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DISCUSSIONS

Ancillary services from wind turbines: AGC from a single Type 4 turbine

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Abstract. Wind turbines possess the technical ability to provide various ancillary services to the electrical grid. Several regions have set ambitious targets of providing an increasing share of annual electrical energy from wind and other renewable sources of generation. Despite this, renewable generators such as wind and solar have traditionally not been allowed to provide significant amounts of ancillary services, in part due to the variable and uncertain nature of their electricity generation. Increasing levels of renewable generation, however, continue to displace existing synchronous generation and thus necessitate new sources of ancillary or system services. This work is part of an ongoing project that seeks to provide empirical evidence of how ancillary services can be provided from wind turbines. We focus specifically on providing secondary frequency response (AGC) and demonstrate that wind turbines have the technical capability to provide this service. The algorithms used are intentionally simple so as to evaluate the capabilities and limitations of the turbine technology. This work presents results from a single, 800 kW, IEC Type 4 wind turbine. 10% of rated power is offered on the regulation market. We do not separate up- and down-regulation into individual services. Up-regulation is offered through a 5% constant power curtailment. The AGC update interval is 4s, to mimic real-world conditions. We use performance scoring methods from the Pennsylvania-Jersey-Maryland (PJM) operator and the National Research Council (NRC) of Canada to quantify the wind turbine's response. We use the calculated performance scores, annual site wind data and 2017 PJM market price data to estimate income from providing secondary frequency regulation. In all cases presented, income from the regulation market is greater than the energy income lost due to curtailment.

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1 Introduction

One means of slowing the pace of climate change is through the decarbonisation of the electric grid. Established means of generating electric power include driving large turbines via coal boilers, burning natural gas, nuclear fission or hydro generators. Decarbonisation refers to reducing the amount of greenhouse gas emissions from generating sources like coal and gas and generating increasing amounts of energy from non-emitting sources such as wind and solar. Several jurisdictions around the world have set targets of supplying an increasing share of their electrical energy from renewable sources such as solar PV and wind. Examples include the EU's targets of 20% by 2020 (Capros et al., 2011) and the Paris Climate Accord (Baruch-Mordo et al., 2018). Although renewable generating technology has matured over the past few decades, it does come with some limitations. Most of the concerns stem from the fact that renewable generation is inherently variable and uncertain and is increasingly displacing large, synchronous generating capacity on the electric grid. Continually displacing synchronous generation brings with it technical challenges such as falling grid inertia that is provided by the electromechanical properties of salient pole machines. Some of these challenges are documented in a 2013 paper from the IEA's Task 25 work (Holttinen et al., 2013) and also Piwko et al. (2012). Further, the system services or ancillary services once provided by conventional generators will now require alternate sources. The question of whether renewable generators can provide these services has been examined in detail in the past in examples such as Banshwar et al. (2017) & Bevrani et al. (2010).

Even given this situation, grid operators around the world have been hesitant to source ancillary services from renewable generators. Part of this can be explained by the variable and uncertain nature of renewable generation. Their outputs depend on factors such as wind speeds and solar irradiance and these can never be predicted with perfect accuracy. Other generators on the power system typically 'accommodate' wind generation, changing their outputs to account for variations in wind generation. Further, the competitive markets that are designed to source these services are often set up to skew heavily towards large, synchronous generators (Denholm et al., 2019). Qualification rules might, for example, include the requirement that generators be ready to provide system services when called upon to do so. As an example, consider system services that depend on active power. This is not a problem for fossil-fuel powered generators as their active power outputs are largely controllable by fuel flow. Such a requirement might, however, disqualify generators such as wind and solar whose active power outputs depend on uncontrollable sources: wind speeds and solar irradiance. These markets are typically not designed to value system services provided by generators whose fuel cost is zero. Finally, since the output of wind generators depends on the wind speed, their ability to participate in day-ahead markets is heavily dependent on accurate wind forecasts.

1.1 Grid frequency response & AGC

The operation of any electric grid is a balance between supply and demand. Grid frequency is often used as a good indicator of the relative balance between supply and demand. If supply exceeds demand, frequency rises. Conversely, if demand exceeds supply, grid frequency falls. Grid frequency is typically controlled in a narrow range. The time response of grid frequency to a disturbance (e.g. sudden increase in load, loss of generation) is shown in Figure 1. Depending on the type of technology used, wind generators possess the ability to participate in the primary, secondary and tertiary response regions of Figure 1. This work focuses specifically on the region of secondary frequency response. At its core, this is an attempt by the grid operator to balance supply and demand through small changes in the power outputs of several generators. A grid operator calculates the difference between anticipated power production and load values, compares these to their measured values and accounts for power flows into other areas. This forms the basis of what is called an Area Control Error (ACE) from which a secondary frequency regulation signal (AGC signal) can be derived. This AGC signal is then scaled and sent to selected generators to regulate their active power outputs accordingly. Typically, generators providing services such as AGC are large, synchronous machines.

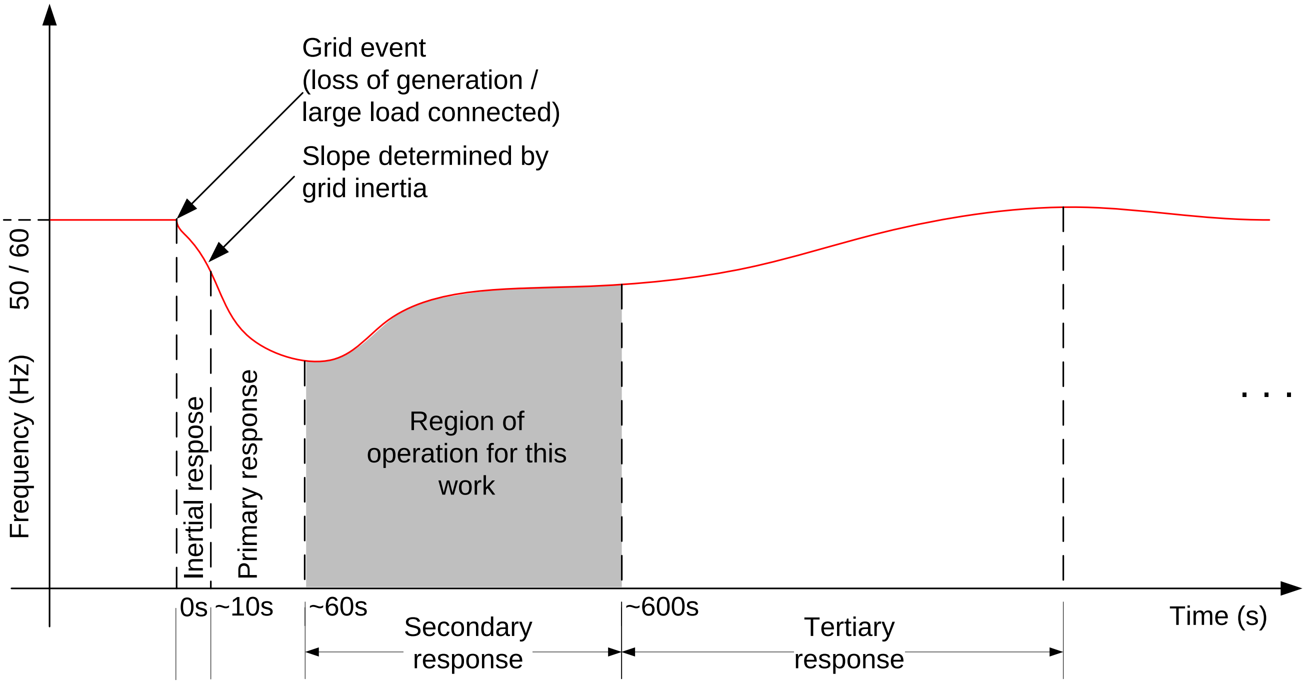

Figure 1. Grid frequency response to a sudden load increase or loss of generation. Region of secondary frequency regulation shown shaded.

1.2 Similar work

Providing ancillary services from wind turbines is neither new nor novel. Much of the publicly available literature consists of simulations (e.g. Aho et al. (2015), Shapiro et al. (2016), Basit et al. (2014)) that demonstrate the theoretical ability of wind generators to provide secondary frequency regulation. Empirical performance data showing how wind farms and individual wind turbines can provide ancillary services is often limited or not publicly available. Our work contributes by disclosing the exact algorithms used (simple as they may be) and presenting a technical and financial analysis of the results of frequency regulation tests. One example of similar work is the EU's TWENTIES project from 2013 (Azpiri et al., 2014). The TWENTIES project examined the ability of three geographically separated, transmission connected wind farms on the Spanish grid to control their active power in response to an external signal. The results of the 30 minute test were encouraging. The TWENTIES work differs from this work in that we do not use a wind speed forecast in our algorithm. We used a wind speed forecast only to select suitable days for testing. Similar to our work, the TWENTIES demonstration provided up-regulation via curtailment and also used a 4s AGC update interval. On a larger scale, the US utility Xcel Energy continues to provide AGC from wind farms on their network (Lew et al., 2013) however a critical analysis of the results is not publicly available. The Wind Energy Institute

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of Canada[1] has published results (Nasrolahpour et al. (2017) & Rebello et al. (2019)) of AGC tests on their own wind farm that consists of five IEC Type 5 wind turbines (directly connected synchronous machines). These works follow a similar analysis method as presented here however the key differences are the turbine technology (Type 5 versus Type 4) and the number of turbines (5 versus 1).

Solar PV represents an inverter-based technology that is similar to what is used in a Type 4 wind turbine. First Solar conducted a demonstration of a solar farm's ability to provide secondary frequency regulation (AGC) (Loutan et al., 2017) in collaboration with the California System Operator and NREL. First Solar's demonstration shares a lot in common with our work. Both use curtailment to provide room for up-regulation and both use inverter-based technologies. Though the exact control algorithms are different (completely electronic for a solar inverter versus some mechanical control for a wind turbine), the results of First Solar's work and this work are encouraging as the end result for the grid operator is the same: wind and solar generators both possess the technical ability to provide system services such as AGC. It is worth mentioning that synchronous areas such as the EirGrid network (in Ireland and Northern Ireland) and ERCOT (Texas, USA) regularly operate their systems with significant amounts of generation coming from renewable sources.

1.3 Limitations

This work is limited to examining the abilities of existing wind generators in providing one specific ancillary service: secondary frequency regulation. Although we aim to present a broad technical and financial analysis, there are numerous other considerations that are not examined here. Examples include wake effects in wind farms (See van Wingerden et al. (2017)) and the effects of market prices (See Holttinen et al. (2016)). The effect of providing system services on the lifetime of wind turbines is also not examined here. This is of particular interest to wind turbine manufacturers and equipment owners. Finally, although our work presents results for a longer time duration than previously published work, this is still insufficient for a complete analysis. Aspects such as seasonality (e.g. summer wind speeds being lower than winter wind speeds), temperature & maintenance requirements are not examined. Examining these will likely require a study spanning several months.

1.4 Motivation & utility of results

Although grid codes of several countries / regions require new wind generators to be capable of numerous ancillary services, empirical, unbiased data on the abilities of wind generators is lacking. Often, provisions are laid down in grid codes or connection agreements but wind generators are rarely called upon to provide an ancillary or system services. An example of public information of this nature is Hydro-Quebec's comparison of fast-frequency response from two wind turbine technologies (Asmine et al., 2017). Our work is intended to make operational data public to allow for greater scrutiny by system / grid operators and to give grid operators an unbiased method of comparison between turbine technologies. The theoretical basis for the difference in active power regulation ability between an IEC Type 3 and Type 4 wind turbine are known, however, operational data is often not public or analysed in a limited manner by turbine OEMs. The work resulting from this project seeks to fill these gaps in a transparent and critical way.

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[1] same authors as this work

Our algorithms and control methods are designed to be as high-level as possible. Note that this work does not develop a method for controlling the active power output of a wind turbine (unlike Aho et al. (2012), for example). The specifics of this control (blade pitch angles, inverter phase angles, etc) are left to the manufacturer's design. We focus solely on the end result and not on the specifics of the control method. This is the exact same viewpoint for a grid operator in the sense that *how* a generator's active power is controlled is not as important as the fact that active power *can be* controlled.

1.5 Ancillary service markets procuring services from wind generators

Broadly, ancillary services (or system services) refer to a set of services that complement the primary grid purpose of supplying energy. Examples include system inertia, voltage control, primary frequency control, operating reserves etc. Ancillary services may or may not depend on active power. Examples that do not depend on active power include reactive power and voltage support while services such as operating reserves and regulation depend on active power. The question of how increasing renewable generation will affect markets for ancillary services has been considered in the past Ela et al. (2012). (Banshwar et al., 2017) present a good overview of the challenges to sourcing ancillary services from renewable sources.

As detailed in Bloom et al. (2017), markets such as California's ISO and EirGrid in Ireland operate with >20% of annual energy coming from renewable generation such as wind and solar. These generators operate with a nearly zero marginal cost of energy and are expected to influence both energy and ancillary service markets. In markets such as CAISO, day-ahead energy prices routinely reach zero. The challenge faced by grid operators is one of integrating the suite of services offered by wind and solar generators and designing markets to allow their effective participation while maintaining system reliability.

1.6 Test site location and description

The tests described in this work were performed at the Saskatchewan Research Council's Cowessess First Nations site in Saskatchewan, Canada (Fig. 2). The site consists of a single wind turbine and a battery storage system and has been in operation since April 2013. The 800 kW wind turbine has a hub height of 73 m and a rotor diameter of 53 m. The battery storage system consists of two parallel banks which sum to 744 kWh of storage capacity and are connected through a 400 kVA inverter. See Jansen et al. (2013) for more details on the test site and equipment. The battery is not part of the results in this work.

A single-line diagram of the Cowessess site is shown in Figure 3. The wind turbine and battery inverter each connect to the 25 kV bus via their own transformers. Note the location and connections of our controller. We control only the active power setpoint (or target) of the wind turbine. All other control such as pitch, power error, etc. are left to the turbine's internal controller. Communication to the turbine's controller is via Modbus.

2 Algorithm & AGC signal

The Alberta Electric System Operator (AESO) provided both AGC signals used in this work. One was a 30 minute duration signal and the other was 4.5 hours long. These are identical to the signals used in Rebello et al. (2019) and Nasrolahpour et al.

Figure 2. Test site location (red) in Canada. Province of Saskatchewan shown shaded.

(2017). This is done to make direct comparison with earlier work easier. The first step to signal preparation was scaling the raw AGC signals to fit within our chosen regulation ranges. This was followed by filtering, as described below.

2.1 AGC signal filtering

A wind turbine is a system with electrical and mechanical components and a finite response time. To account for this, we apply a simple differential magnitude filter to the raw AGC signals from the AESO. The purpose of this filter is to prevent repeated, small changes to the power target of the wind turbine. Note that the power output of any wind turbine has small variations in it, i.e. it is very rarely a steady value. The changes in the AGC signal must be greater than the magnitude of these changes in order for the wind turbine to respond in a meaningful way. From empirical data we calculate a standard deviation of 11 kW in the wind turbine's power output. The differential magnitude filter output will not change until the difference between the present and next AGC values is more than 11 kW. Additional information about this method is in Rebello et al. (2018). The results of this filtering are shown in Figure 4. The average value of the resulting AGC signal is close to zero.

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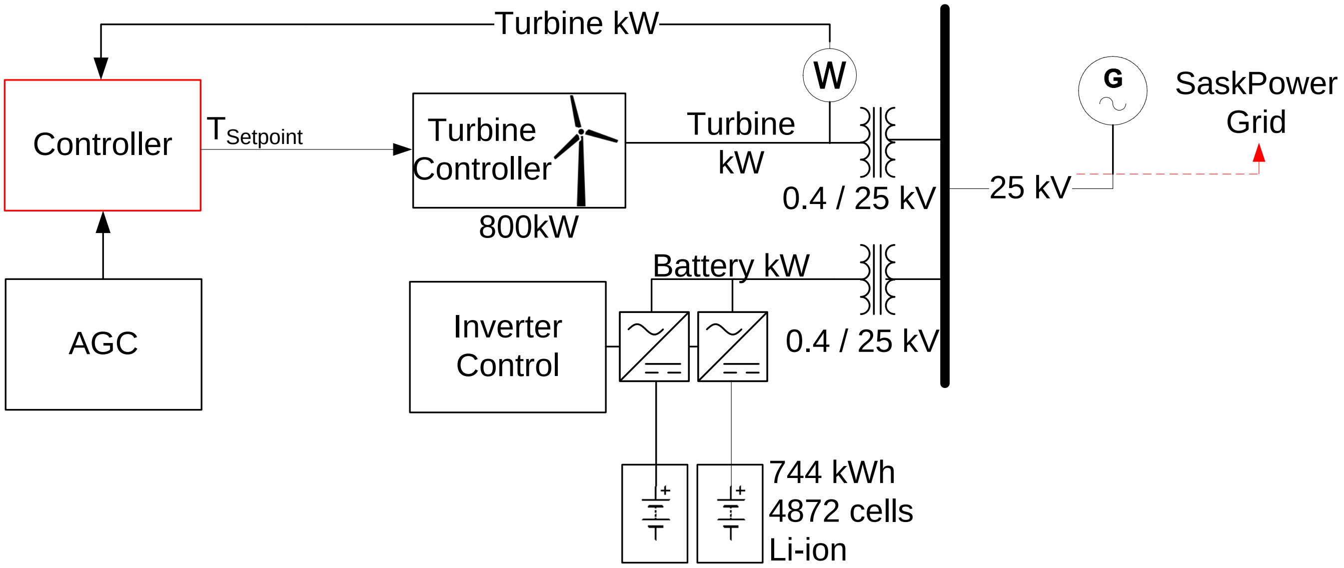

Figure 3. Single-line diagram of the Cowessess First Nations site in Regina, Saskatchewan. Note that the battery is not part of the results presented here.

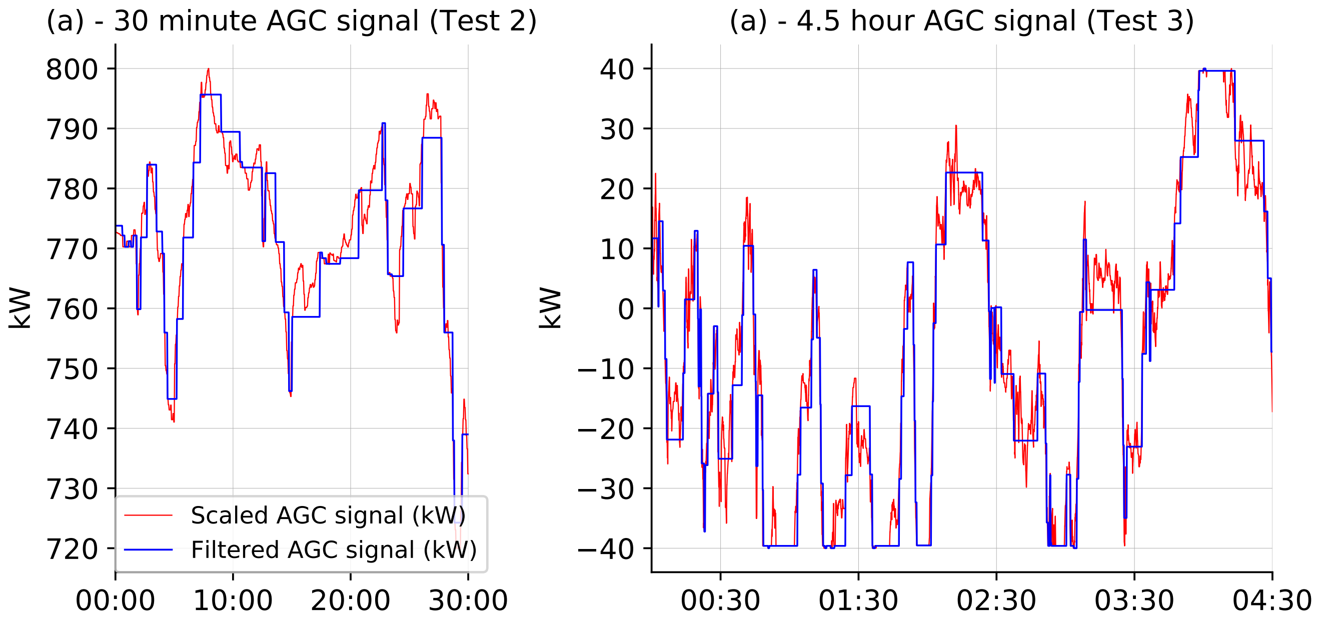

Figure 4. Scaled AGC signals and result of applying a differential magnitude filter.

2.2 Test outlines

The experiments presented in this work are grouped into two tests as summarized in Table 1. We also present a variation of Test 2 where the regulation offer is 200 kW. This is not included in Table 1 for clarity.

Table 1. Summary of the tests presented in this work

	Duration	Description	Regulation offer
Test 2	30 m	Wind turbine operating above rated wind speed	80 kW
Test 3	4.5 h	Wind turbine operating below rated wind speed	80 kW

Test numbers are kept consistent with other project documentation. The two tests presented here are the only ones with the wind turbine operating independently. Future publications will document results with the wind turbine and the site's battery system operating in tandem.

2.3 Algorithms & Methodology

Figure 5 illustrates the algorithms used in the two tests presented here. Test 2 simply sends power setpoint targets to the wind turbine. No calculations are performed here. All AGC target values range from 720 kW to 800 kW. These are the filtered AGC values from Figure 4. We use a wind forecast to select a time when the wind speeds are above the turbine's rated wind speed. As such, the turbine is expected to generate rated power and no power estimation is required.

The algorithm for Test 3 is slightly more complex as it is performed below rated wind speed. The turbine's power output varies with the wind speed. The challenge here is estimating the turbine's power generation potential. We use averaged (30 s) wind speed data from the turbine nacelle anemometer. We then estimate the expected power generation from the turbine using the power curve. Note that this power curve was constructed from measured, historical data (1 year) and is not the manufacturer's power curve. We then subtract 40 kW from the expected power production value. Finally, we add the AGC signal bias value to calculate the power target for the wind turbine. This value is updated every 4 seconds and is sent to the turbine's control system.

In both Test 2 & 3, our controller (red block in Figure 3) receives wind speed data from the turbine's control system. We then read in the AGC signal and send a power target to the turbine controller. This setup is similar to what a grid operator would use. An indication of the power available in the wind, as calculated by the wind turbine's control system, is available as $P_{available}$. We do not use this value in this work but instead calculate our own estimate as described above.

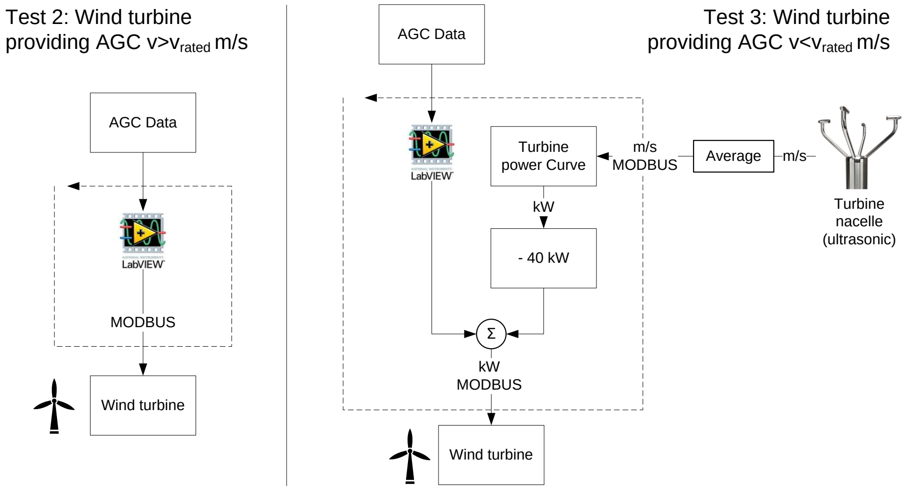

Figure 5. Algorithms for (a) Test 2 and (b) Test 3

3 Results: Performance scores, discussion & analysis

3.1 Performance scores

A performance score is a numerical measure of a generator's ability to follow an external control signal. We use two methods of calculating performance scores.

1. Natural Resources Canada method (Kabiri and Song, 2018)
2. PJM method (Pilong, 2015)

A summary of the results from the NRC and PJM performance score calculations is shown in Figure 6. Readers are directed to the references above for full details of the calculation methodologies. One major difference between the two methods is that the NRC performance scores are based entirely on the error between the target and the measured power while the PJM method accounts for delay, accuracy and precision. Comparing scores between the two methods is therefore not possible.

3.2 Test 2 - 80 kW regulation offer

Results from one instance of Test 2 are in Figure 7(a). Although the test was repeated several time, only one example is shown here. Observe that a drop in the wind speed caused a drop in the power output. This has a noticeable effect on the performance score. These results are also negatively affected by a scaling error in the turbine's control system where power setpoints were incorrectly scaled assuming a rated power of 840 kW. This is the reason why the measured turbine power is greater than the target values and why a gap between the two is clearly visible. Note that the general trend of the red and blue traces agrees well. Due to time and weather constraints, it was not possible to repeat this test during identical conditions however, a substitute is presented below.

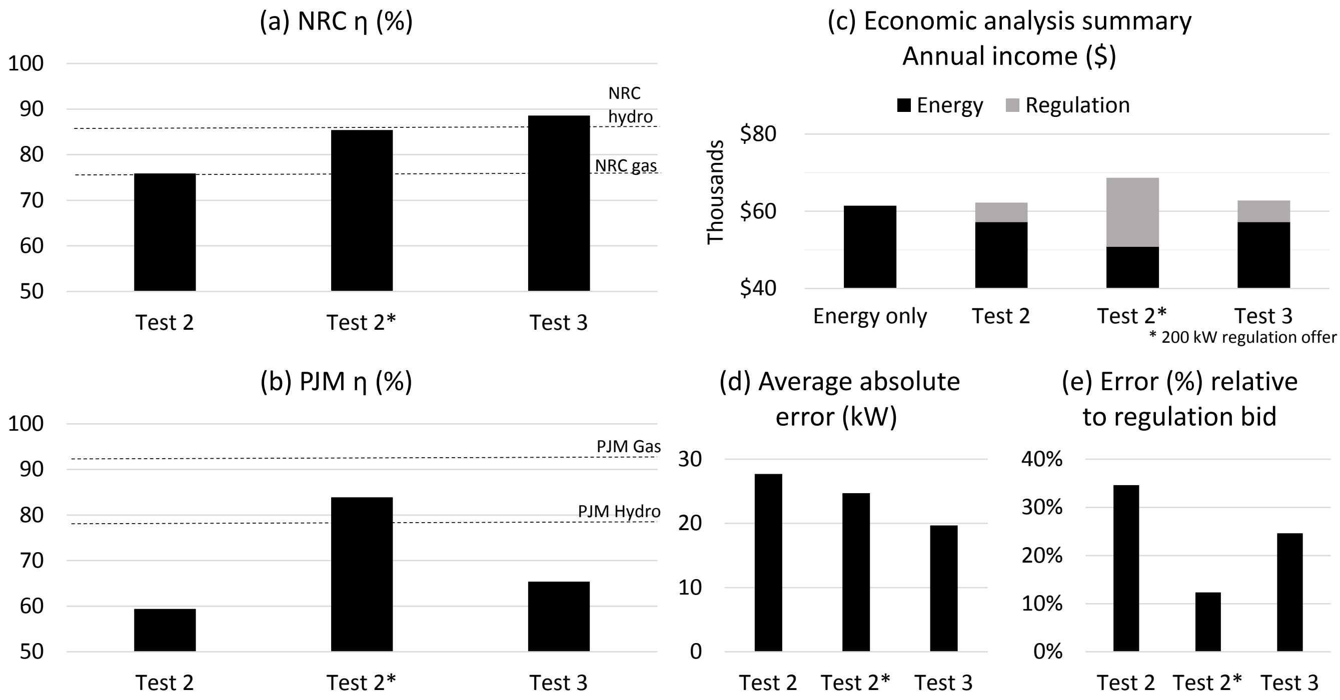

Figure 6. (a) & (b) Performance score summary. Dashed lines show performance figures for other generation technologies; (c) Annual economic summary with various performance scores; (d) Error trends in each test & (e) Error relative to regulation bid magnitude

3.3 Test 2* - 200 kW regulation offer

Results from this test are presented in Figure 7 (b). This test is not exactly the same as Test 2 above. A major difference is that the regulation offer here is 200 kW versus 80 kW above. Further, the scaling error with power setpoints from Test 2 was corrected. Both these fact combine to improve the performance scores. A further reason for the improved performance scores here is the fact that the magnitude of the error is comparable to earlier iterations however, relative to the regulation bid, the error percentage is now smaller resulting in an improved performance score. This is visible in Figure 6 (d) & (e). What is clear from Figure 7 (b) is that a Type 4 wind turbine is able to control its active power accurately.

The data presented in Figure 7 (b) represents a situation where the wind speeds were sufficient to allow rated power production but cold temperatures required curtailment to below rated power. We argue that the performance of the turbine in these conditions is identical to that at higher power levels as it is determined by the turbine's control system (e.g. pitch action). Due to the significant gap (or headroom) between the power setpoints in Figure 7 (b) and the possible power, we also reduce the chance of a drop in wind speed affecting the performance score. This, of course, comes at the cost of reduced energy income. The resulting performance score is comparable to PJM performance scores reported for hydro generators Croop (2017).

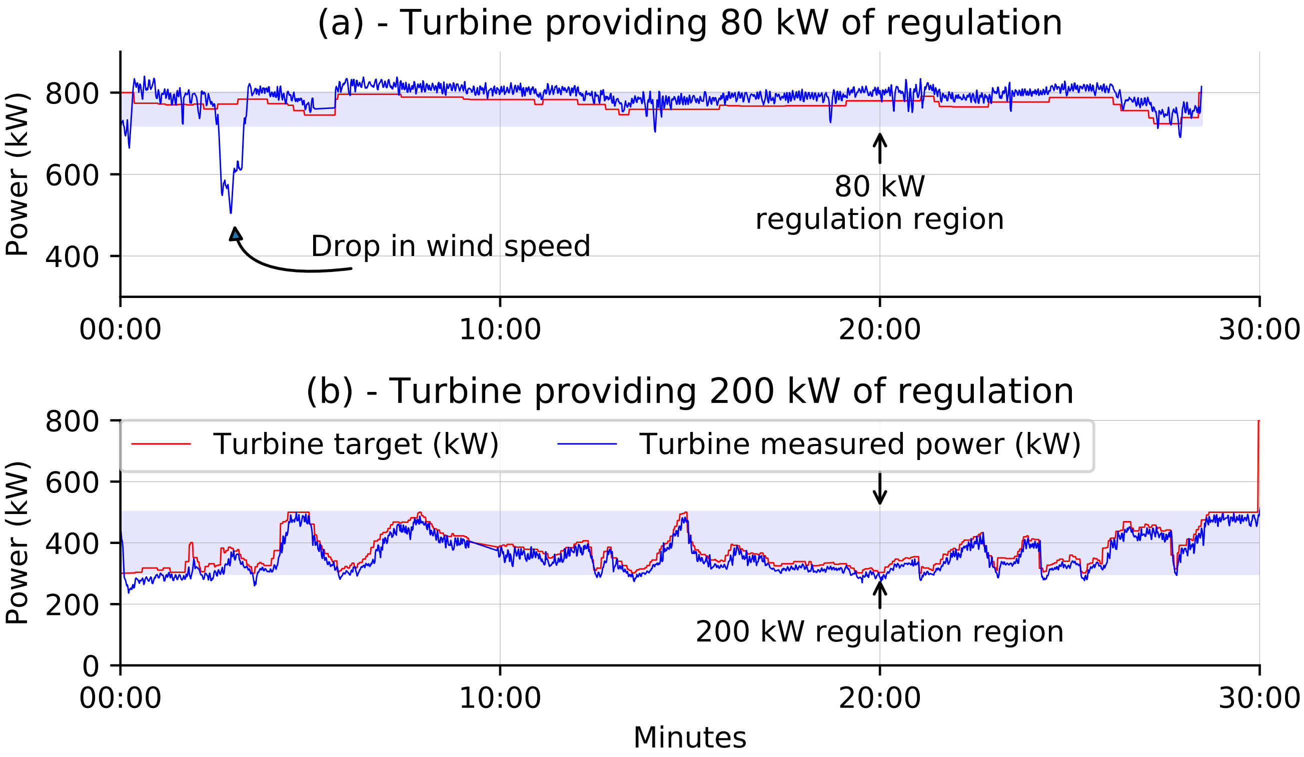

Figure 7. (a) Providing 80 kW of regulation from a single 800 kW wind turbine when operating at rated power. Note that the offset observed is discussed in Section 3.2. (b) Providing 200 kW of regulation. Blue shaded region in (a) & (b) is the range of possible regulation

3.4 Test 3

Test 3 represents turbine performance below rated power. The power setpoint scaling error from Test 2 was corrected here. Observe from Figure 8 that the target and measured power values track each other well. Correcting the scaling error improves the calculated performance scores relative to Test 2, however, note that the error magnitude relative to the regulation bid magnitude is similar to that in Test 2 (see Figure 6 (e)). This limits the performance score obtainable.

3.5 General Comments

Note from Figure 6 (d) that the general error trend across all three tests is broadly comparable. The effect of the scaling error is most pronounced in Test 2 as this was performed at rated power and the full magnitude of the error affected the results. Previous runs of Test 3 were affected by this error but the effect is less pronounced as the error is proportional to power. After correcting for this error, a repeat of Test 3 showed reduced error magnitude (Figure 6 (d)), however, the error magnitude was broadly comparable to Test 2* (200 kW). This suggests that a major contributing factor to the performance score is the magnitude of

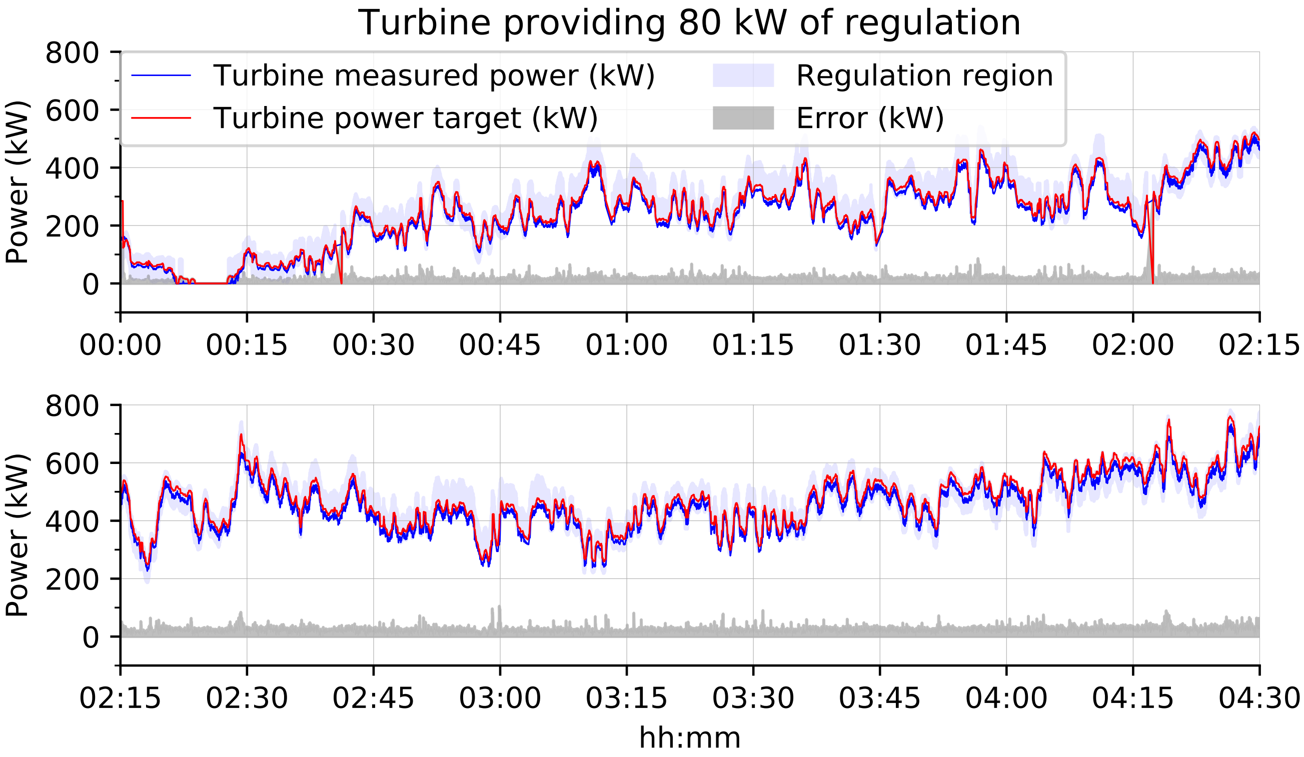

Figure 8. Test - 3: Providing 80 kW of regulation when wind speeds are below rated. Blue shaded region is the range of possible regulation

error relative to the regulation bid. An error of 20 kW with a regulation bid of 80 kW is more significant than an error of 24 kW with a 200 kW regulation bid.

In addition to the effect of stochastic variations in turbine power output, our results were affected by a few other factors. One is time delays caused in part by the communication network and in part by the turbine's control system response time. Observations indicate that the net delay is approximately 12 seconds. A time delay negatively affects performance scores. Some of this is unavoidable as a wind turbine is a mechanical system with a finite response time. Another factor that affected the performance scores is data logging errors. The precise cause of these errors is not known but the effect is that our logged data has several intervals where data is missing.

4 Financial Analysis

The previous section established that providing AGC from a single Type 4 wind turbine is technically possible. We now run a financial analysis to examine the profitability of providing secondary frequency regulation from a single wind turbine. We use PJM's ancillary services market for this to be consistent with our other works (Rebello et al. (2019) & Nasrolahpour et al. (2017)). Broadly, PJM's ancillary services market pays for providing capacity as well as performance (see Pilong (2015)). Capacity payments are for committing to provide ancillary services on the market and depend on the capacity (in MW) offered. Performance payments depend on the generator's performance when called upon to provide an ancillary service such as AGC. PJM's AGC market uses the metric of a performance score in calculating performance payments. The higher the performance score, the higher the payment received. For the calculations below, we assume that the wind turbine does not bid into the day-ahead energy market. Non-regulation energy is sold to the grid at the spot price. Regulation energy is sold at a separate price which depends on the amount of energy sold and the signal mileage ratio.

4.1 Inputs & assumptions

Inputs:

1. One year of 2017 PJM market data for spot prices and regulation (Available online at PJM's Data Miner website)
2. One year of historical power generation data from the Cowessess site. Note that this is power data, not wind speed data and therefore includes turbine down time
3. Performance scores (PJM) calculated earlier

Assumptions:

1. We use PJM's faster moving Reg-D signal as this is the regulation signal used for technologies such as battery storage
2. We assume that the hourly average of the Reg-D signal is close to zero. This implies that the net effect of the regulation signal on average energy values is zero. Energy generated is affected solely by the curtailment applied (see Section 2.3). The effect of this curtailment is therefore to reduce energy payments by a constant value.
3. We use one year (2017) of historical power generation data from the Cowessess site. We then assume the hourly average power value to be a steady power generation value for that hour. The energy generated for that hour is therefore the average power value minus our curtailment.$(P_{avg}(t)\, kW - P_{curtailment}\, kW) \times 1h$
4. Regulation is provided each hour that the hourly average power is above the regulation offer (80 kW or 200 kW)
5. We ignore maintenance costs as quantifying these effects is beyond the scope of this work

4.2 Results & discussion

The expected annual income with each of the performance scores calculated here is shown in Figure 6 (c). Observe that the total annual income when providing regulation is greater than the income from providing energy alone. This indicates that despite the limitations of this work, there is potential for even a single wind turbine to participate in the secondary frequency regulation market and for participation to be profitable.

The curtailment used represents energy which is not sold to the grid and therefore an opportunity cost to providing regulation services. Our calculations show that even with the lowest performance scores we calculated, regulation market income more than accounts for the lost energy cost. Any improvements to the performance score will only increase regulation market income.

Table 2. Annual financial summary with 2017 PJM market data (Also see Fig. 6)

Test	η_{PJM} (%)	Energy income ($)	Regulation income ($)	Total annual income ($)
Energy only	N/A	61,464	0	61,464
Test 2 - 80 kW	59.4	57,198	5059	62,257
Test 2 - 200 kW	83.9	50,799	17,865	68,664
Test 3	65.4	57,198	5587	62,785

Observe from Table 2 that the regulation market income with the improved performance score of Test 2* (200 kW) leads to a 11.7% increase in total income over supplying energy alone. The trade-off is lower income from energy sales due to the 100 kW curtailment required. This indicates that there is significant incentive for even a single wind turbine to participate in the secondary frequency regulation market. Even with the lowest performance score obtained in Test 2 (59%), participating in PJM's secondary frequency market is still profitable. With improvements in control algorithms and a reduction in turbine error, this will only be more favourable. This result is encouraging as even though wind generators are not required (or allowed in some cases) to participate in the ancillary services markets, existing market structures make participation profitable. This situation may change when significant amounts of energy and ancillary services are supplied by renewable generators with a marginal fuel cost of zero.

5 Conclusions

This work presents the results of a series of tests evaluating the ability of a single, 800 kW Type 4 wind turbine to provide secondary frequency regulation (AGC). The turbine is located in Regina in the Canadian province of Saskatchewan. Tests are performed at and below rated wind speeds. The regulation offer is 10% of rated turbine power. We use a constant power curtailment to create room for up-regulation. Due to errors in the first series of tests, a second test was performed at rated wind speed however the regulation offer was changed to 25% of rated power. Performance scores of 59% and 65% are calculated with the PJM method above and below rated wind speeds respectively. Stochastic errors inherent in the wind turbine's power output limit the performance scores achievable. With an increased regulation offer, we observe that the magnitude of stochastic error is relatively constant. This leads to an improved performance score. Using the performance scores calculated, 2017 PJM market data and one year of historical site power data, we estimate the income possible from PJM's regulation market. We find that participating in the regulation market is profitable even with the lowest performance score, despite the opportunity cost of applying power curtailment.

Data availability. Data presented in this work was obtained through several Non-disclosure Agreements, however, results can be obtained by contacting the authors. Disclosing data sets may require signing NDAs.

Competing interests. We declare no competing interests

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