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Examining the Variability of Wind Power Output in the Regulation Time Frame

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Examining the Variability of Wind Power Output in the Regulation Time Frame

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***Abstract*—The integration of increasing amounts of renewable power sources, such as wind power, has been a source of concern for power system operators because of the variability and uncertainty of the power output. One way the impacts of variability and uncertainty are mitigated is through the holding of reserves that can quickly increase or decrease generation to mirror changes in demand. At small timescales, this is known as regulation reserve. In this work, we examine the distribution of changes in wind power for different timescales in the regulation time frame as well as the correlation of changes in power output for individual wind turbines in a wind plant. The wind plant in question is located in the Xcel Colorado service territory in the United States, and contains approximately 300 megawatts of wind power capacity.**

***Keywords*—wind power, renewable generation, power system integration, variability**

I. INTRODUCTION

Renewable generation is playing an increasingly important role in power system operations as the amount of energy supplied by renewable generators expands. Increasing amounts of wind and solar generation being introduced into power systems has raised concerns about how system operations will have to change to accommodate their variable and uncertain output [1]. Large installations of wind power capacity necessitate that variability and uncertainty become a critical concern for power system operators; however, power system operators are already accustomed to accommodating variable and uncertain load. The impacts of load variability and uncertainty can be mitigated through the holding of reserves that match demand by quickly increasing or decreasing generation. In this work, we are primarily interested in the short-term regulation reserve time frame, which maintains system frequency by balancing supply and demand at the seconds-to-minutes timescale [2].

The impacts of the variability and uncertainty of renewable generation on power systems operations has been a major concern of large-scale renewable energy integration studies [2–9]. The studies typically simulate a future power system with varying high-wind penetration scenarios, and evaluate the impacts on the grid and the operating costs that result. They most commonly consider wind integration as a decrease in net load. Milligan et al. [9] provide an overview of studies regarding the impact that wind energy plants may have on regulation and reserves in an integrated system. The most common concern for studies that consider the impact of wind integration on reserves is that the additional uncertainty incorporated into the power system will increase operating expenses because of the necessity for increased reserves, in particular costly fast-acting reserves that can accommodate rapid changes in generation [6–9]. Doherty and O'Malley [8] found in their integration study of the all-Ireland electricity system that as wind capacity increases, the system must increase the reserve carried or face measurable declines in reliability. However, the portion of their analysis that corroborates this claim is restricted to long forecasting horizons (greater than one hour ahead), because extra reserves must be committed to cater for possible wind power deficits between the time the operating decisions were made and the period in question. In this paper, we are concerned with the seconds-to-minutes-ahead forecasting horizons of the regulation timescale. The smoothing of wind power variability at short timescales has been shown to be an advantage of increased geographic distribution of wind farms [10–11]. Additionally, Focken et al. [10] showed that this smoothing occurred in longer forecast horizons, ranging from minutes to hours.

In this paper, we examine the distributions of changes in wind power output that occur at different timescales in the regulation time frame. We also consider the correlation of changes in power output for individual wind turbines within the plant. The wind plant considered in this paper is located in the Xcel Colorado service territory in the United States and has a wind power capacity of approximately 300 megawatts (MW).

The remainder of this paper is organized as follows. Section II describes the methods and data used in the analysis. Section III reports the results of analyzing the distributions and correlations of wind power output changes, both at various timescales within the regulation time frame and at different spatial scales. Conclusions are drawn and implications for future studies and for power systems operations are outlined in Section IV.

II. METHODS AND DATA

This section outlines some of the important methods involved in the study. Section II-A contains information regarding the data sets analyzed in this paper. Section II-B provides some relevant background information regarding statistical methodology that may aid the reader in understanding the results that follow.

A. Data Utilized

The wind data used in this study came from a wind plant in the Xcel Colorado service territory with a total wind power capacity of approximately 300 MW. The data consisted of the 1-min average power output from each of the turbines in the wind plant. Two different models of turbines were included in the data set, so the data from each of the different turbine groups were analyzed independently. The first data set consisted of 53 1.5-MW turbines; the second comprised 221 1-MW turbines.

B. *Methodology*

Histograms and probability density functions were used to describe both the range of values that a given random variable can take and the likelihood of a sampled random variable falling in a specific range. In this paper, we used them to characterize the ramps in wind power output at varying timescales.

Often when analyzing data, we want to know if two variables are correlated. Correlation measures the linear dependence between two variables, and correlation values fall within the range of -1 to 1. A value of 1 indicates that one variable is a positive linear function of the other, -1 means one variable is a negative linear function of the other, and 0 indicates a lack of correlation entirely. In this paper, we used the Spearman [12] correlation statistic, ρ, defined in (1):

$$\rho = \frac{n(\sum_{i=1}^{n} x_i y_i) - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{\sqrt{n(\sum_{i=1}^{n} x_i^2) - (\sum_{i=1}^{n} x_i)^2}\sqrt{n(\sum_{i=1}^{n} y_i^2) - (\sum_{i=1}^{n} y_i)^2}} \quad (1)$$

where x and y are the random variables in question and n is the length of the random variables [12–14].

In Section III-B, the correlation coefficients calculated using (1) are displayed using a heat map, which is a graphical representation of data wherein the individual values in a matrix are represented as colors [15] . In the heat maps that follow, the sets of individual wind turbines were examined for cross-correlation; thus, the heat map displays darker colors for a pair of turbines that were relatively uncorrelated and lighter colors for correlations of greater magnitude.

III. RESULTS

Having established the importance of reserve-focused analysis of wind power generation, and provided the necessary background information, we characterized the variability of wind power in the regulation timescale. Section III-A examines the distributions of changes in power output at varying timescales, and Section III-B analyzes the correlation of power generation and ramps in power between individual turbines within the plant.

A. *Distribution of Ramps at Varying Timescales*

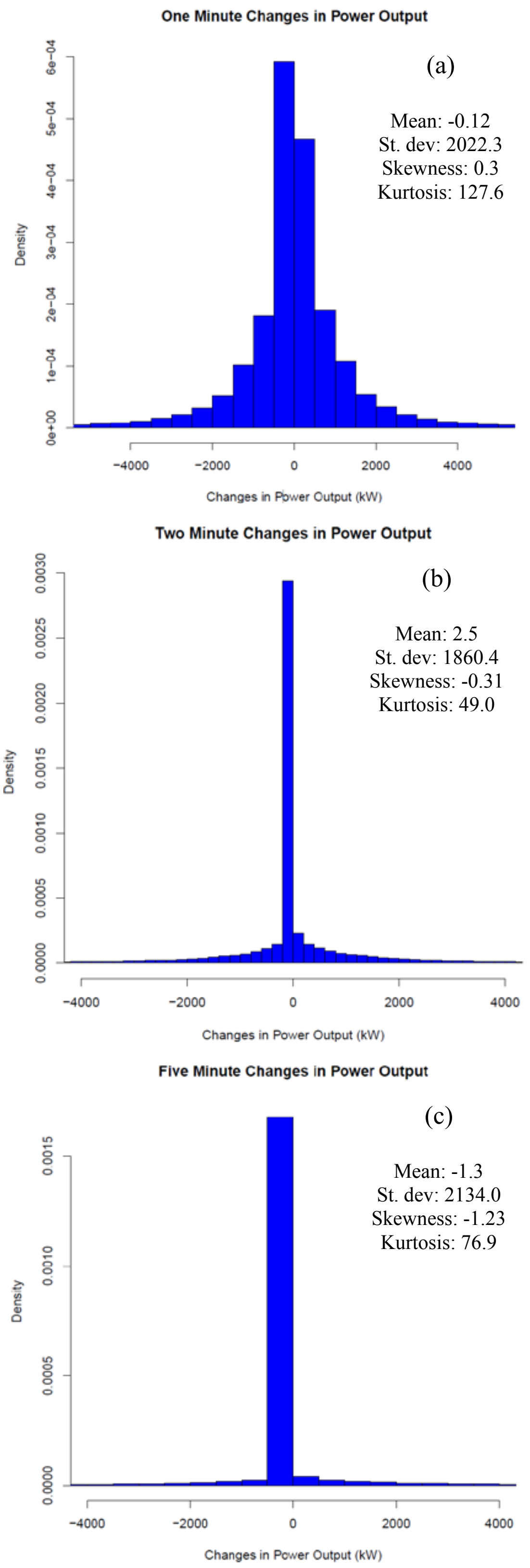

Figure 1. Histograms illustrating the distributions of changes in aggregated wind power output for all turbines in both data sets measured during a period of seven months in 2011 at timescales of (a) 1 min, (b) 2 min, and (c) 5 min. Note: The scope of the histograms is limited to clarify visual appearance; the 1-min, 2-min, and 5-min data had ~6000, ~8500, and ~4500 data points exceeding the magnitudes of the displayed x-axes, respectively. These quantities all represent very small percentages of total data.

Figure 1 (a–c) shows the distributions of changes in wind power output from 53 turbines of the same make and model at a single wind plant at the regulation timescales of (a) 1 min, (b) 2 min, and (c) 5 min, measured during a period of seven months in 2011. In all cases, the distributions were centered at 0, with minimal skewness; however, the relative magnitude of the peak increased with increasing timescale. For all three regulation timescales, the distribution exhibited "fat tails" that were indicative of significant instances of high-magnitude ramps. These ramps are the most problematic for power system operators. To further characterize these changes in wind power output, in Section III-B we examine their correlation across arrays of turbines.

B. *Correlation Analysis*

The first subset of the wind power data examined consisted of 53 turbines of the same make and model located at a single wind plant. Figure 2 shows the correlation of wind power output between each of the individual turbines at the 1-min timescale during the course of an entire month. As shown in the color key, the power output of the individual turbines was well correlated, with an average Spearman's ρ value of approximately 0.81. Note that the data included times when individual turbines were not operational. For example, turbine four had a fairly low correlation with most of the other turbines. This can be explained by a nearly weeklong period at the beginning of the month when the turbine was out of service.

Although understanding the correlation of wind power output is important for the incorporation of wind, more critical for determining the regulation reserves necessary is the correlation of changes in power output between individual turbines. As shown in Figure 3, the correlation coefficients of the 1-min changes in individual turbine power outputs in the same wind plant were very low, with an average around 0.05. There seemed to be slightly higher correlation among adjacent turbines, as shown in the lighter shading among turbine combinations adjacent to the diagonal of self-correlation. These low-correlation coefficients indicated that the factors that cause variability in wind turbine output at the regulation timescale are very localized weather patterns, such as gusts of wind that impact a only single turbine at a time.

Examining the larger group of 221 1-MW turbines provided another interesting example. Because of the greater number of turbines, there also existed greater spatial variation. However, as seen in Figure 4, there were lower correlation coefficients across the board than from the 53 turbine data set. The average power output correlation coefficient was 0.36, compared to 0.81 for the larger turbines. This result corroborates the work by Hudson et al. [14] that found that as the number of wind turbines included in a sample increased, the relative regulation support required by the system decreased. Hudson et al. attributed this result to intra-system geographic diversity, illustrated by the phenomenon that "when a wind gust sweeps through the site, it reaches some turbines sooner than others" [14].

Again, a few of the turbines that experienced significant outages during the month of data were immediately apparent because of their much lower correlation coefficients.

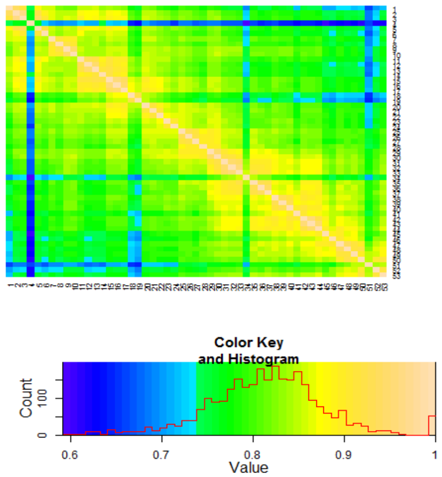

Figure 2. Heat map of the correlation coefficient of 1-min power output for 53 turbines of the same wind plant for the month of August 2011.

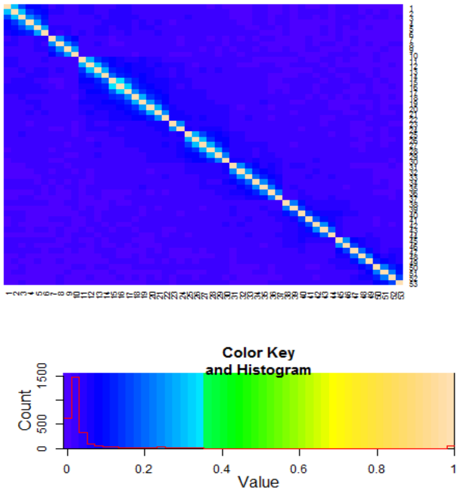

Figure 3. Heat map of the correlation coefficient of 1-min power output changes for 53 turbines of the same wind plant for the month of August 2011.

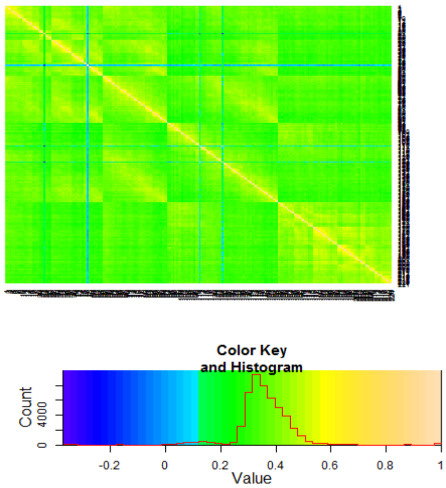

Figure 4. Heat map of the correlation coefficient of 1-min power output for 221 turbines of the same wind plant for the month of November 2011.

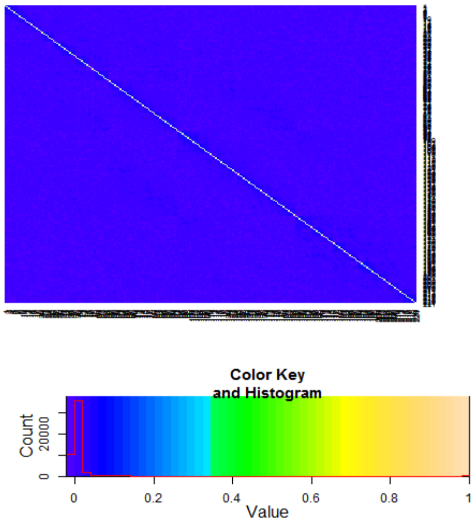

Figure 5. Heat map of the correlation coefficient of 1-min power output changes for 221 turbines of the same wind plant for the month of November 2011.

The correlation between the changes in 1-min power output between the 221 1-MW turbines are shown in Figure 5. Again, the changes in 1-min power output between the individual turbines were very poorly correlated, and even included some instances of negative correlation. The mean value for the Spearman's ρ value for the 221 turbines was essentially 0, showing that the 1-min fluctuations of power from individual turbines in the same wind plant were uncorrelated.

IV. CONCLUSIONS

In this work, we examined the distributions of wind power output at varying timescales within the regulation time frame. Although most of the distributions of changes were clustered around a strong peak at zero at all regulation timescales analyzed, the distributions for all timescales also exhibited significant instances of higher magnitude ramps in the tails of the histograms. To characterize these ramps further, we also considered the correlation of changes in power output for individual wind turbines throughout the plant. Although understanding the correlation of wind power output is important for the incorporation of wind, more critical for determining the regulation reserves necessary is the correlation of changes in power output between individual turbines. Although power output levels of individual turbines were found to be significantly correlated, the changes in power output between individual turbines were uncorrelated. This lack of correlation at the regulation timescale indicates that the impact on the levels of regulation reserve required to accommodate variability will be less than previously theorized, because the changes in power output for individual turbines are smoothed by increased numbers of turbines and the resulting geographic variability.

ACKNOWLEDGMENTS

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