b)

2.3. AGC signal scaling and filtering

The AGC signal is extracted from the AGC MW set-point by subtracting the energy dispatch value. This AGC signal is then scaled to fit in a 1 MW range using a scaling factor. The signal maximum and minimum were set to +0.5 MW and -0.5 MW respectively. The result of this is shown in Figure 4 (blue plot).

The scaled & limited AGC signal cannot be applied directly to the wind park for several reasons. Primary among these is the stochastic nature of the park power output. This could result in drowning out the effect of the AGC signal change if the change in prevailing wind speed produces a greater change in the park power output. Other factors include the finite response time of the park controller, turbines response time and communication delays.

To avoid repeated, small changes to the park power target, a differential magnitude filter is implemented. The filter output changes only when the difference between the new AGC set-point value and the existing value is greater than 100 kW as shown in Equation 2. The 100 kW value for Δ_{filter} was determined through empirical evaluation.

$$\begin{aligned} & \text{if } |x[n] - x[hold]| > \Delta_{filter} \\ & \quad \text{then } y = x[n] \\ & \quad \text{else, } y = x[hold] \end{aligned} \quad (2)$$

The AGC signal before and after filtering is shown in Figure 4. It is important to note that the filtered AGC signal shown in Figure 4 is not used for performance score calculations. Signal filtering is performed internally and is not seen by the network operator. Performance score calculations must be done using the network operator's AGC signal. In this case, this is the scaled and limited signal as shown in Figure 4.

2.4. Operating region of the wind turbines

This work seeks to demonstrate that a wind park can be used to provide regulation services when operating below rated power. This is in continuation to the work in [12], which performed a similar test but with the wind turbines operating at rated power. These two situations are contrasted in Figure 5. The result of operating below rated power is that the output of the wind farm is not steady at 10 MW but varies depending on the prevailing wind speed. The "theoretical power" thus calculated is constantly varying.

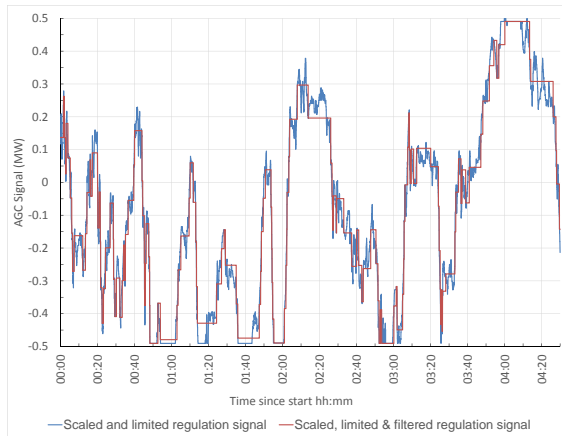


Figure 4: Historical AGC signals and filtered AGC signal as used for park power setpoint

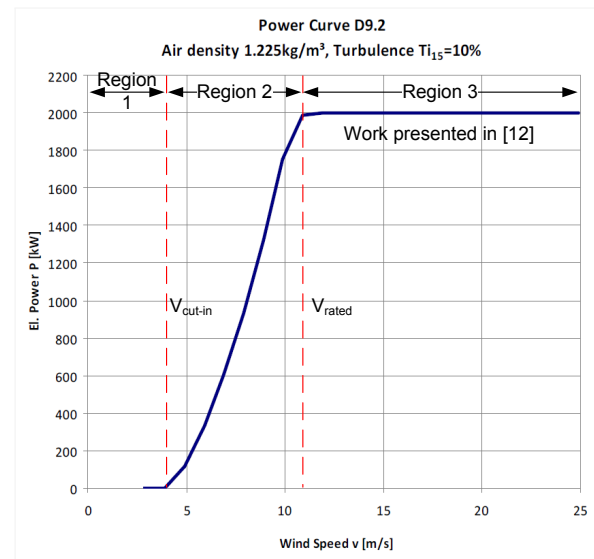


Figure 5: Turbine operating region of this work (Region 2) versus that of [12] (Region 3)

Table 1: Experiment statistical summary

	AGC local filt. (kW)	Power Park Target (kW)	Net park power (kW)	Power Error (kW)	Abs. Power Error (kW)	Pitch T1 (°)	Pitch T2 (°)	Pitch T3 (°)	Pitch T4 (°)	Pitch T5 (°)	T1 Pow. (kW)	T2 Pow. (kW)	T3 Pow. (kW)	T4 Pow. (kW)	T5 Pow. (kW)
Max.	490	6366	6877	1381	1899	13.1	12.0	12.9	12.8	11.8	1805	2040	2023	1728	1942
Avg.	-79	4058	4059	1	235	2.7	4.4	4.2	3.6	3.7	802	830	845	818	825
Min.	-490	1553	1593	-1899	0	0.7	0.8	0.7	0.7	0.7	90	219	258	41	173

3. Results

The test was performed on March 7th, 2018 from 12:00 until 16:30 during a period when the 10-minute average wind speed ranged from 6.7 to 9.5 m/s. This is between the cut-in wind speed of 4.5 m/s and the rated wind speed of 10.5 m/s. A statistical summary of the experiment period is presented in Table 1 where it is important to note that this 4.5-hour test had a range of net park power from 1600 kW to 6800 kW, which is half of the entire 0 to 10 MW range of the wind park. Figure 6 shows the test results as a time series.

3.1. Park Performance Scores

A performance score quantifies how well the generator's output follows the AGC signal. There are multiple methods to calculate the performance score. We use two different methods to calculate the performance score. Results from both methods are summarised in Table 2 and the two methods are detailed below.

3.1.1. NRC Method The first performance scoring method used is the National Research Council Canada (NRC) method developed for AESO conventional generators [15]. This method

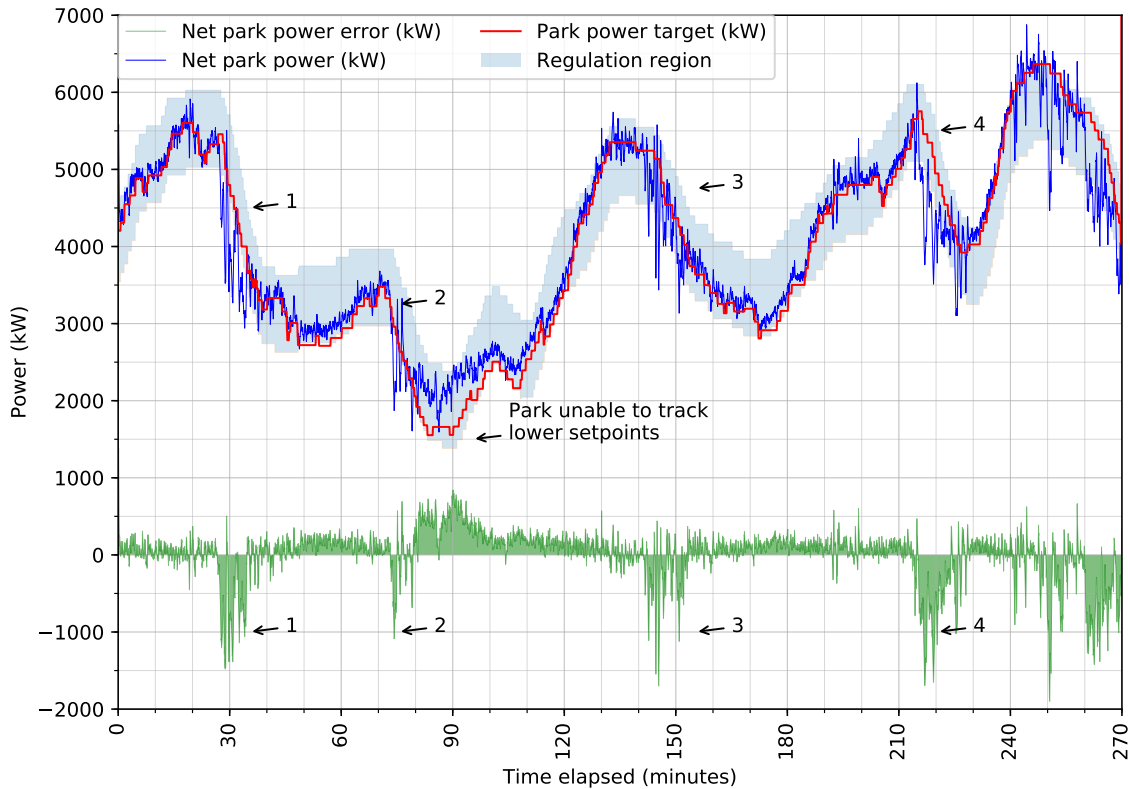


Figure 6: Results from experiment. Numbered points indicate instances of decreasing average wind speeds.

Table 2: Performance score comparison with other technologies [15] [16]

	NRC η	PJM η
Coal	67%	76% (Reg A)
Hydro	86%	78% (Reg D)
Gas	75%	91% (Reg D)
Energy Storage	-	92% (Reg D)
This work ^a	28%	64%
Rated Power ^a [12]	94%	74%

^aPJM reg signal not used

is based on that developed in [17]. The performance score (η) is between 0 and 1 with 1 being perfect performance. To begin, we first calculate a value of δ which is a ratio of two sums. The numerator sum is the deviation of the net park power from the AGC setpoint for each 2 second interval. The denominator sum is the deviation between the economic dispatch value and the AGC setpoint. This is shown in Equation 3 [15].

$$\delta = \frac{\sum_t |AGC \text{ setpoint} - Net \text{ output}|}{\sum_t |AGC \text{ setpoint} - Economic \text{ dispatch}|} \quad (3)$$

Converting Equation 3 to our terminology results in Equation 4 where (*Theoretical power – Regulation bid*) represents the lower limit of regulation. In our case, the lower limit of regulation is equal to the economic dispatch value.

$$\delta = \frac{\sum_t |Park\ Power\ target - Net\ park\ power|}{\sum_t |Park\ Power\ target - (Theoretical\ power - Regulation\ bid)|} \quad (4)$$

The Performance Score is then calculated with a sigmoid function of δ . The best performance is when the net park power is equal to the park power target, which would result in $\delta = 0$ and $\eta = 1$.

$$\eta = \frac{erfc(a \cdot \delta - b)}{erfc(-b)} \quad (5)$$

Where $erfc$ is the complementary error function and a and b are 3.0 and 1.25 as in [15].

We calculate an NRC performance score of 28% for our test. The performance scores at different net park powers is shown in Figure 7 for this test period along with the results from [12] (full power operation). The dashed line indicates power ranges where data is not available. Note how quickly the performance improves for power levels above 4000 kW.

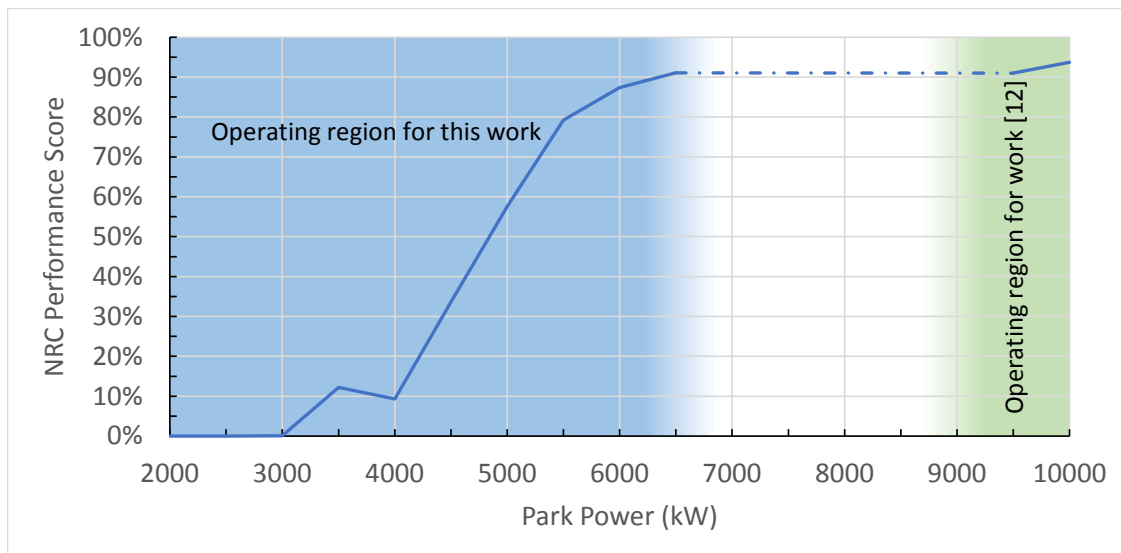


Figure 7: NRC performance score collated across this work and [12]

3.1.2. PJM Method The second performance scoring method is that of PJM (Pennsylvania-New Jersey-Maryland). PJM's performance score calculation method [18] [19], is the average of three performance metrics: Accuracy, Delay, and Precision. A performance score for each of the five hours of the test was calculated. The last hour had only 30 minutes. The weighted average of each hour's performance scores was calculated to find the PJM performance score for the test period resulting in a net performance score of 64%. The values of Unit AREG and Fleet TREG were set to 0.5 MW and a park ramp rate of 32 MW/min was used. The results are in Table 3.

3.1.3. Performance Summary As shown in Table 2, the net performance score calculated according to the NRC method is 28%. This is in contrast to the 94% reported in [12]. The reason for this difference is the amount of time spent in the low power range (< 4000 kW) and the large error when the wind speed was decreasing (See Figure 6). This is a consequence of the NRC score being based entirely on precision. The PJM method has a lower weighting for

Table 3: Hourly PJM Performance scores over test period

Hours	1	2	3	4	5	Weighted avg
Accuracy Score	0.63	0.75	0.53	0.62	0.57	62.8%
Delay Score	0.92	0.92	0.90	0.92	0.75	89.9%
Precision Score	0.43	0.37	0.46	0.32	0.25	38.3%
Composite Score	0.66	0.68	0.63	0.62	0.53	63.7%

precision [18] and therefore, the difference between the rated power test (calculated from [12] data) and this test's results is not as stark.

Based on the results presented in Table 2, the net NRC performance score implies that a wind park is not effective at providing secondary regulation. This would appear to be a consequence of the wind park operating below 4000 kW for 46% of the test period. The turbine technology results in poor accuracy in this region, as seen in Figure 7. It is evident that performance improves as the wind park's power output increases. Although the PJM performance score is below that of traditional generators, some of the difference can be explained as above. One limitation of our results is limited data with which to calculate performance scores. The solution would be to perform a longer duration test over the whole park power range. This test will produce more data to calculate performance scores at each power level. These performance results can be used to restrict participation in the secondary regulation market to when the performance score is acceptable.

3.2. Examining performance scores

This section examines the reasons for poor performance scores at low power levels and when the wind speed is decreasing. Both explanations rely on Figures 6, 7 and 8.

3.2.1. Poor performance at low power levels As visible in Figure 6, the net park power follows the park power target closely but deviates during a few intervals when the power error is significant. From Figure 7, the effect of the power error on the performance score is most noticeable at park power levels below 4000 kW. Figure 8 presents one hour of the test and focuses on blade pitch angles and individual power outputs for two turbines. Data from two turbines is used for simplicity but the inferences made here are valid for all five turbines. Observe the large difference in the park power target and the park net power in Figure 8 (a) - Region II where the generated power is greater than the target power. This would indicate that a lower limit of curtailment has been reached. As visible in Figure 8 (c), the turbines do not curtail their individual power outputs to below 500 kW, resulting in a large, positive power error. Observe also that the turbine power reduces to below 500 kW only when the wind speed is insufficient to produce 500 kW. When the wind speed permits, each turbine's power output is actively controlled to a minimum of 500 kW by the pitch system. This is visible in Figure 8 (b), Region II. The rotor speed stays almost constant over the entire period presented in Figure 8. It is unclear why the turbines do not curtail their active power outputs to below 500 kW. This lower curtailment limit applies to each turbine individually and not the park as a whole. Each turbine sees a different instantaneous wind speed and reaches this 500 kW limit independent of the other turbines. This causes the net park power error to increase below 4000 kW and not simply 2500 kW (5×500 kW). A possible solution is to limit the active power region in which the wind park participates in the regulation market.

3.2.2. Poor performance during periods of decreasing wind speed The theoretical power is based on the 10 min average wind speed. The averaging process acts as a filter and adds a delay between the instantaneous and average trends. When the instantaneous wind speed drops, the power

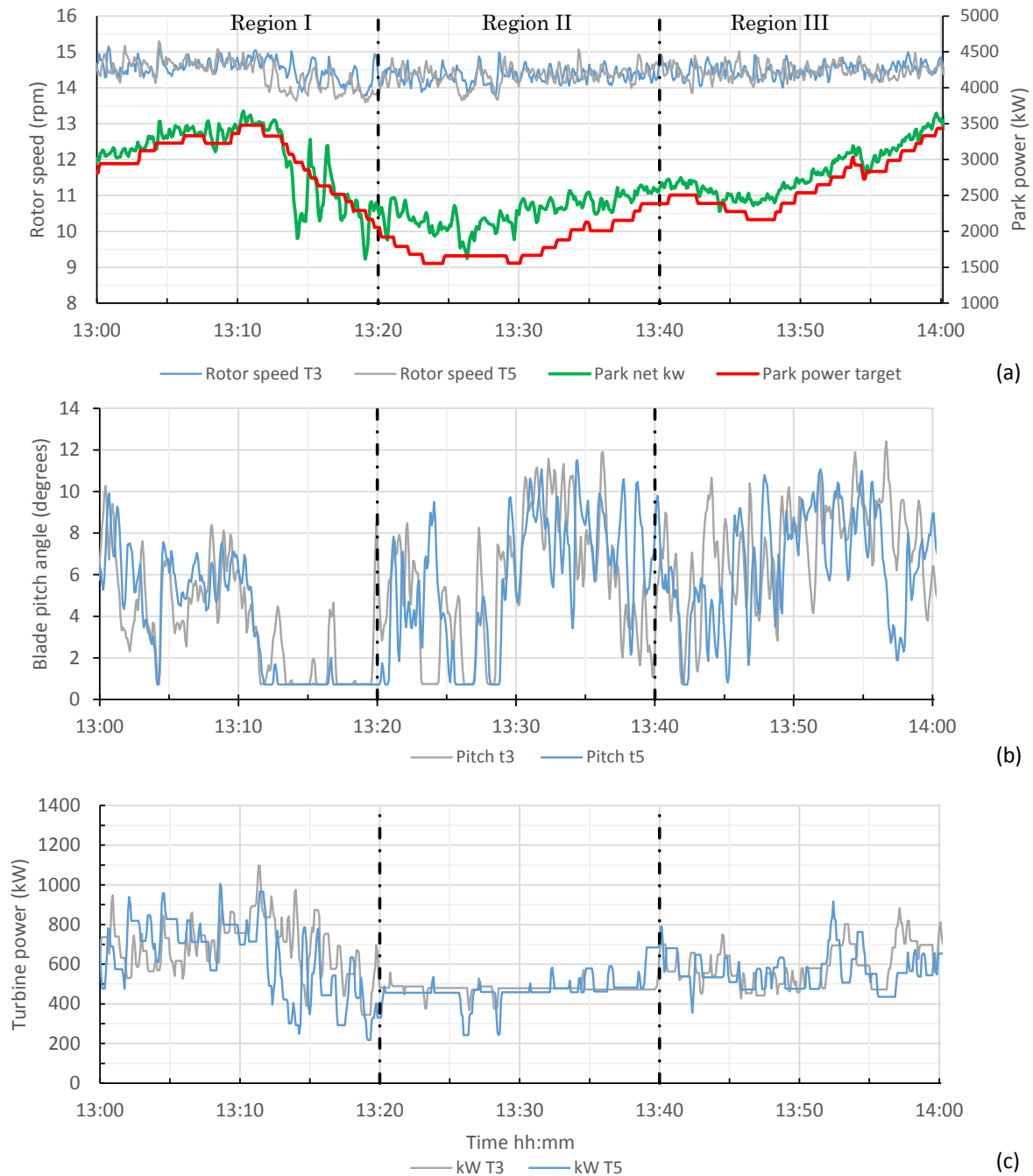


Figure 8: Turbine performance during different operating situations. Region I illustrates performance during decreasing wind speeds, Region II illustrates the power error in the low power region (See Section 3.2.1) and Region III illustrates performance during increasing wind speeds.

available in the wind reduces before the 10 min average value does. This leads to a situation where the Park Power Target is higher than the sum of the instantaneous powers available from the five turbines. This is the cause of the mismatch between the net park power and the park power target as the wind speed decreases (See numbered regions of Power Error in Figure 6 and Region I in Figure 8). In these cases, the park power target is greater than the power available in the wind and the turbines cannot meet the target, producing a negative power error. In Region I in Figure 8 (b) observe that the turbine blades pitch towards zero degrees to maximise power production. Over the whole test duration, the power error is highest when the wind speed is insufficient to meet the park power target. From Figure 9, observe that the percentage power error is negative and has the greatest magnitude at zero pitch angles. The simplest solution to this problem is to reduce the wind speed averaging interval to below 10 min. Determining an optimal value requires further investigation.

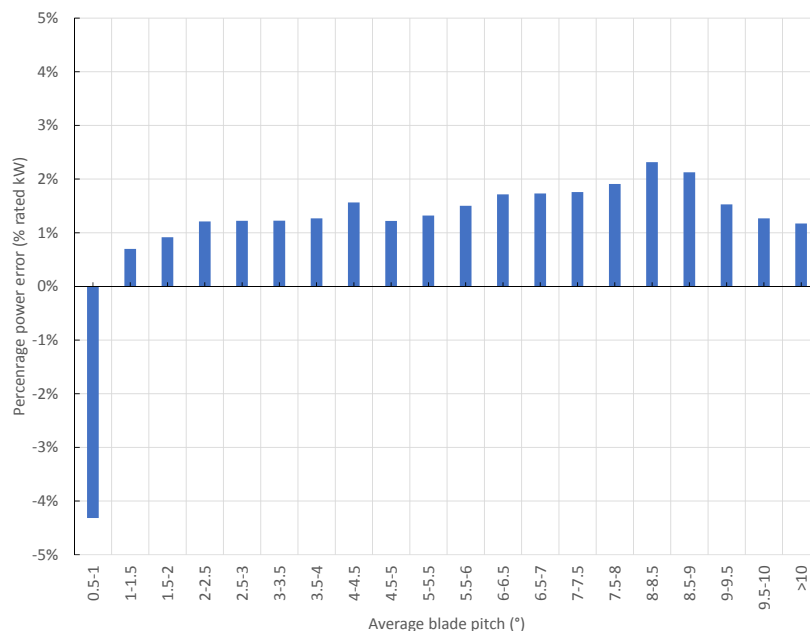


Figure 9: Blade pitch versus power error

4. Conclusion

Obtaining secondary frequency regulation services (i.e. up- & down- AGC) from wind plants is technically viable. This work presented a simple algorithm to allow for wind park participation in the secondary regulation market. The algorithm presented allows for 1 MW of regulation room on a 10 MW wind farm through dynamic curtailment. An external, historical AGC signal is used as a bias for the park power set-point. Park performance was evaluated using two calculation methods, NRC's method and the PJM method. This demonstration was carried out on a wind park with Type 5 wind turbines, a design that is uncommon. The algorithm developed results in poor performance during periods of decreasing wind speeds. We also observe poor performance at lower park power levels. This is likely a consequence of the control system of the specific turbines tested.

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