Wind Ramp Events at Turbine Height–Spatial Consistency and Causes at two Iowa Wind Farms

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Abstract

Ramp events cause a change in power output of 50% or more of the total capacity of wind turbines. As wind energy becomes a more prevalent power source, an understanding of ramp events becomes important. This study analyzes the spatial consistency of ramp events between two Iowa wind farms approximately 160 km apart in order to improve wind forecasting. The meteorological causes, timing, and consistency from the surface to wind turbine height were all studied in relation to the spatial consistency between wind speed data from a meteorological tower in Pomeroy, IA and nacelle data from six 80 m wind turbines in a central Iowa wind farm. Finally, there were several cases at the central Iowa wind farm where some turbines experienced a ramp, but others did not. The causes of these anomalies were also explored.

1. Introduction

The U.S. Department of Energy's scenario to generate 20% of electrical energy from wind by 2030 (Department of Energy 2008) drives meteorologists to have a better understanding of the wind profile from the surface to turbine height. Wind energy can be an unreliable resource because wind is inconsistent. With added issues from lack of storage capabilities, ramp events are another downfall to wind energy that bring sudden changes in power output with wind speeds ramping up or down to the cut-out range. If these events were better understood, they could be forecasted. However, little work has been done to study the behavior of these events, so the best forecasting method has not been discovered yet.

This study is a continuation of a previous study by Showers Walton et al. (2012). The previous study discovered that there were many causes for ramp events in Pomeroy, IA from 29 May 2008—12 November 2009, but storms and the presence of a strong pressure gradient, suggesting strong winds and mixing, were the most prevalent causes, agreeing with other studies that found convection, fronts, and low level jets (LLJ) to be the biggest causes of ramp events (Freedman et al. 2008). In order to determine a meteorological cause for ramp events, Freedman et al. (2008) utilized surface maps from the National Climatic Data Center (NCDC), wind profilers from the National Oceanic and Atmospheric Administration (NOAA), sounding data from the National Weather Service (NWS), NWS high-resolution Automated Surface Stations (ASOS) data, and archived Next-Generation Radar (NEXRAD) Weather Surveillance Radar 88 Doppler (WSR-88D) level II data. This study used similar resources to that of Freedman et al. (2008) in order to determine the causes of ramps in Pomeroy, IA from 26 June 2010–8 September 2010 and for the central Iowa wind farm from 26 June 2010–8 September 2010 and 28 June–16 August 2011. Showers Walton et al. (2012) also discovered that 40% of the ramps in central

Iowa occurred within 6 hours of a ramp in Pomeroy, suggesting spatial consistency. This study expanded on this result through the analysis of the meteorological cause of these ramp events.

Ramp events in a study by Deppe et al. (2012) in Pomeroy, IA found peaks in frequency of these events in December and June, with minima in February and August. In a West Texas study, ramp events were found to be most frequent in spring and summer (Freedman et al. 2008). Contrasting definitions of a ramp event or meteorological differences between locations of studies could cause differences in the peak frequencies. Deppe et al. (2012) found ramp-ups to occur most often from 0000–0300 UTC (1800–2100 LST) as the surface layer decouples from the overlying atmosphere and the LLJ forms. Ramp-ups in the West Texas study were also found to follow this pattern, peaking at 0100 UTC (1900 LST) (Freedman et al., 2008). Ramp-downs were not found to have a distinct pattern in the West Texas study; however, in the Pomeroy study they were found to peak from 1200–1500 UTC (0600–0900 LST). Around this time, the surface begins to warm and the LLJ ends. These findings were kept in mind when analyzing data for this study.

2. Data and Methods

This study utilizes wind speed data from Pomeroy, IA and wind speed and direction data from six nacelles in a central Iowa wind farm that underwent extensive quality control in Showers Walton et al. (2012). All data was taken every 10 min and periods when the wind speed suddenly dropped to zero were considered erroneous and therefore excluded. Ramp-ups and ramp-downs were classified by a change in wind speed of 3 ms^{-1} or more between 6 and 12 ms^{-1} in 4 hours or less as in Deppe et al. (2012). Meteorological causes were sought out for the Pomeroy, IA ramps in 2008 and 2009 using Iowa State University's meteorological archive data server, the Iowa Environmental Mesonet (2012) archives, Unisys (2012) archive, and the Hydrometeorological Prediction Center (2012) surface analysis archive. These resources provided mean sea level pressure maps, radar, wind profilers, and surface station archives to determine possible meteorological causes for ramp events.

Ramp causes were assigned by assessing large scale features such as the presence of a front or a LLJ. If neither of these phenomena were present, radar archives were used to look for storms and associated outflow. Finally, if no cause could be attributed to the reasons above, the pressure gradient and PBL growth was analyzed assuming that with a strong pressure gradient there will be stronger winds which could cause mixing and, therefore, a ramp event. PBL growth could result in turbulent mixing due to diabatic heating which could cause a ramp event.

This same method was applied to establish a cause for ramp events in Pomeroy from 26 June–8 September 2010, the central Iowa turbines from 26 June–8 September 2010 and 28 June–16 August 2011, and ASOS 10 m wind data within 20 miles of the central Iowa turbines from 26 June–8 September 2010 and 28 June–16 August 2011. According to the power law, winds near the surface are not the same as at 80 m. Therefore, the ramp definition was scaled down for the ASOS winds according to the equation:

$$(1)\ \frac{u_{10}}{u_{80}} = \left(\frac{z_{10}}{z_{80}}\right)^{\alpha}$$

Where u_{10} and z_{10} are the wind and height at 10 m, and u_{80} and z_{80} are the wind and height at 80 m. In a neutral atmosphere, α can be assumed to be 1/7; however, this is a poor assumption at night because of the nocturnal LLJ. Therefore, from sunset to sunrise α was set to 1/4. This resulted in 10 m ramps being a 3 ms^{-1} change from 4.5–8.9 ms^{-1} during the day and from 3.6–7.1 ms^{-1} at night.

Ramps occurring in central Iowa within 6 hours of a ramp of the same type in Pomeroy, IA were considered to be the same ramp. This study looked into the causes of these spatially consistent ramps to determine a relationship between the speed of the ramp and its meteorological cause. Finally, when a ramp only occurred at some of the six central Iowa turbines, this study considered the meteorological cause and wind speeds at turbines that did not experience a ramp to determine whether they were close to ramping or if the ramps at the other turbines were due to small-scale phenomena.

3. Results

This study expanded on the results of Showers Walton et al. (2012) which discovered a variance in the peak in frequency of ramp-ups by location and year, but there was a general consensus that ramp-ups peak in the late night/early morning, 2200–0200 LST, and again from 0600–1000 LST (Fig. 1, 2).

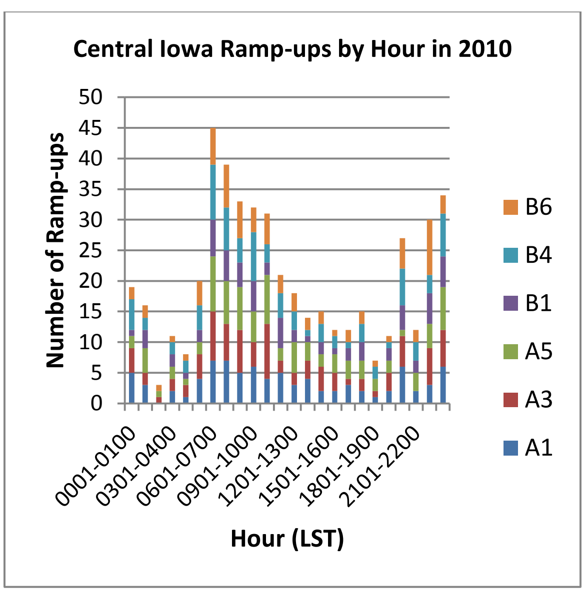

Figure 1: Number of ramp-ups by hour at each turbine in central Iowa (A1-B6)

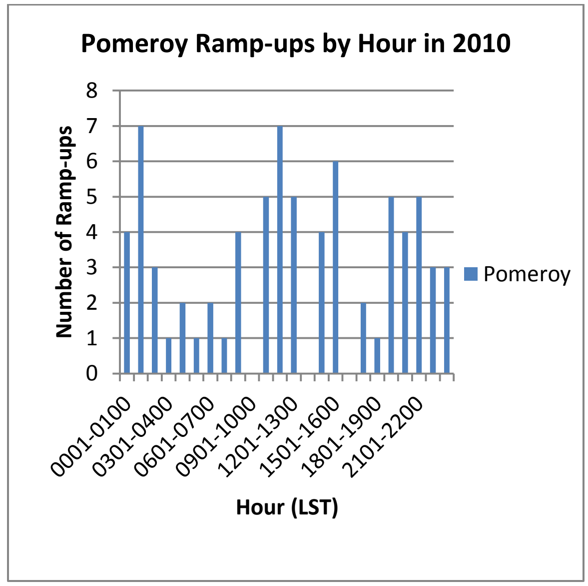

Figure 2: Number of ramp-ups by hour at the Pomeroy meteorological tower

While there is a smaller peak in frequency from 1800–2100 LST +/- 2 hours as in Deppe et al. (2012), the main peaks in this data set did not match up. This could be due to the much shorter data set used by this study, 2 ½ months compared to 2 years, or the difference in seasons. This data set only observed summer ramp events which would imply more convection and turbulent mixing with different timing than the winter. Ramp-downs didn't seem to follow as distinct of a pattern as ramp-ups, as seen in Fig. 3 and Fig. 4.

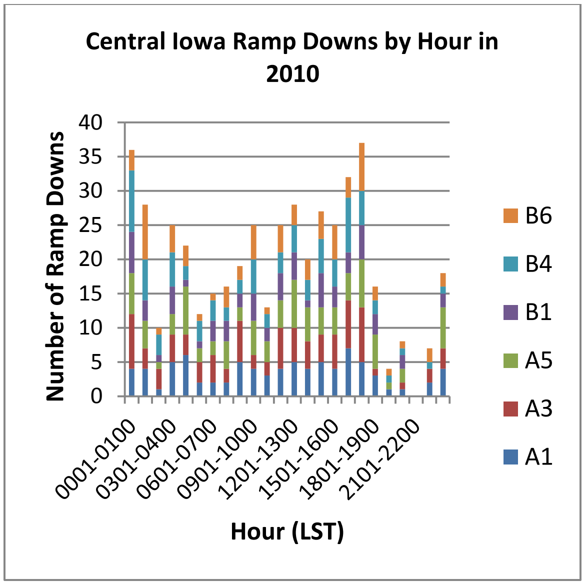

Figure 3: Number of ramp-downs by hour at each turbine in central Iowa. Notice multiple peaks in frequency

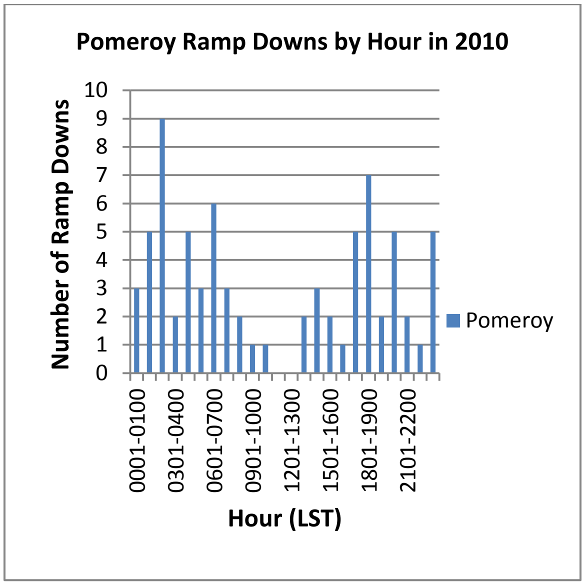

Figure 4: Number of ramp-downs by hour at the meteorological tower in Pomeroy, IA. Two significant peaks in frequency around 0300 and 1800 LST.

As noted by Fig. 3 and Fig. 4, the timing of ramp-downs is very different in central Iowa than in Pomeroy suggesting little pattern exists for ramp downs.

Meteorological causes attributed to ramp events were used to determine their relationship with spatially correlated ramps between Pomeroy and central Iowa. Forty percent of all ramps in central Iowa occurred within six hours of a ramp of the same type in Pomeroy, IA. Thirty six percent of all ramps in central Iowa occurred within two hours of a ramp in Pomeroy (Fig. 5).

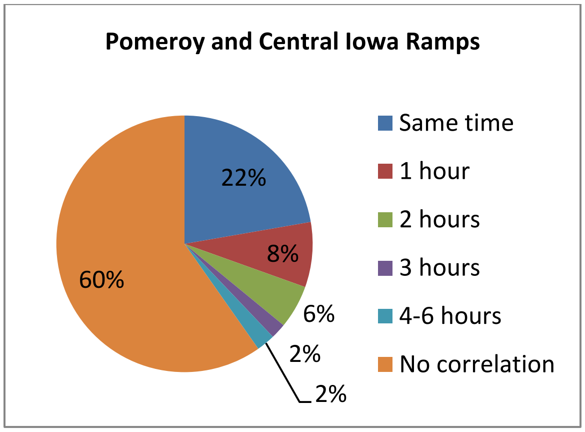

Figure 5: Spatial consistency of ramps from Pomeroy to central Iowa

The presence of a strong gradient was the biggest contributor to spatially consistent events that occurred 2 hours apart. Twenty-six percent of the ramps were due to unknown causes (Fig. 6). This could be due to a short data set, missing profiler data, or small-scale features such as turbulence.

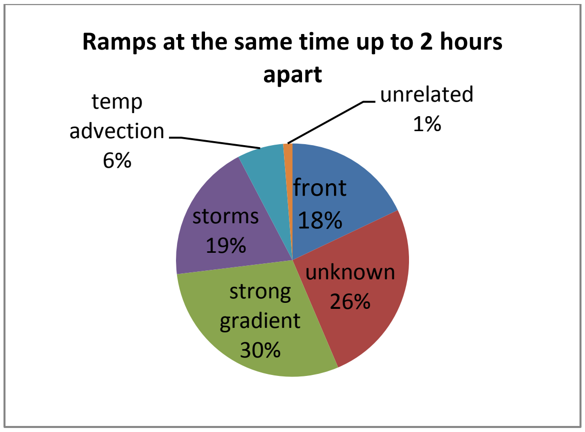

Figure 6: Causes of ramps in central Iowa occurring at the same time as ramps in Pomeroy up to 2 hours prior.

Fronts in these cases were oriented in a way that they affected both locations around the same time. Storms were oriented in a similar manner or were rapidly moving.

When reaching 3-6 hours apart, ramp events were found to be due to fewer variables (Fig. 7).

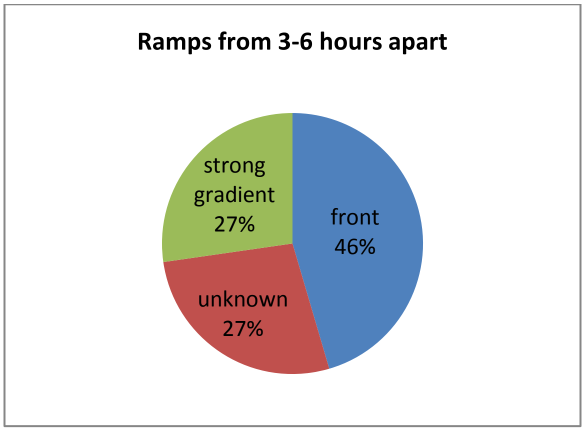

Figure 7: Causes of ramps in central Iowa occurring 3-6 hours prior to a ramp of the same type in Pomeroy, IA

At this stage, 46% of ramps were due to fronts. There are still a good portion of ramps that are due to unknown causes for the same reasons listed above.

This study determined the meteorological cause for 154 ramp events in Pomeroy, IA in 2010 and 1485 ramp events among the six turbines in central Iowa in 2010 and 2011 found by Showers Walton et al. (2012). Most of the Pomeroy ramp events were due to unknown causes with the presence of a strong gradient or front close behind (Fig. 8).

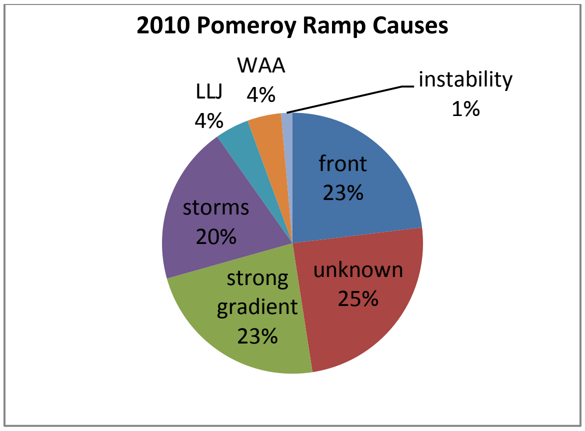

Figure 8: Causes of 2010 Pomeroy ramps determined meteorological data archives

It should be noted, however, that there were several cases where wind profiler data was unavailable and there was only 2 ½ months of data available. Therefore, more data is needed to create a comprehensive climatology of 80 m ramp behavior. Most of the 2010 central Iowa ramps, evaluated during the same time period as the Pomeroy ramps, were also due to the presence of a strong gradient or storms (Fig. 9).

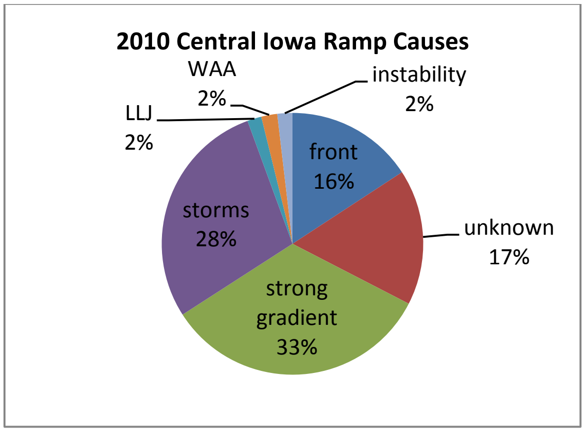

Figure 9: Cause of 2010 central Iowa ramps determined by meteorological data archives

The results of each cause between the two sites are within 10% of each other indicating a consensus among the data and across the state. Finally, the 2011 central Iowa ramps were mostly due to unknown causes (Fig. 10).

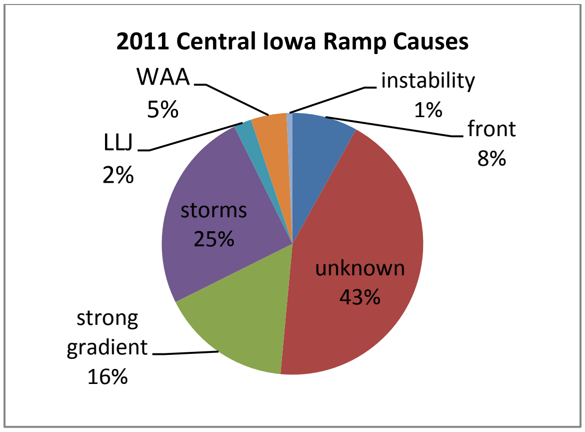

Figure 10: Cause of 2011 central Iowa ramps determined by meteorological archive data

Again, data encountered many periods where wind profiler data was unavailable so ramps due to LLJ would not be determinable. This period was also shorter, only 1 ½ months. These findings imply consistency in causes of ramps showing that they are due to both large and small-scale features.

ASOS wind speed data at 10 m was used during the same time period as the central Iowa data in order to establish a relationship between 10 m and 80 m ramps. As shown by Eq. 1, the definition of a ramp was scaled for 10 m according to the power law. Using the new definition, this study found 115 scaled ramp events at 10 m in 2010 in central Iowa and 63 scaled ramp events in 2011 in central Iowa. In using the original ramp definition, 59 unscaled ramps were found in 2010 and 27 unscaled ramps were found in 2011. This study was not able to collect 10 m data for Pomeroy due to the ASOS station being down during the data period.

A scaled 10 m ramp was able to capture a ramp at 80 m 47% of the time during the 2010 dataset and 56% of the time during 2011. This is not a perfect system; however, when there was a scaled ramp at 10 m, 72% of the time there was a ramp at 80 m in 2010 and 59% of the time in 2011. This implies that when the surface ramp is able to capture the upper level ramp there is spatial consistency. It seems that most of the time ramps at the surface are related to ramps above; however, in the 28% that are unrelated in 2010 and the 41% that are unrelated in 2011 most of these events seem to be completely cut-off from the 80 m layer. Ten meter wind speed data is readily available in the Midwest, unlike 80 m data. Therefore, this relationship between ramps at the surface and ramps at 80 m could help improve forecasting.

Since there were several wind turbines available in central Iowa, this study looked into the behavior of ramp events within a wind farm. Several cases were found where one or more turbines did not experience a ramp while the others within the same line did. When one or more turbines did not experience a ramp, the speed by which the turbine was off from 3 ms^{-1} was calculated. This value was converted to a percentage in order to see how close the turbines that missed a ramp were to a 3 ms^{-1} change (Fig. 11).

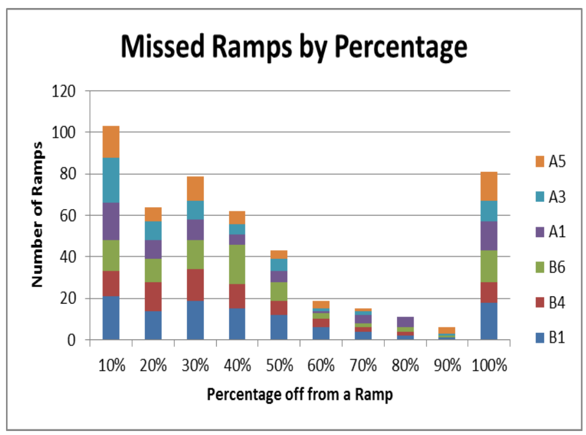

Figure 11: The number of non-ramps by turbine organized by percentage away from a ramp

Turbines assigned a value of 100% experienced a ramp of the opposite type (a ramp-up when there were ramp-downs at the other turbines) or were outside the limits of this study's definition of a ramp. Once ramps enter the first line of turbines in a wind farm there is evidence suggesting small-scale turbulence is created causing the ramp to die out or even turn into a ramp of the opposite type.

4. Conclusions

Ramp-ups and ramp-downs are hard to predict due to many meteorological causes and few studies on these events. This study has discovered ramps to be spatially consistent within 160 km at 80 m. Forty percent of all ramps in central Iowa found in this study occurred within six hours of a ramp of the same type in Pomeroy, IA. To ensure that the ramps reaching central Iowa were the same ramps that took place in Pomeroy, meteorological data archives were used to determine the cause of each ramp. Most of the ramps in central Iowa that occurred within 2 hours of a ramp in Pomeroy were associated with a strong pressure gradient, implying strong winds and possible wind shear. Ramps in central Iowa occurring within 3-6 hours of a ramp in Pomeroy were mostly due to frontal passage.

Ten meter ramp events in central Iowa found using a scaled definition through the power law revealed a correlation between ramps at the surface and ramps at 80 m with 47-56% of 80 m ramps captured at 10 m. Since 10 m wind observations are more abundant in the Midwest than 80 m observations, 10 m wind speeds could be used to estimate behavior at wind turbine height making forecasting of ramp events simpler.

Finally, this study looked into the behavior of ramp events within a wind farm. In cases where one or more turbines did not experience a ramp the percentage by which that turbine was off of reaching a ramp was studied. It was found that most of these were either off by only 10%, exhibited an opposite ramp, or were outside the defined wind speeds. This indicates micro-scale features are taking place to evolve ramps throughout wind farms which with more in depth study could improve forecasting.

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