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Preprint

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Presented at the 13th International Workshop on Large-Scale Integration of Wind Power Into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants
Berlin, Germany
November 11-13, 2014

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Conference Paper
NREL/CP-5D00-62815
February 2015

Contract No. DE-AC36-08GO28308

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Controlling Wind Turbines for Secondary Frequency Regulation: An Analysis of AGC Capabilities Under New Performance Based Compensation Policy

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***Abstract*—As wind energy becomes a larger portion of the world's energy portfolio there has been an increased interest for wind turbines to control their active power output to provide ancillary services which support grid reliability. One of these ancillary services is the provision of frequency regulation, also referred to as secondary frequency control or automatic generation control (AGC), which is often procured through markets which recently adopted performance-based compensation. A wind turbine with a control system developed to provide active power ancillary services can be used to provide frequency regulation services. Simulations have been performed to determine the AGC tracking performance at various power schedule set-points, participation levels, and wind conditions.**

The performance metrics used in this study are based on those used by several system operators in the US. Another metric that is analyzed is the damage equivalent loads (DELs) on turbine structural components, though the impacts on the turbine electrical components are not considered. The results of these single-turbine simulations show that high performance scores can be achieved when there is sufficient wind resource available. The capability of a wind turbine to rapidly and accurately follow power commands allows for high performance even when tracking rapidly changing AGC signals. As the turbine de-rates to meet decreased power schedule set-points there is a reduction in the DELs, and the participation in frequency regulation has a negligible impact on these loads.

I. Introduction

Wind energy is becoming a more significant contributor to the global electrical energy generation portfolio as more wind turbines are installed. In some regions of the world the wind resource, electricity transmission infrastructure, and many other factors present favorable conditions for installing large amounts of wind energy. Many of these regions are reaching high penetrations of wind energy, reaching or exceeding 20% of their annual electricity demand from wind energy [1]. A trend can be observed in the United States (US) in which the system operators in regions with higher wind penetrations have accommodated the increase of wind generation variability by procuring additional frequency regulating reserves [1]. Frequency regulation, sometimes referred to as secondary frequency control, is a required ancillary service for which participating generation capacity is dedicated to following the power commands from the system operator. The regulation power command is referred to here as the automatic generation control (AGC) signal which is used to regulate grid frequency and maintain scheduled power exchanges between areas [2]. Economic ancillary service markets exist to compensate generators that participate in frequency regulation, and the US ancillary service markets are now required to implement performance based compensation for regulation services, meaning that participating resources that follow the AGC signal more accurately can receive higher economic compensation [3], increasing the motivation for fast responding generation to provide frequency regulation services.

Historically, wind energy has not participated in market-based frequency regulation, even though wind turbines made by many of the leading manufacturers have the capability of controlling their active power output [4], and recent studies have shown that as long as there is adequate wind resource, wind turbines can track power commands rapidly and accurately [5]. This increases the motivation to study the AGC tracking performance of wind turbines with the new performance metrics used for frequency regulation compensation. In this paper we analyze the simulated performance of a wind turbine when providing frequency regulation services. The wind turbine control system is capable of providing active power control (APC) services, as described in [6] and [7], and is used to track AGC power commands. The performance of the wind turbine and control system are evaluated using performance metrics that are used to determine economic compensation in several US markets. The fatigue loading induced on the structural components of the turbine are also evaluated when providing regulation services. It is important to note that the results shown in this paper are for a single turbine, and it is expected that using a wind power plant consisting of multiple wind turbines will improve the AGC tracking performance scores due to the spatial filtering of the wind provided by aggregating multiple turbines.

This paper is organized as follows:

- Section II provides an overview of the wind turbine APC controller.
- Section III explains the regulation performance metrics that are used by several US system operators that determine economic compensation for these services.
- Section IV highlights selected simulation results including the AGC tracking performance scores and the fatigue loads induced on turbine components.
- Section V provides concluding remarks and areas of future research.

II. Wind Turbine Frequency Regulation

The primary goal of a traditional wind turbine control system is to maximize energy production while protecting the turbine components from damaging loads. When the wind turbine is generating power below the nameplate capacity of the turbine, or rated power P_{rated}, traditional control systems use the power electronics to actuate the load torque on the generator shaft τ_g to control the rotational speed of the rotor for maximum power capture from the wind stream. When the turbine is producing power at P_{rated}, the control system actuates the blade pitch motors to change the collective blade pitch angle β and shed the excess aerodynamic power to regulate the power production. An example of a traditional, or baseline control system can be found in [8].

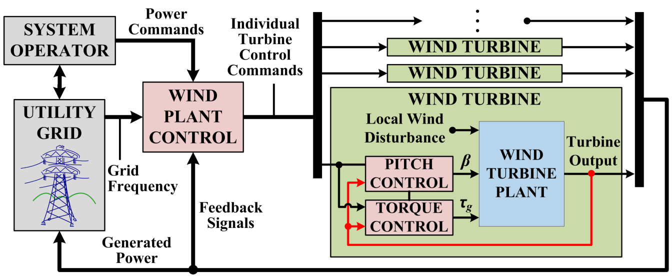

Figure 1. A schematic depicting the interconnection between the wind power plant control system, individual turbine control system, utility grid, and system operator.

The participation of wind energy in frequency regulation requires that each wind power plant establish communication with the system operator to receive the power dispatch schedule, the regulation capacity, and the AGC power command. The wind power plant control system sends power commands to the individual turbines, which need not be uniform. A schematic of the interconnection between the wind power plant control system, individual turbine control system, utility grid, and system operator can be seen in Figure 1.

The desire for wind energy to participate in active power control ancillary services has motivated industry and academia to research and develop control systems that are capable of providing these services. Much of the industry research that has been performed in this area remains largely proprietary, but several of the major wind turbine manufacturers have demonstrated the capability of providing APC ancillary services. An overview of prior work in wind turbine APC control systems can be found in [4].

A. Wind Turbine APC Control System

The research presented in this paper uses an individual wind turbine control system based on prior research presented in [7]. This controller was designed to be practical, directly implementable on utility scale turbines, and be capable of providing all of the APC ancillary services. The control system is designed to be implemented as shown in Figure 1, where the wind power plant controller passes the power commands and grid frequency directly to the individual turbines. This APC wind turbine control system has been extensively tested in simulation and has been validated through field tests on the 3-bladed controls advanced research turbine (CART3) at the National Renewable Energy Laboratory (NREL).

The APC control system uses a standard baseline pitch control system as described in [8], so all APC capability is implemented through modifications of the generator torque control loop, though there are other methods of implementing wind turbine APC through the blade pitch control system or through combined torque and pitch control, as described in [4] and [7]. It should be noted that in this paper we do not consider the internal controls of the power electronics, as the power electronic controller timescales are an order of magnitude smaller than those used in this study.

The APC control system is capable of operating in three power de-rating modes, each using a different power reserve strategy as follows:

- Mode 1- The control system tracks an absolute power command. If there is insufficient wind to generate the commanded power the control system will aim to maximize power capture as the baseline controller would.
- Mode 2- The control system aims to maintain a specified power reserve.
- Mode 3- The control system aims to maintain a power reserve that is proportional to the available power in the wind.

Providing frequency regulation requires that the control system receive and track AGC power commands P_{agc} which are added to the power dispatch schedule P_s. The results presented in this paper are limited to operation in de-rating mode 1, as the power commands in this mode use an absolute reference, whereas in modes 2 and 3 the power reference is determined by the estimated power available in the wind, which is not standard practice and would produce performance scores that are dependent on various parameters, such as the bandwidth of the low-pass filters used to estimate the power available in the wind.

III. Frequency Regulation and Control

There are several active power control regimes that span various time-scales, each having a different purpose and implementation. The focus of the research in this paper is on the capability for wind turbines to follow a power schedule dispatch or set-point P_s and provide frequency regulation services by following an AGC power command P_{agc} as directed by the system operator. An overview of the other frequency control regimes may be found in [9].

In the US, system operators will typically schedule power generation resources to meet the load forecast and procure sufficient ancillary services using a least-cost co-optimization [10]. The compensation for resources has historically included an energy payment and a capacity payment for the amount of generation capacity that is dedicated to following the AGC power commands. In 2011 the US Federal Energy Regulatory Commission (FERC) issued Order 755 which requires system operators in regions with organized wholesale power markets to implement performance-based compensation for resources providing frequency regulation services [3]. The system operators have adopted various performance metrics to qualify how well resources track the AGC power command signal and each factor the performance scores into their compensation model differently [10]. This paper will use the performance metrics adopted by CAISO, the California independent system operator, and PJM, a system operator spanning 13 states including Pennsylvania, Ohio, and Virginia. The performance scores from these regions were chosen because they use different performance scores that are thoroughly documented and were among the earliest to implement performance based compensation. The CAISO and PJM performance metrics are described in Sections III-A and III-B, respectively. Many US frequency regulation markets are divided into regulation-up and regulation-down services, provided by resources that have capability and capacity to increase or decrease their power when the AGC command is positive or negative, respectively. In the US the AGC signal is generated by the system operator every 2 to 6 seconds [2].

Each resource participating in frequency regulation is assigned a power dispatch schedule P_s, regulation capacity up R^U, and regulation capacity down R^D. For simplicity, this paper will refer to the AGC power commands P_{agc} as they are received by the resource, and are assumed to be bounded by $[-R^D, R^U]$. All values are expressed as a percentage of the rated power of the resource P_{rated} so that the performance scores can be analyzed without obfuscating the results with unnecessary parameters. The net power command P_{cmd} for the resource to follow at each time step k is

$$P_{cmd}(k) = P_s(k) + P_{agc}(k) \tag{1}$$

$$P_R(k) = P_{gen}(k) - P_s(k) \tag{2}$$

$$E(k) = P_R(k) - P_{agc}(k) \tag{3}$$

where P_{gen} is the power generated by the resource, P_R is the AGC response of the resource, and E is the AGC tracking error.

A. CAISO Performance Metrics

CAISO uses an AGC update interval of 4 seconds and a performance evaluation period of 15 minutes. CAISO has implemented performance based compensation through the use of a form of "mileage payment" which is added to the energy and regulation capacity payments. The term mileage refers to the absolute amount of power injected and withdrawn, or amount of actuation a resource provides. This mileage payment is adjusted based on the performance of the resource and is calculated as the product of the mileage price, the actual mileage M_a, and the accuracy performance score S_A,

$$M_a = M - U \tag{4}$$

$$M = \sum_{k=2}^{K_d} |P_{agc}(k) - P_{agc}(k-1)| \tag{5}$$

$$S_A = \max\left\{0, \frac{M - \sum_{k=1}^{K_d} |E(k)|}{M}\right\} \tag{6}$$

where M is the mileage of the AGC command, U is the under-response of the resource, and K_d is the number of time samples in the performance evaluation period. It should be noted that the performance score has a lower saturation limit of 0 and is only calculated during periods in which M is non-zero. The under response U is calculated as $U = \sum |E(k_u)|$ where k_u are time samples when $P_{agc}(k)$ changes direction and $\operatorname{sign}(P_{agc}(k+1) - P_{agc}(k)) = \operatorname{sign}(E(k))$.

The CAISO region is one of the US regulation markets which divide the regulation service into regulation up and regulation down services, denoted with superscripts U and D, respectively.

B. PJM Performance Metrics

The PJM region also uses an AGC update interval of 4 seconds, but the measured resource response is sampled every 10 seconds and uses 1 hour performance evaluation period. The PJM performance scores are calculated as the hourly average of a weighted sum of three different metrics, the precision score S_P, the correlation score S_C, and the delay score S_D as described in [11]. The precision score is

$$S_P = \max\left\{0, 1 - \frac{K_d}{n} \frac{\sum_{k=1}^{K_d} |E(k)|}{\sum_{k=1}^{K_d} |P_{agc}(k)|}\right\} \tag{7}$$

where n is the number of samples in which P_{agc} is non-zero. The delay score S_D and correlation score S_C are

$$S_C(k) = f_C\left(P_{agc}(k), P_R(k+\delta_k)\right) \tag{8}$$

$$S_D(k) = f_D(\delta_k) \tag{9}$$

$$f_C\left(X(k_x), Y(k_y)\right) = \frac{X(k_x : k_x + k_W)^T Y(k_y : k_y + k_W)}{X(k_x : k_x + k_W)^T X(k_x : k_x + k_W)} \tag{10}$$

$$f_D(d) = \left|\frac{k_W - d}{k_W}\right| \tag{11}$$

$$\delta_k = \underset{d \in [0:k_W]}{\operatorname{argmax}} (f_D(d) + f_C(P_{agc}(k), P_R(k+d))) \tag{12}$$

where f_C is referred to as the "normalized correlation coefficient" between two signals and k_W is the number of measured samples in a 5-minute window [11]. It should be noted that the PJM documentation refers to S_C as the "accuracy score" but this paper will refer to it as the correlation score so it is not confused with the CAISO accuracy score.

Resources in the PJM region must pass a qualification test before being used as a regulation reserve by scoring above

0.75 when responding to AGC test signals. A resource will become disqualified if the performance score over the past 100 hours drops below 0.4 [11].

IV. Results

Simulations were used to analyze the performance of a wind turbine with the APC control system when participating in frequency regulation. The metrics that were analyzed are the power production, the damage equivalent loads (DELs) that are induced on the turbine components, and the AGC power command tracking performance metrics described in Sections III-A and III-B.

A. Simulation Environment

The results are generated when following absolute power commands in de-rating mode 1. The power schedule is fixed at a constant value for each simulation to provide insight into the power set-point and level of participation that can be achieved for each mean wind speed.

The AGC commands used during simulations are the 40-minute test signals used to qualify facilities in the PJM area, and consist of the traditional low-frequency AGC signal, RegA, and a high-frequency AGC signal, RegD, described in [11]. These AGC signals are normalized to ± 1 and the positive and negative commands are scaled by R^U and R^D, respectively. An example of the received power commands for both the RegA and RegD signals can be seen in Fig 2.

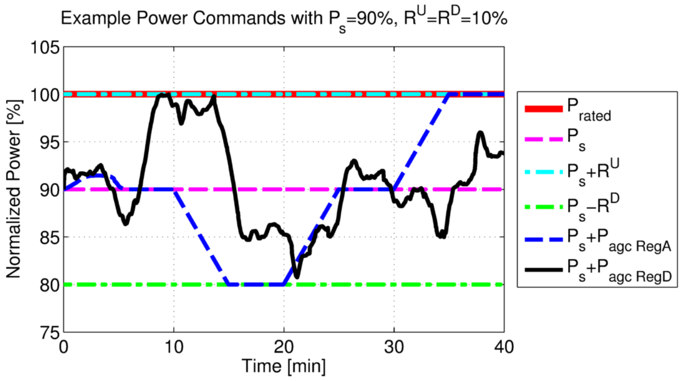

Figure 2. An example of the power commands when $P_s = 90\%$ and $R^U = R^D = 10\%$. This example illustrates the low-frequency and high-frequency AGC signals used for qualification in the PJM area, denoted as RegA and RegD, respectively.

The simulations were run with the FAST wind turbine simulation code developed at NREL, which calculates the response of aeroelastic wind turbine models to turbulent wind inflow using blade element momentum theory [12]. The turbine model used in this study is the CART3 FAST turbine model. The turbulent wind fields were generated with the NREL TurbSim code for a range of mean wind speeds using the IEC von Karman and Kaimal spectral models and IEC turbulence characteristics A, B, and C, as defined in [13] and [14]. Results presented in Sections IV-B and IV-C were calculated from the aggregate results of six sets of 40 minute simulations, one for each combination of spectral model and turbulence characteristic.

The standard deviations of the rotor averaged wind speeds for wind fields with different mean wind speeds can be seen in Table I. The normalized mean power generated from the baseline control system is also shown in Table I. It should be noted that the rated wind speed of the CART3 turbine is approximately 12.3 m/s, which means a uniform wind field at this speed will allow the turbine to reach P_{rated} in steady-state.

$\overline{v}$ [m/s]	σ [m/s]	σ_A [m/s]	σ_B [m/s]	σ_C [m/s]	$\overline{P}_{Baseline}$ [%]
10	1.35	1.52	1.33	1.19	53
12	1.52	1.72	1.49	1.33	88
14	1.68	1.90	1.65	1.48	99
16	1.85	2.09	1.81	1.62	100

Table I
The standard deviation σ of the rotor averaged wind speed for the total ensemble and turbulence characteristic A, B, and C, as well as the mean power generated by the baseline control system normalized to P_{rated} for wind fields with mean wind speeds from 10 to 16 m/s.

B. AGC Power Command Tracking

Figure 3 shows the performance scores as wind speeds vary from 11 to 15 m/s with $P_s = 80\%$ and $R^u = R^D = 20\%$. The wind fields with 11 m/s mean do not have enough power available to allow adequate tracking at this set-point and participation level. As expected, the performance improves as the mean wind speed of the simulations increase. The performance scores when using the RegA and RegD signals are very similar to each other, indicating the amount of actuation induced by the RegD signal is not a limiting factor. The metric P_{Loss} represents difference in normalized mean power generated between each scenario and the baseline control system which aims to maximize power production. The normalized actual mileage M_a/M is used to show the relative effect that the under response U has on the mileage payments.

Figure 4 shows the performance metrics at various power set-points when $R^U = R^D = 20\%$ and using the RegD AGC signal for mean wind speeds of 12 m/s. The results are shown for each IEC turbulence characteristic with A being the most turbulent, C being the least turbulent. As expected, the overall performance degrades as the power set-point increases due to the limitations of the wind resource. It can also be seen that higher performance scores can be achieved as the turbulence decreases, particularly when operating at higher power set-points. Figure 4 also shows the accuracy score for "up" and "down" regulation separately, denoted by S_A^U and S_A^D, respectively.

One interesting trend that can be observed in the results shown in Figures 3 and 4 is that the PJM delay score S_D remains very high, even when the other performance scores decrease, because even when the wind turbine cannot closely track the AGC command, the rapid actuation capability of the

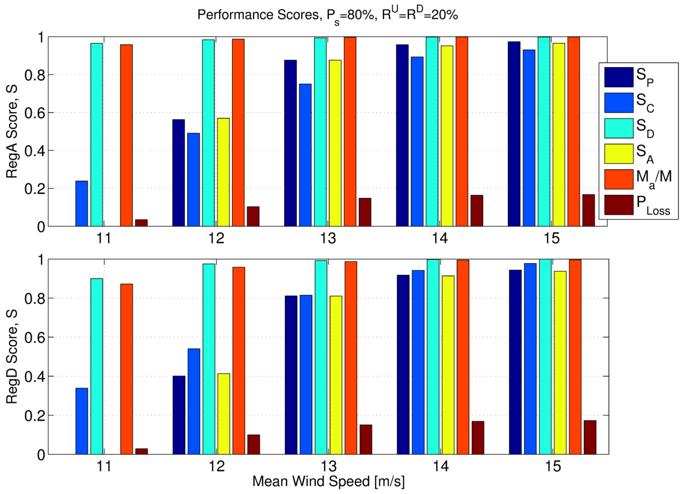

Figure 3. The performance scores when $P_s = 80\%$ and $R^U = R^D = 20\%$ when tracking the RegA and RegD power commands.

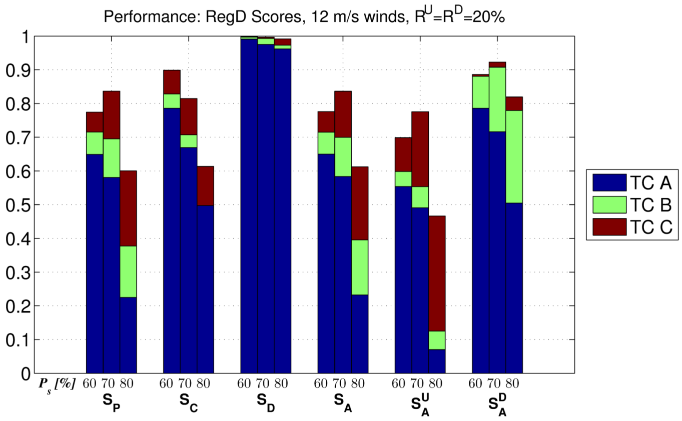

Figure 4. The performance scores when tracking the RegD AGC command at various set-points with $R^U = R^D = 20\%$ for each turbulence intensity class with mean wind speeds of 12 m/s.

wind turbine allows for the maximum normalized coherence to occur with very little time shift.

Another useful analysis is determining the performance scores under higher wind speeds when the power schedule is equal to the rated power of the turbine $P_s = P_{rated}$ so that the wind turbine is not persistently shedding power that could have otherwise been captured. Figure 5 shows the accuracy performance score when R^D is 10%, 20%, and 30% with mean wind speeds of 13, 14, and 15 m/s. This figure shows that performance improves as R^D increases because there is a decreased probability of experiencing wind resource deficiencies as R^D increases, as the power available from the wind is the factor limiting performance, not the increased magnitude of actuation.

C. Damage Equivalent Loads (DELs)

It is important to assess the impact of providing AGC services on the fatigue loads of turbine structural components. The fatigue loads are represented as DELs, which are

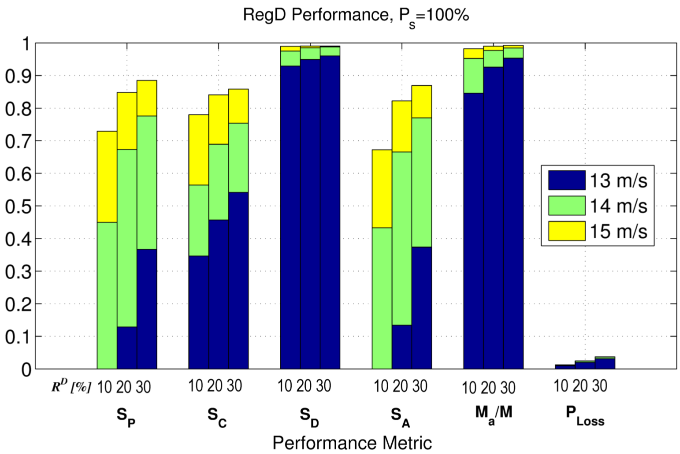

Figure 5. The performance scores when the power schedule is equal to P_{rated} and tracking the RegD AGC command at various levels of participation down.

calculated from the bending moment load cycles with an alpha version of MLife, a damaging loads assessment code developed at NREL [15]. The DELs were calculated using a Wöhler exponent of 10 for the composite blades and 3 for the low-speed shaft and steel tower. The RegD signal is used as the AGC command in the DEL analysis since this signal induces more actuation and has a higher frequency content than the RegA signal.

The DELs, mean power, and RMS pitch rates were compared for wind fields with a mean of 14 m/s for various power set-points and participation amounts, as seen in Figure 6. All metrics are presented as the percentage change from baseline operation, or maximum power capture scenario. The RMS blade pitch metric is compared to represent the wear-and-tear on the pitch motors. It should be noted that larger negative numbers represent a more significant decrease compared to the baseline, which is an improvement for the DELs and the RMS pitch rates.

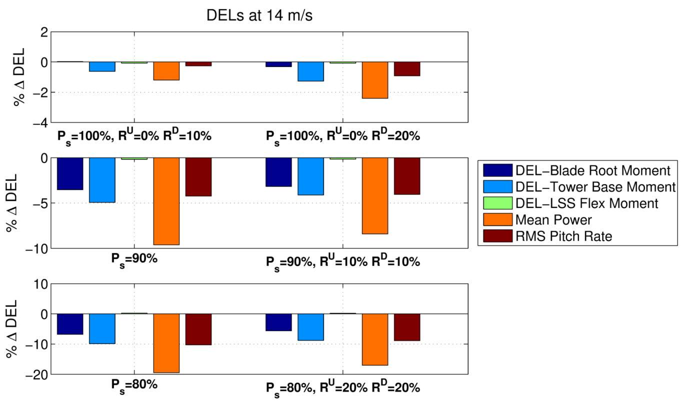

Figure 6. The DELs for 14 m/s mean wind speeds normalized by the DELs when operating in baseline operation (maximum power capture).

It can be seen in Figures 6 that de-rating the turbine generally reduces the DELs, the RMS pitch rates, and naturally the power capture. Participating in regulation services appears to have very little effect on the damage equivalent loads. This analysis did not consider the effects on the power electronics because the timescales required to model the power electronics are an order of magnitude smaller than those used in this research.

V. Conclusions and Future Work

This paper presents the results of simulating an individual wind turbine with a control system that is capable of providing frequency regulation services by tracking an AGC command scaled to various participation factors added to a constant power schedule. The control system used in this study utilizes industrial standard sensors and actuators and many manufacturers currently have wind turbine control systems with similar capabilities. The US regulation markets now compensate resources partially based on their performance scores, which provides increased motivation for resources with rapid actuation capability to participate in AGC.

The simulation results presented in this paper show that when significant wind resource is available, a wind turbine can control its power output to track the AGC signal very rapidly and accurately, allowing for high performance scores. The simulation results show that the wind turbine can achieve similar performance scores when tracking both rapidly and slowly varying AGC test signals. The results also show that the turbine and control system used in this study experience a performance score decrease for wind fields with a mean wind speed of 12 m/s, which is close to the rated wind speed of the turbine. The amount of performance degradation depends on the turbulence of the wind fields, with less turbulent winds producing higher performance scores. Decreasing the power set-point also allows for increased performance scores, particularly at wind fields with mean wind speeds of 12 m/s. Reducing the power of the scheduled set-point also has a beneficial effect on the damage equivalent loads (DELs) and the participation in regulation services has a negligible impact on these loads.

Providing regulation services does require that a wind turbine or wind power plant to capture less than the maximum available power from the wind. This means that the expected economic revenue for participating in regulation services must be greater than the expected loss in revenue for the energy sales in order for this service to be viable, particularly because wind turbines have no fuel costs. In the US, production tax credits are given to wind power plant owners based on the energy production, and adds an economic bias toward capturing maximum power rather than participating in regulation services.

It is important to note that the results shown in this paper represent the performance of a single 600 kW wind turbine. It is recommended that future work analyze the performance scores of larger scale wind turbines, wind power plants, and non-collocated wind power plants. It is expected that the performance scores of wind power plants would be higher than those of an individual wind turbine, as the spatial filtering of aggregating the power of multiple turbines over a larger geographical area would reduce the effective variability in the wind resource.

It is clear that accurate wind forecasting is a very important component to the viability of wind power plants participating in the current frequency regulation markets, as the performance scores are largely dictated by the available wind resource. wind power plant owners would require an expected increase in revenue before opting to provide regulation services, which is highly dependent upon their confidence in these probabilistic wind forecasts.

Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

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