




Synchronized Phasor Data for Analyzing Wind Power Plant Dynamic Behavior and Model Validation

Y.-H. Wan

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-57342
January 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

Synchronized Phasor Data for Analyzing Wind Power Plant Dynamic Behavior and Model Validation

Y.-H. Wan

Prepared under Task No. WE11.0930

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5500-57342
January 2013

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

List of Acronyms

AC	alternating current
BPA	Bonneville Power Association
DOE	U.S. Department of Energy
EHV	extra-high-voltage
GPS	Global Positioning System
LRS	Laramie River Station
LVRT	low-voltage ride-through
MISO	Midwest Independent Transmission System Operator
NREL	National Renewable Energy Laboratory
NERC	North American Electric Reliability Council
NSP	Northern States Power
OG&E	Oklahoma Gas and Electric Company
PMU	phasor measurement unit
PSC	Public Service Company of Colorado
SCADA	supervisory control and data acquisition
VFD	variable frequency drive
WAPA	Western Area Power Administration
WECC	Western Electricity Coordinating Council
WPP	wind power plant

Table of Contents

List of Figures

List of Tables

1 Introduction

The U.S. power industry is undertaking several initiatives that will improve the operations of the power grid. One of those is the implementation of "wide area measurements" using phasor measurement units (PMUs) to dynamically monitor the operations and status of the network and provide advanced situational awareness and stability assessment.

Wind power as an energy source is variable in nature. Similar to other large generating plants, outputs from wind power plants (WPPs) impact grid operations; conversely, grid disturbances affect the behavior of WPPs. The rapidly increasing penetration of wind power to the grid has resulted in more scrutiny of every aspect of wind plant operations and the demand that large WPPs should behave similarly to conventional power plants under normal and contingency grid conditions. The low-voltage ride-through (LVRT) requirement for WPPs is one such example. Other proposed requirements include frequency response and simulated plant inertia.

To completely describe the system condition (state) of the electric power grid at any instant, it is necessary to know the voltage (V), current (I), and apparent power (S) of every point (node/bus) of the system. All three quantities in the alternating current (AC) power system are complex numbers that can be represented by phasors with both a magnitude and a phase angle. Out of the three phasor quantities, only two (any two) are needed to derive the third based on the equation $S=VI^*=P+jQ$. The advance of computing power and worldwide availability of Global Positioning System (GPS) time signals make it possible for a PMU to measure voltage and current at a precise time and output these quantities in phasor form. GPS time signals can be accurate within 1 microsecond (µs) anywhere the signal is available. GPS time signals enable the synchronization of measurements across the very large distances that power system interconnections span. This new technology not only produces very accurate phasor measurements but also enables synchronized measurements in the same instant.

Current PMUs can output synchronized phasor measurements at 60 Hz. The faster PMU data rate enables the observation and analysis of many grid and WPP dynamic behaviors that were not possible with the standard utility supervisory control and data acquisition (SCADA) system, which typically provides one measurement every 4 to 6 seconds (s). Because of precise timing and higher data rates, synchronized phasors provide much better information for investigating interactions between WPPs and the grid. This gives system operators and planners unprecedented insight into the grid. A new set of tools have been developed around PMUs and synchrophasor data that enable operators and engineers to make real-time system stability assessments and post-event analyses. The U.S. Department of Energy (DOE), North American Electric Reliability Council (NERC), utilities, vendors, federal and private researchers, and academia are collaborating on the research, installation, and application of phasor data under the North American SynchroPhasor Initiative. However, although utilities are installing more than 1,000 new PMUs in the grid with support from the DOE Smart Grid Investment Grant, there is no concerted effort to put PMUs at large WPPs.

This task seeks to obtain PMU data from WPPs and grid reference points and develop software tools to analyze and visualize synchrophasor data to better understand WPP dynamic behaviors under normal and contingency conditions.

2 Objectives

The purposes of this task are to obtain PMU data from large WPPs and grid reference points and analyze the data for a better understanding of the dynamic interactions between WPPs and the grid under normal and contingency conditions. Such analysis will help system operators and turbine designers understand how a plant's LVRT capability can survive a forced outage of the critical transmission line and under what conditions. Phenomena such as inter-area oscillations, system frequency response and damping, and other forced oscillations in the system can be studied in more detail over a much wider area. The PMU data will also be used for WPP model validation. This task is part of our ongoing effort related to renewable energy plant modeling, documentation, and industry support. The three primary objectives are to:

1. Work with utilities and WPP operators to obtain PMU data;
2. Adopt and develop software tools to analyze and visualize PMU data; and
3. Use PMU data to validate the dynamic WPP models being developed at the National Renewable Energy Laboratory (NREL).

3 Approach

Two parallel efforts were used to gain access to PMU data from WPPs and grid reference points: existing (historic) PMU data from utilities and new PMU data from WPPs.

3.1 Existing PMU Data From Utilities

Two utilities, Oklahoma Gas and Electric Company (OG&E) and Bonneville Power Administration (BPA), have expressly required PMU installations at all large WPPs as part of the interconnection agreement for their systems. We approached both, but we were able to reach a nondisclosure agreement with only OG&E to access its PMU data. OG&E has 94 PMUs installed in its system, including nine PMUs to monitor six of the seven WPPs in its system (the six monitored wind plants totaling 930 MW of installed capacity). We received data from 79 OG&E PMUs for the period from December 2010 through June 2012. This large amount of data will allow us to develop algorithms to detect unusual behaviors of WPPs. We will take advantage of the nondisclosure agreement and request additional data sets from OG&E. Figure 1 shows the locations of OG&E PMUs. The data rate from OG&E PMU is 30 Hz.

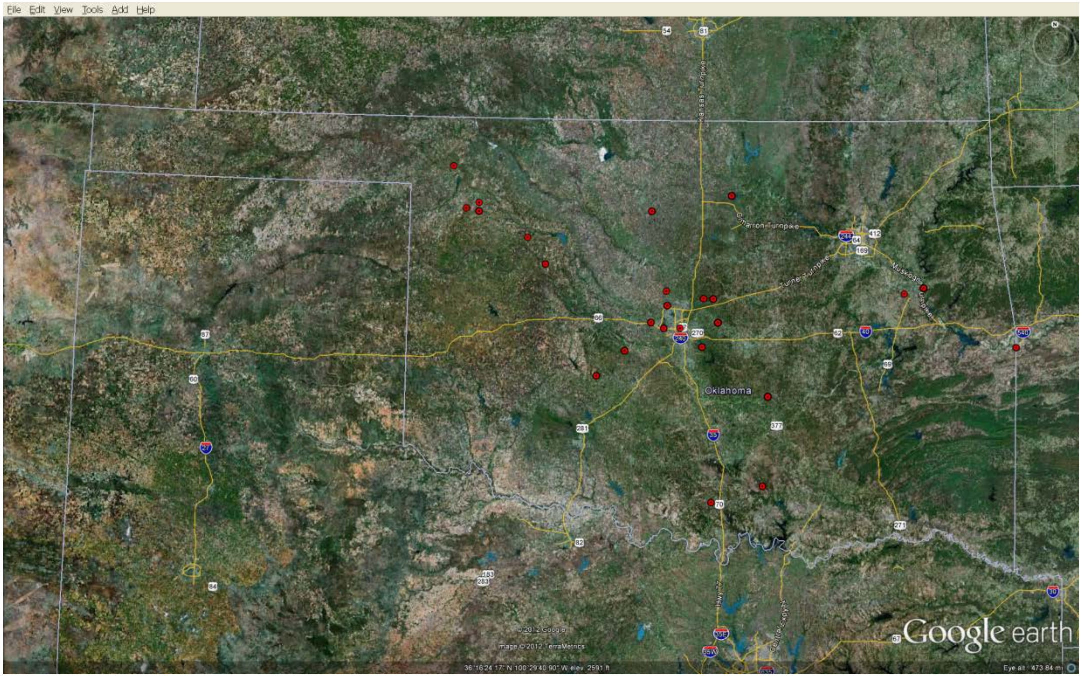

Figure 1. Locations of OG&E PMUs.

Table 1 below lists the six WPPs in the OG&E system where PMU data is available.

Table 1. WPPs with Synchronized Phasor Data

Name	Transmission Voltage	Installed Capacity	Turbine Manufacturer
Keenan	138 kV	152 MW	Siemens
OU WindSpirit	138 kV	101 MW	Siemens
Centennial	138 kV	120 MW	GE
Minco Wind	345 kV	200 MW	GE
Crossroads	345 kV	228 MW	Siemens
Taloga	138 kV	130 MW	Mitsubishi

NREL also completed a confidentiality and nondisclosure agreement with the Western Area Power Administration (WAPA) to gain access to its PMU data. WAPA has five PMUs in its Colorado Missouri, Upper Colorado, and Lower Colorado Regions, located at the Ault (near Loveland, Colorado), Craig (near Craig, Colorado), Shiprock (near the Four Corners area in New Mexico), Yellowtail (southeast of Billing, Montana), and Mead (near Hoover Dam, Nevada) substations (Figure 2). None of these substations connects to or is near a WPP; however, the PMU data from them can provide adequate information about the electric system conditions in Colorado because of their locations in the high-voltage transmission grid, and they will be the grid reference points when PMU data from a Colorado WPP become available through our work with the Public Service Company of Colorado (PSC), an operating company of Xcel Energy for Colorado. (Details of working with the PSC are discussed in Section 3.2 below.) We received sample PMU data from WAPA. The data rate of WAPA PMU is also 30 Hz.

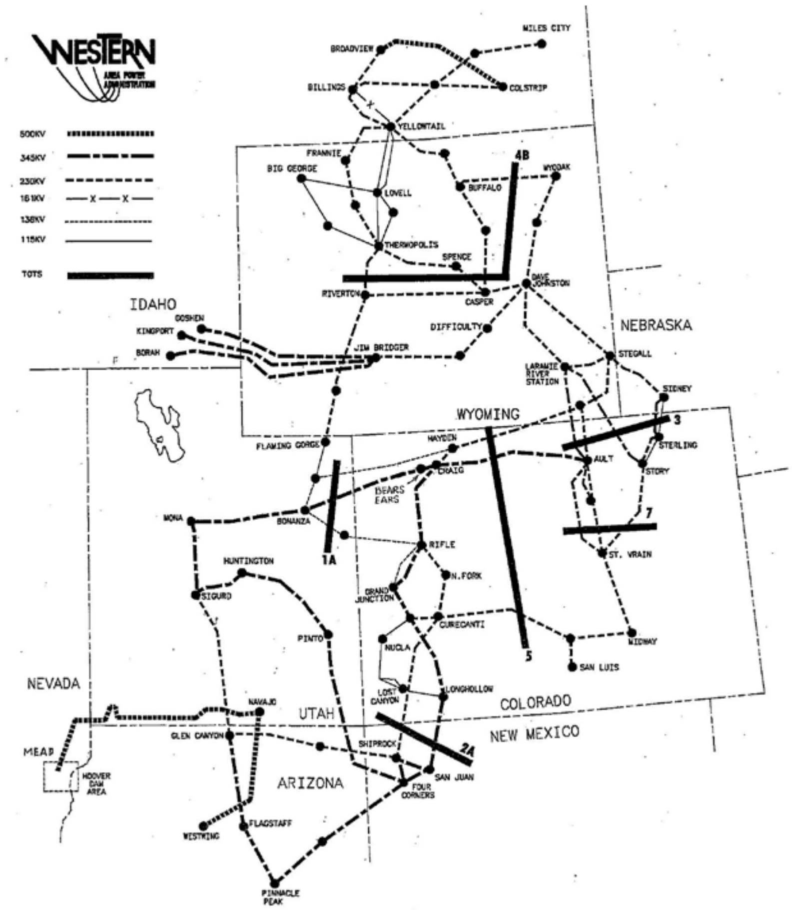

Figure 2. Transmission system in the WAPA Colorado Missouri region.

Northern States Power (NSP)—an operating company of Xcel Energy for Minnesota, Wisconsin, and North Dakota—is participating in the Midwest Independent Transmission System Operator (MISO) SynchroPhasor Deployment Project and will have 25 PMUs in its system when the installation is complete; two of them will be at WPPs. The MISO project will establish a synchrophasor infrastructure that will provide PMU data for the entire MISO reliability footprint and intermediary areas when completed. We are currently working on a research nondisclosure agreement with NSP and MISO to gain access to their PMU data.

3.2 New PMU Data From WPPs

NREL is in discussion with Xcel Energy to have a PMU installed at a substation in Colorado to obtain synchronized phasor data from a line connected to one of the WPPs in the PSC system. PSC does not have any PMUs installed in its system now, but it has indicated its willingness to work with NREL to provide PMU data. This work is planned for completion by the end of September 2013.

4 PMU Data Analysis

4.1 WAPA PMU Data

The five PMUs in the WAPA system provided the following phasor measurements:

Ault

- Ault-Craig: 345 kV line voltage
- Ault-Craig: 345 kV line current
- Ault–Laramie River Station: 345 kV line voltage
- Ault–Laramie River Station: 345 kV line current
- Ault–Fort Saint Vrain: 230 kV line voltage

Bears Ears

- Bears Ears–Craig: 345 kV line voltage
- Bears Ears–Craig: 345 kV line current
- Bears Ears–Bonanza: 345 kV line voltage
- Bears Ears–Bonanza: 345 kV line current

Shiprock

- Shiprock–San Juan: 345 kV line voltage
- Shiprock–San Juan: 345 kV line current
- Shiprock–Four Corners: 345 kV line voltage
- Shiprock–Four Corners: 345 kV line current
- Shiprock–Lost Canyon: 230 kV line voltage
- Shiprock–Lost Canyon: 230 kV line current
- Shiprock: 230 kV bus voltage
- Shiprock: 115 kV bus voltage
- Shiprock-Kayenta: 230 kV line current
- Shiprock–Hood Mesa: 115 kV line current

Yellowtail

- Yellowtail: 230 kV east bus voltage
- Yellowtail: 230 kV west bus voltage
- Yellowtail–KCB: 230 kV transformer current
- Yellowtail–PP&L: 230 kV tie-line current

- Yellowtail-Crossover: 230 kV line current

Mead

- Hoover: 230 kV south bus voltage
- Hoover: 230 kV north bus voltage
- Hoover #1: generator current
- Hoover #2: generator current
- Hoover #3: generator current
- Hoover #4: generator current
- Hoover #5: generator current
- Hoover #6: generator current
- Hoover #7: generator current
- Hoover #8: generator current

In addition to the above phasors, all PMUs also provided frequency and rate of frequency change (dF/dt) outputs.

The WAPA PMU binary data files NREL received were extracted directly from a phasor data concentrator in WAPA's control center. The same data is transmitted to BPA as part of the Western Interconnection Synchrophasor Program implemented by the Western Electricity Coordinating Council (WECC) for real-time system monitoring. The data came to NREL via optical disks sent through regular mail or e-mail attachments because there is no secured communication link between the WAPA control center and NREL.

Each binary file contained 5 minutes (min) of data streams from all five WAPA PMUs. The binary files are in a proprietary format, and a software package called PhasorFile was used to convert the data into different formats that could be read and processed by other programs, such as MatLab and Excel. The PhasorFile program also has a basic graphing capability that allows users to visually scan the data set (any four quantities at a time). Figure 3 is an example of the graphic display. The PhasorFile program was developed by BPA and is publically available; however, this software package does not possess the ability of data quality check for missing or erroneous data. Also, the program does not detect any grid events (such as large voltage swing and frequency deviations) automatically. These capabilities need to be developed separately.

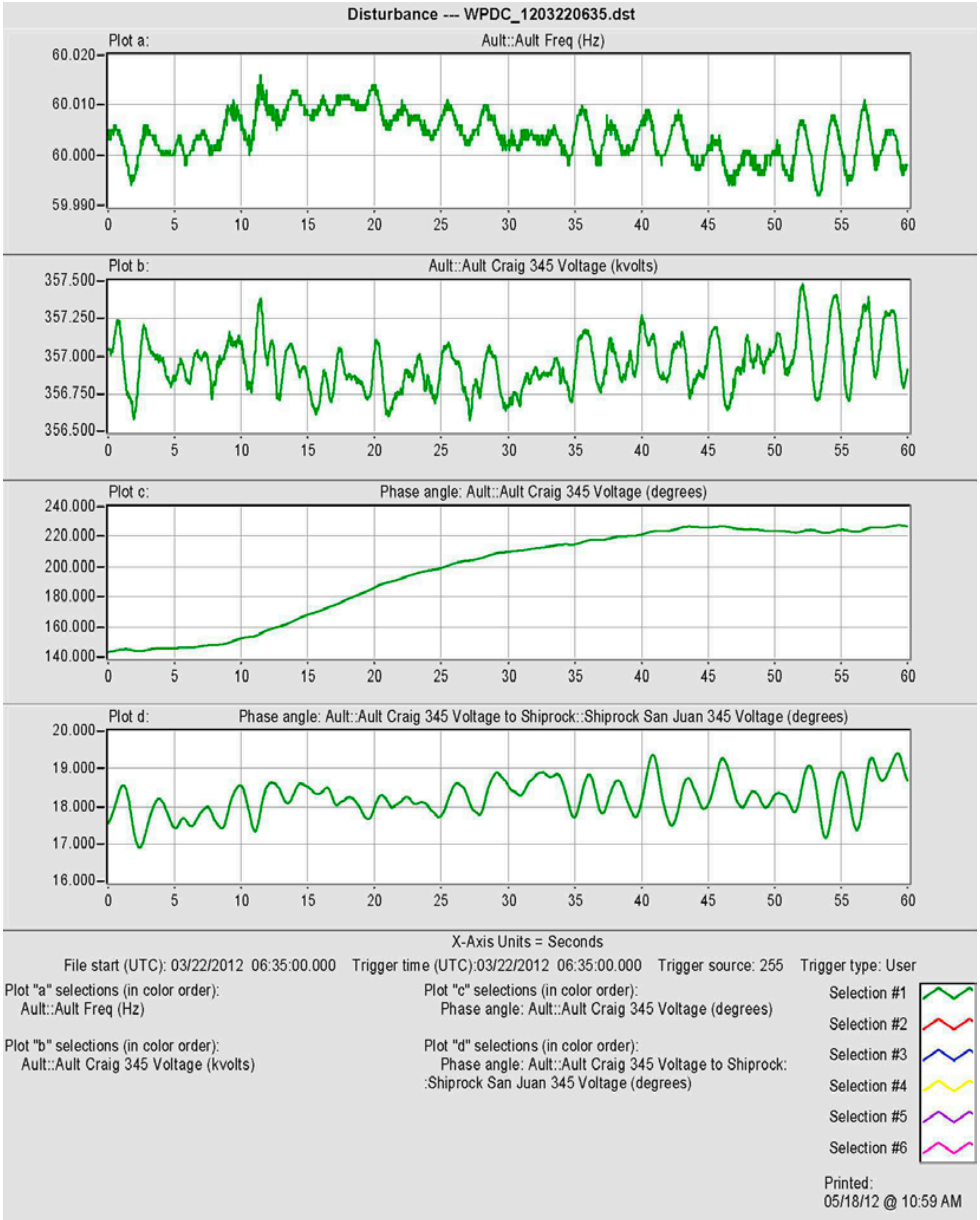

Figure 3. PhasorFile graphic display example.

Plot a in Figure 3 is the trace of frequency recorded by the Ault PMU during a 1-min window. Plots b and c are the voltage magnitude and phase angle of the Ault-Craig 345 kV line measured at Ault during the same 1-min window. Plot d is the phase angle difference between the voltage phasors at Ault and Shiprock. The traces in Figure 3 are typical patterns of voltage phasors and frequency in normal operating conditions. The three electric grids of North America (Canada and the United States) are very reliable and have very stable system frequencies. The maximum frequency deviation from peak to peak was only 0.02 Hz (or 0.033%). Only when an abnormal operating condition occurs do the system frequency, voltage, and current experience large changes.

The frequency in Plot a in Figure 3 shows some features of an oscillation. The results of a spectrum analysis on the frequency time series using discrete Fourier transformation routine confirm the existence of a low frequency (about 0.4 Hz) oscillation during this period (see Figure 4). It turns out that this type of short-duration, low-frequency oscillation is not unusual in the PMU sample data we received. Inter-area oscillations in a large interconnected system are typically in this range (0.1 to about 1 Hz), and may always be present in the PMU data during normal operations of the system because of load switching in the system and the resulting slight differences in the response of generators in one subregion and another. It is not easy to detect exactly the source of such oscillations. Much more PMU data from different parts of the system is needed to pinpoint the cause.

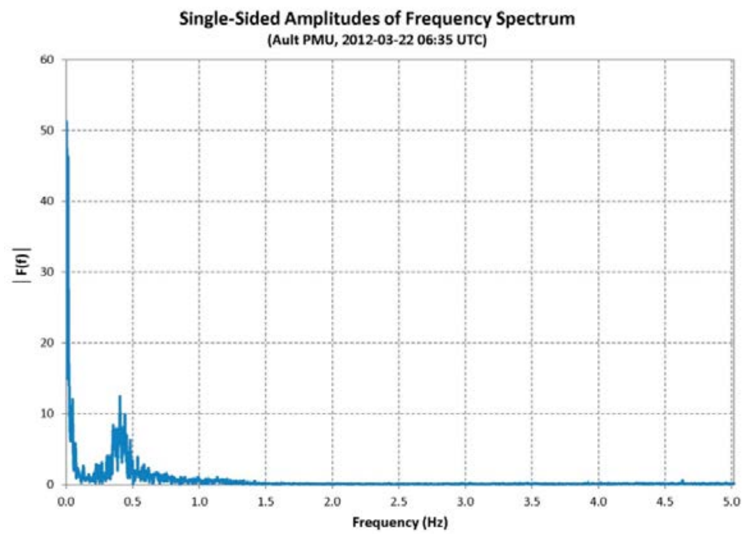

Figure 4. Spectrum analysis showing low-frequency oscillation.

A routine to detect larger frequency deviation was developed to identify windows of data for disturbance analysis. After some experiments and discussions with BPA engineers, a threshold of 60 mHz (the difference between consecutive frequency values) was chosen to flag data points in the frequency time series for further event analyses. A lower threshold would catch too many events that are not important, and too high a threshold may cause the routine to miss some grid events. The 60-mHz frequency deviation is still a relatively small value compared to the range of frequency fluctuations under normal operation conditions of the grid. For example, WECC's Off-Nominal Frequency Load Shedding Plan does not require utilities to begin shedding load until the system frequency drops to 59.1 Hz (or 900 mHz off the nominal frequency of 60 Hz) for 1 min.[1]

The frequency deviation detection routine found one frequency event from the available WAPA PMU data. Figure 5 shows the frequency disturbance recorded by PMUs at the Ault, Shiprock, and Yellowtail substations. (PMU data streams from Bear Ears and Mead were bad during this time.) Plot a of Figure 5 shows frequency traces for 10 min; whereas Plot b shows frequency traces for the first 30 s of Plot a to display frequency disturbance in more detail. As shown, the

[1] www.wecc.biz/library/Documentation Categorization Files/Retire and Archive/Off Nominal Frequency Load Shedding Plan.pdf. It was approved by the WECC board of directors on March 17, 2011.

frequency at Ault experienced a relatively large initial drop of 600 mHz and some oscillations before it started to recover. The frequency at Yellowtail dropped about 270 mHz and oscillated briefly before it settled on a slow recovery trajectory. The frequency at Shiprock had a smaller drop (200 mHz) without oscillations. The frequency took almost 10 min to return to its predisturbance level.

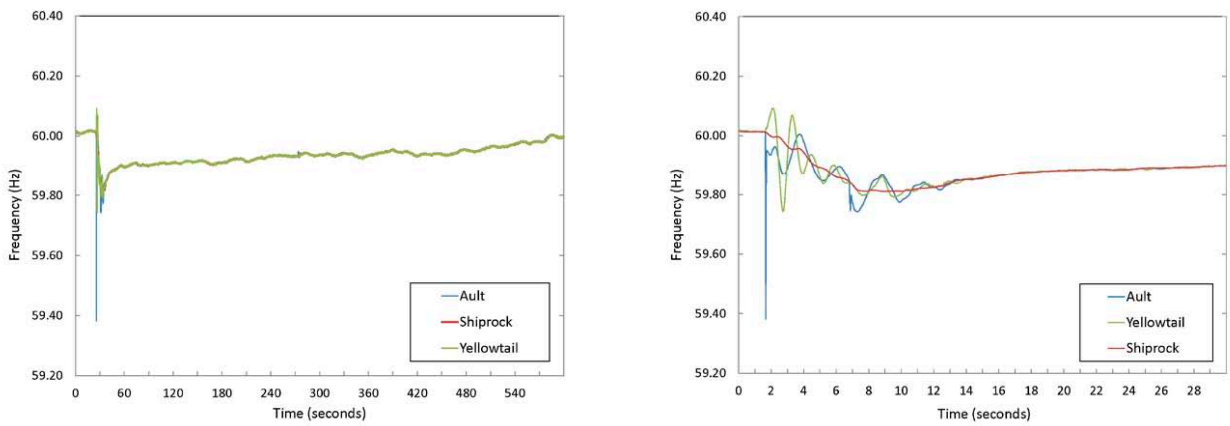

Figure 5. Frequency disturbance example.

Although the exact cause of this frequency drop could not be determined with the available data, it was certainly associated with a sudden loss of generation. The PMU data set from Ault showed that the 400-MW flow on the 345 kV line from the Laramie River Station (LRS) to Ault was interrupted at the moment the frequency drop began. At the same time, flows to Ault on other lines increased. Figure 6 shows the changes in power flow to Ault and bus voltage fluctuations before and after the event—the 680-MW flow from LRS to Ault dropped to 0; the Craig-to-Ault flow reversed direction and increased to 378 MW; the flow from Shiprock to San Juan (in the direction toward Ault) increased to 140 MW (from 15 MW before the event). The voltage at the Ault substation 345 kV bus experienced a sharp dip, but the 345 kV bus voltage at the Shiprock substation was only slightly affected. This suggests that a generating unit at LRS had tripped. It also partially explains the measured frequency data shown in Figure 5. Ault and Yellowtail are closer to LRS than Shiprock; therefore, the frequencies measured at these two locations showed more fluctuations than the frequency at Shiprock. However, one cannot be sure if this scenario was true without examining other data, but the available information indicates that it was highly probable.

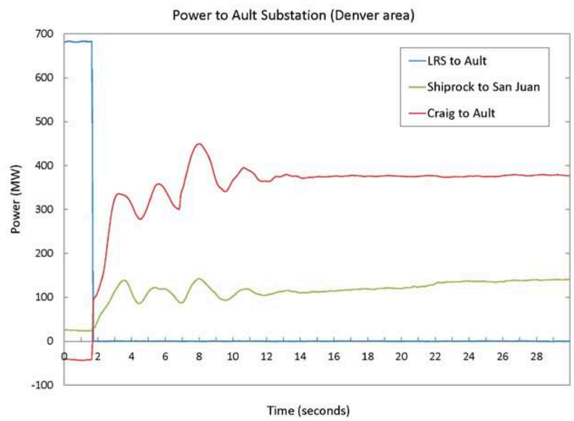

Figure 6. Power flow changes and voltage fluctuations associated with frequency disturbance.

Figure 7 and Figure 8 are two additional examples of frequency events detected in the WAPA data set. In the minor event shown in Figure 7, the frequency dipped briefly to 59.94 Hz, as did the voltages of the 345 kV buses in the WAPA system. The likely cause could have been a switch operation (opened and reclosed) somewhere in the WECC system. If synchrophasor data from WPPs were available during the same period, wind plant response to such disturbance could be analyzed.

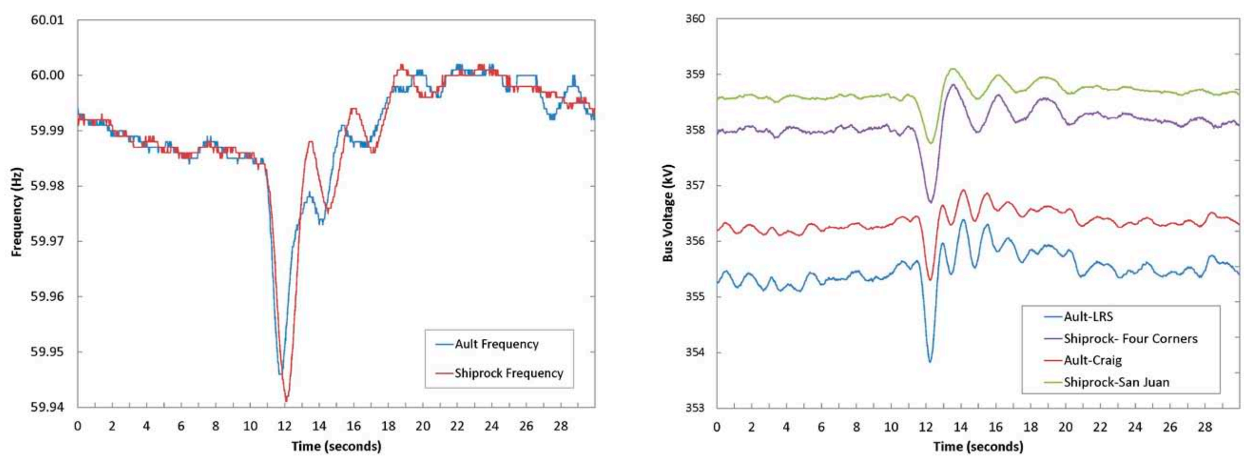

Figure 7. Example of minor frequency and voltage disturbances.

The event in Figure 8 showed a second frequency dip about 170 s after the first one. The magnitudes of both frequency drops were relatively small. The voltage profile at the Shiprock 345 kV bus confirmed that this is minor. The scale of the plot makes the voltage dip appear large, but the actual voltage drop was only 0.4%. Power flow on the Shiprock-to-Four Corners 345 kV line suggests that the first frequency dip could have been caused by the loss of generating capacity in the Four Corners area. The loss of generation that triggered the second frequency dip likely occurred at a place farther away from the Four Corners area because there were no apparent changes in the line flow out of the Four Corners area.

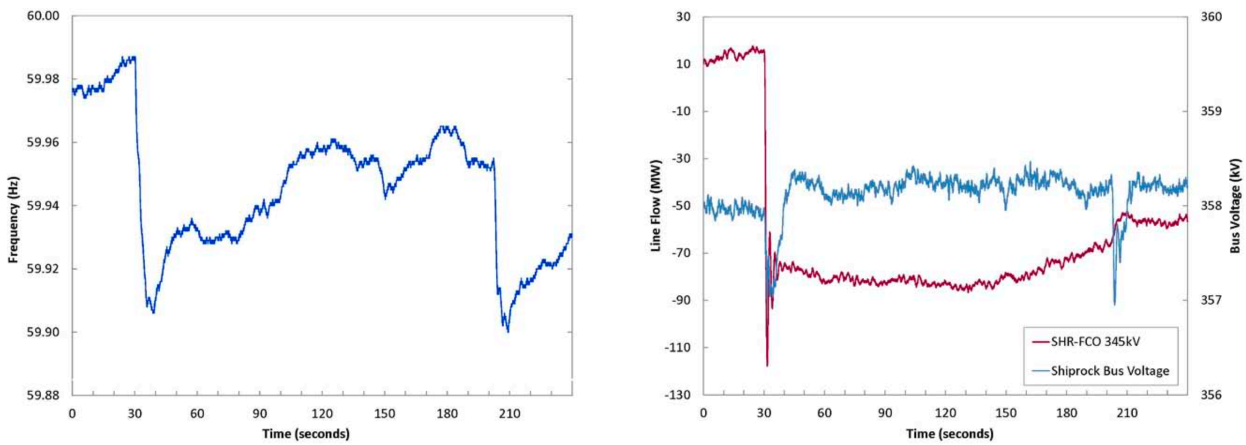

Figure 8. Event of double frequency dips.

The real use of the WAPA PMU data is for it to be a grid reference point when we can obtain synchronized phasor data from a WPP in this region. No further analysis of the WAPA data will be performed until synchronized phasor data from a wind plant in Colorado is available.

4.2 OG&E PMU Data

PMU data from OG&E were delivered to NREL via an external hard drive. OG&E processed the raw data to include only positive-sequence line-to-neutral voltage, line current, frequency, and dF/dt from every PMU before sending it to NREL. Fifteen minutes of data from all PMUs were compressed and stored in a single file to reduce the storage space needed for the data. Despite these data reduction measures, 17 months of OG&E PMU data still requires about 2 TB of disk space. When fully decompressed and converted to text format (so other programs can access it without further processing), the data set requires 11 TB of disk storage space. Because of the disk storage limitation, we chose to decompress and convert the entire 2011 data set first for analysis in this report. OG&E also provided a list of known disturbances (breaker operations in its transmission system) during the 17-month period of delivered PMU data.

4.2.1 Transient Event Example

Figure 9 shows the real and reactive power from the Centennial WPP during the 24-hour period starting 0:00 June 10, 2011, UTC. The real and reactive power values are calculated from voltage and current phasors of a PMU at the grid interconnection point of this WPP. Each of these two traces in Figure 9 was based on 2,592,000 data points.[2] The size of the plot prevents it from showing many details. This particular day was chosen at random among all days that do not have a grid disturbance according to the disturbance list provided by OG&E to establish a baseline measure of normal wind plant operations as observed through PMU data. However, PMU data of the day revealed not only normal behavior of a WPP but also several events that are unusual.

[2] 24 (hours/day) x 60 (seconds/hour) x 30 (data points/second) = 2,592,000 (data points/day)

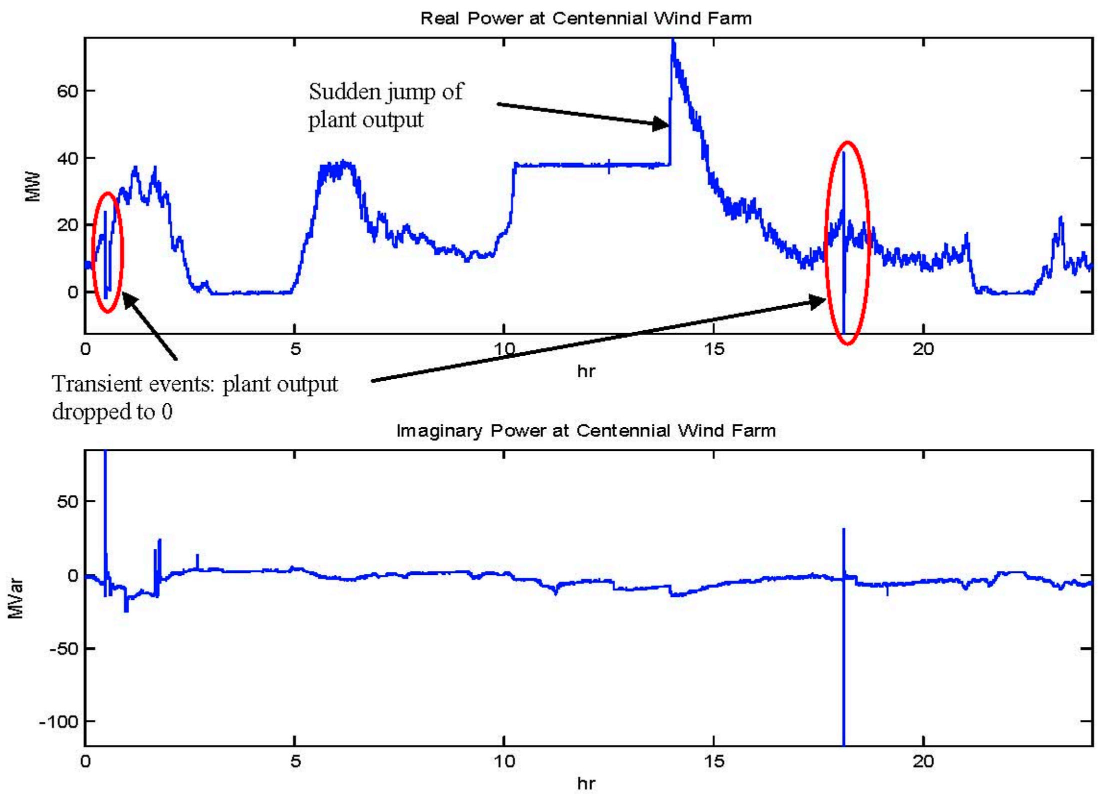

Figure 9. Wind plant output for a 24-hour period on June 10, 2011, UTC.

As noted in Figure 9, this supposedly grid disturbance–free day contained three clearly distinguished events: twice the plant output dropped to 0 momentarily, and there was a seemingly sudden jump of output mid-day. Discussions with OG&E engineering staff provided an explanation for the sudden jump of plant output around 13:56 UTC (8:56 a.m. CDT). According to OG&E engineering staff, the relatively flat output of the Centennial WPP was because of curtailment. A 345 kV line, which was designed to carry wind power from the northwest region of Oklahoma (where the majority of wind power capacity is located), was damaged by a tornado on May 24 and was out of service until the evening of June 9. During that time, three wind plants in the general area (Centennial, Keenan, and OU WindSpirit) had to limit their outputs to avoid the lower voltage transmission lines in the area from being overloaded during high-wind periods. The 345 kV line was returned to service on June 9, 8:00 p.m. CDT, and the curtailment order was lifted on June 10, 8:45 a.m. CDT. The three affected WPPs started to ramp up soon after. The output of Centennial WPP increased 40 MW in 5 min; however, the maximum ramping was only 12 MW per minute (or about 10% of the installed capacity per minute). The scale of the plot makes it appear to have been a much steeper increase.

Figure 10 shows the real and reactive power profiles during the other two transient events noted in Figure 9. Figure 11 shows voltage profiles. Scales in Figure 10 and Figure 11 are different from that of Figure 9 to show more details.

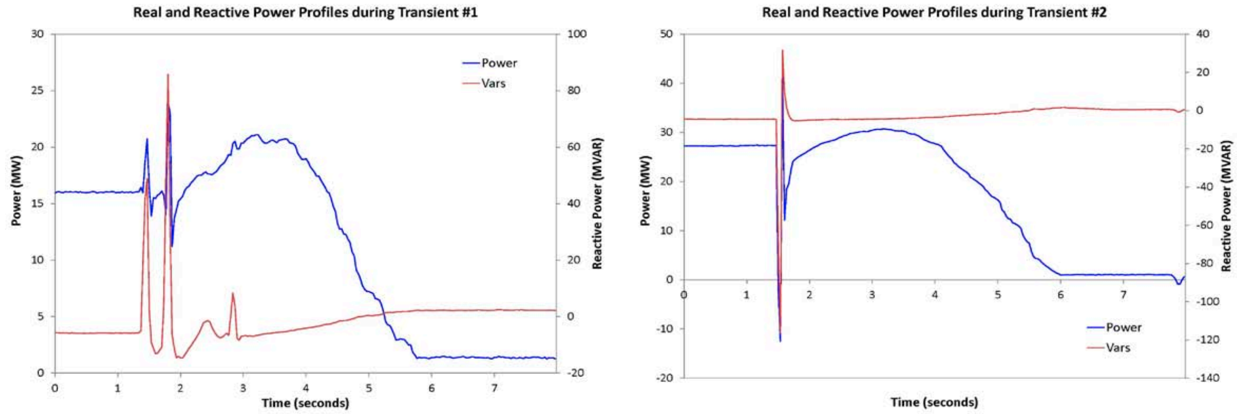

Figure 10. Real and reactive power profiles during transient events.

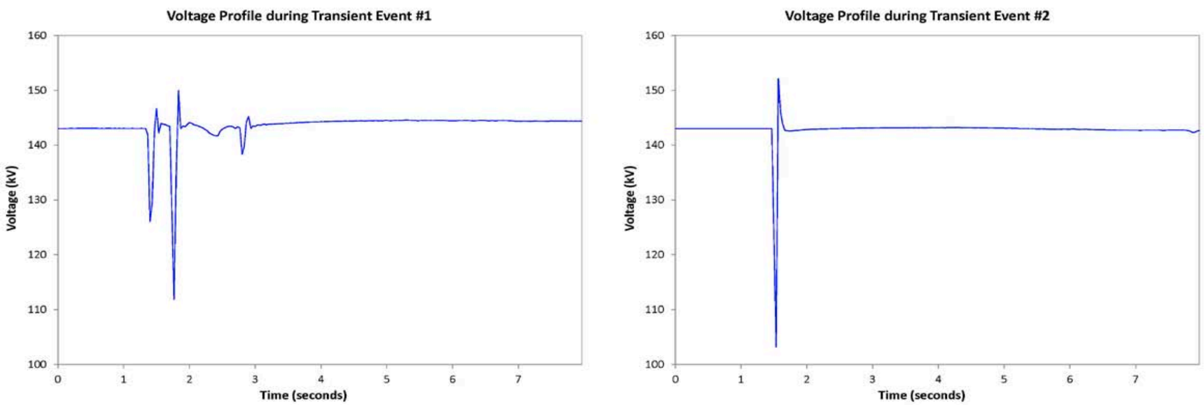

Figure 11. Voltage profiles during transient events.

During the first transient event—which occurred at 0:30:17.267 UTC (June 9, 7:30 p.m. CDT), when the plant output dropped to near 0—the wind plant was still producing reactive power (indicated by the positive values of reactive power at the time of near-0 power), which suggests that whatever disturbance caused the plant power to drop to near 0 occurred outside the plant. Records from OG&E did not show any breaker operation during that time. The grid disturbance very likely occurred in the neighboring transmission system of the general area. It is also clear from the voltage profile that they were not breaker open-and-reclose operations because of the very short voltage dip durations (about 4 cycles), which were not long enough for a breaker to open and reclose. OG&E engineering staff stated that there was a weather front moving through the area during the time. It is very likely that those voltage transients were caused by lightning. These conditions caused the turbine controllers to act to either shut down or reduce the power output of the turbines. It took about 4.3 s for the power to decrease to a low but fairly constant value, so we are certain the main breaker was not open and the wind plant stayed online. There was a small positive value of power (slightly more than 1 MW) during the period. A WPP of this size (120 MW installed capacity, as shown in Table 1) will draw 1 MW to 2 MW when no turbine is generating power because of parasitic losses associated with pad-mounted step-up transformers, cables, and all electronic monitoring and control equipment in the WPP.

During the second transient event—which occurred at 18:05:14.467 UTC (1:05 p.m. CDT), when the plant output dropped to 0—the real power swing was larger and the reactive power was flowing into the plant (indicated by the negative value of the reactive power). This suggests that the disturbance was within the plant (behind the PMU at the grid interconnection point). OG&E records showed there was a fault on phase C of one of the circuits in the plant's collecting system at the time of the transient, and the fault might have caused some of the turbines to shut down; however, this type of localized fault should not affect the whole plant. It took about 4.5 s for the real power to decrease to a low value (less than 1 MW). The plant seemed to remain online, but most of its turbines were shut down.

The low power condition lasted slightly more than 3 min and the output power picked up again (not shown in Figure 10, but can be observed in Figure 9). Voltage profiles from other PMUs in the general area, including those at 345 kV buses, all showed a voltage dip at the same time. Figure 12 provides four voltage profile examples for the 15-min period surrounding the second transient event. PMU 114 signals are from Keenan WPP, and PMU 56 signals are from OU WindSpirit WPP; both are about 15 miles away from Centennial WPP. PMU 112 is at a 345 KV substation in the same area. (Outputs from all three WPPs feed into this substation.) PMU 1 is at a 345 kV bus north of Oklahoma City (100 miles away from the three WPPs). It seems unlikely that a single-phase fault on a low-voltage circuit within a WPP would affect voltages on faraway extra-high-voltage (EHV) transmission buses. However, the data suggests that that was what actually occurred. It is not clear which turbines were shut down and which remained online. It would require additional data from the plant SCADA system and fault recorder in the general area to clearly establish the sequence of the events and conditions of the system. For a transient of this magnitude, fault recorder data may not be available because the voltage dip might not have been deep enough to trip an event recording.

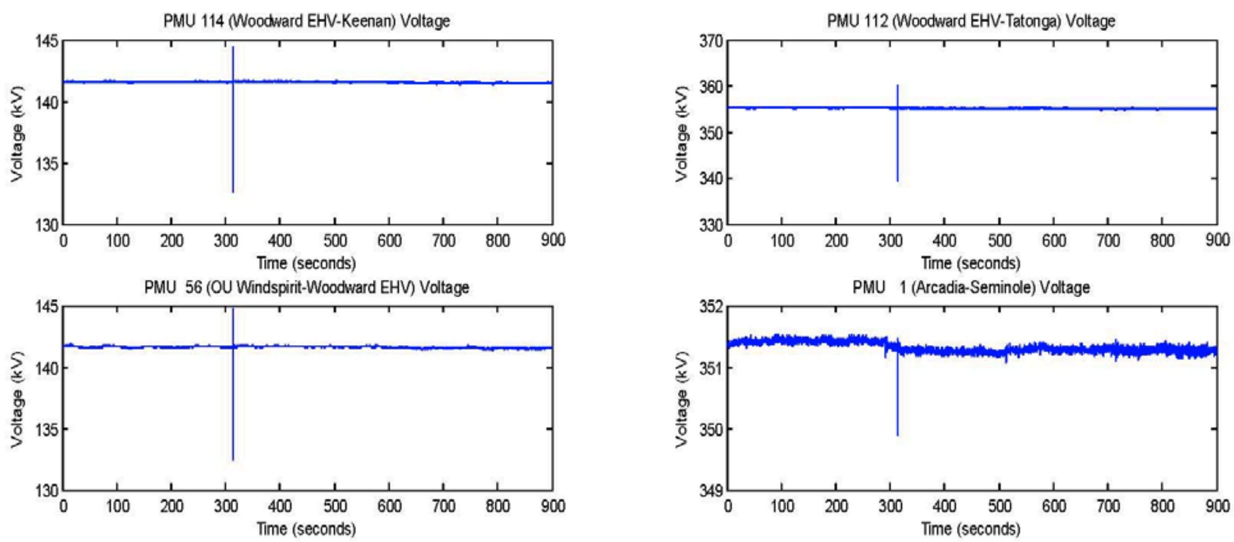

Figure 12. Other voltage profiles during the second transient event.

4.2.2 WPP Voltage Oscillations

PMU data can help operators detect subsynchronous oscillations in the system that are too fast for the SCADA system to capture. One example of such subsynchronous oscillation is shown in Figure 13, which plots the voltage signals from two WPPs during a 33-min window from April 5, 2011, 12:27 UTC to 14:00 UTC (8:27 AM CDT to 9:00 AM CDT).

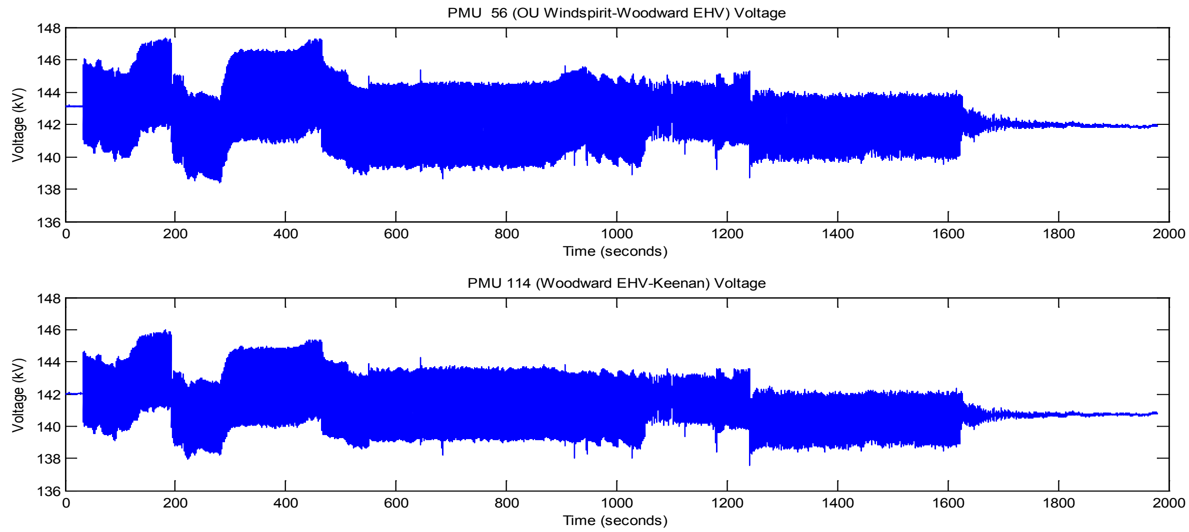

Figure 13. WPP voltage oscillations.

The voltage oscillations at both plants followed almost identical paths and lasted more than 25 min unabated. The voltage oscillations had a peak-to-peak amplitude of 5.1 kV (3.7% of the nominal voltage of 138 kV). Figure 14 shows output power of these two WPPs during the same period. As shown, the plant output power also oscillated. It appears that the plant operators at Keenan WPP tried to damp the oscillation by reducing plant outputs as directed by OG&E control center operators. However the oscillations were not stopped until both plants significantly reduced their outputs: Keenan WPP output first dropped 20 MW (in 1 s), and 571 s later another 49 MW (in 2 s); OU WindSpirit WPP gradually dropped 48 MW over 5 min. Lower power output helped Keenan WPP reduce its power oscillation, but it did nothing to mitigate the voltage oscillation.

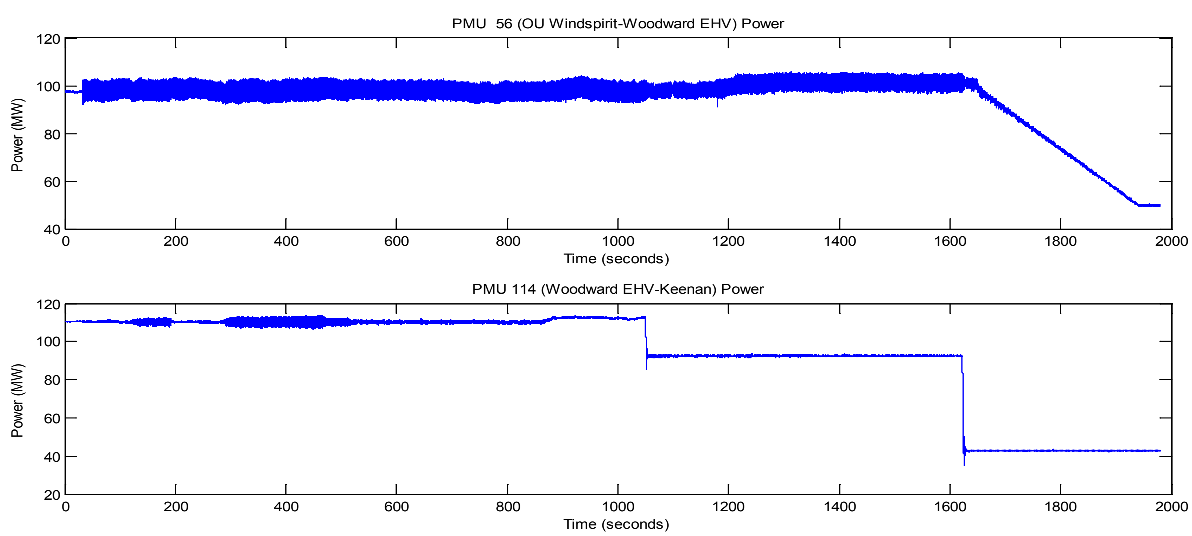

Figure 14. WPP output power during voltage oscillations.

It is not clear what triggered the oscillation. During that time, the OU WindSpirit WPP was producing near full capacity (97% of the installed capacity); whereas Keenan WPP was producing at a relatively lower level of 72% of its installed capacity. Figure 15 shows that both voltage and power oscillated at 13.33 Hz. The output power of Keenan oscillated at a smaller amplitude (as shown in Figure 14). Figure 16 shows the voltage signals and their frequency components of both WPPs 12 min before the start of the oscillation. The data did not show any grid event or transient prior to the oscillation. Both voltages had almost identical frequency spectrums. They contained prominent frequency components of 5 Hz, 5.46 Hz, 8Hz, 10 Hz, 12 Hz, and 14 Hz. However, neither voltage signal before the oscillation contained the 13.33-Hz frequency. The components around 5 Hz might have been caused by variable frequency drive (VFD) motors in the nearby industrial plants, but the 8 Hz, 12 Hz, and 14 Hz appeared to be inherent to the wind turbines. Both WPPs have Siemens wind turbines. According to OG&E engineers, the turbine manufacturer was notified of this event, and it modified the turbine controller logic in an attempt to damp such oscillations.

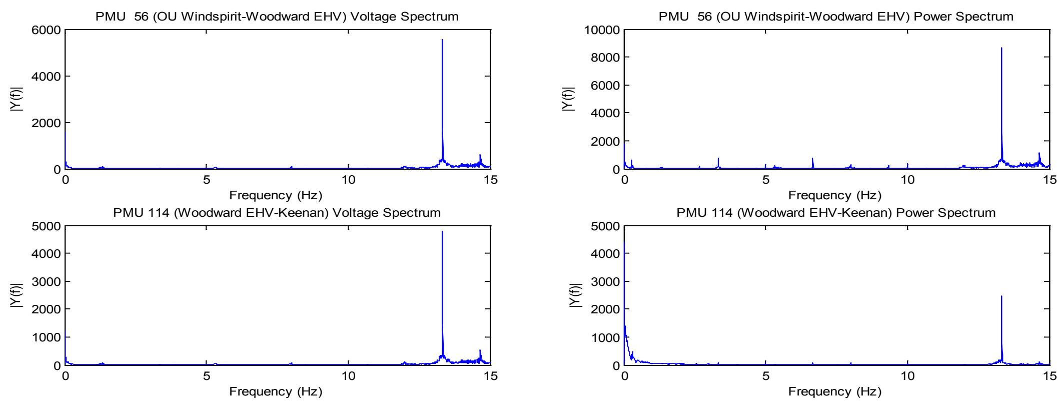

Figure 15. Frequency analysis of the voltage signals during oscillation.

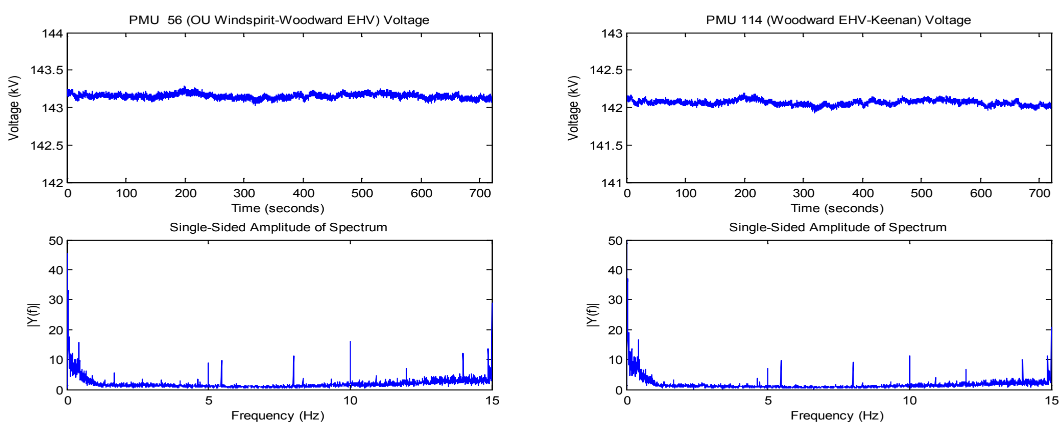

Figure 16. Frequency analysis of WPP voltage signals before oscillation.

There were several incidents of WPP voltage oscillations after the April 5 event. The subsequent voltage oscillations were either 12.44 Hz or 13.33 Hz, and their amplitudes were either greater or smaller than that in this case. One thing in common about the observed voltage oscillations was the high level of wind plant outputs (more than 80% of the installed capacity) when voltage oscillation occurred. The available data shows that when the oscillation amplitudes (peak-to-peak) exceeded 5% of the nominal voltage, the WPP operators reduced the plant output (as directed by OG&E control center operators) in a fashion similar to that shown in Figure 14 to abate the oscillation.

4.2.3 Voltage Transient and Oscillation

The analyses of PMU data from OG&E and discussion in the previous section indicate that voltage at some WPPs may have a tendency to oscillate at a frequency around 13 Hz and 14 Hz under certain wind conditions. Small voltage oscillations of different frequencies appear to be present at WPPs constantly. A grid disturbance in or around the wind plants may excite one or more of these small voltage oscillations and make them more prominent. The most common frequency of these types of oscillations is between 13 Hz and 14 Hz. These types of voltage oscillations are generally not observed on SCADA signals because of the low data rate of one data sample for every 4 to 6 s. However, nearby utility customers may experience flicker when a voltage oscillation occurs. The oscillations die down when wind conditions change, and the turbine controller also tries to damp it. Another one such voltage oscillation incident occurred on December 14, 2011. Figure 17 shows the voltage signals from five WPPs on December 14, 2011, from 12:27 to 13:00 UTC (6:27 a.m. CST to 7:00 a.m. CST).

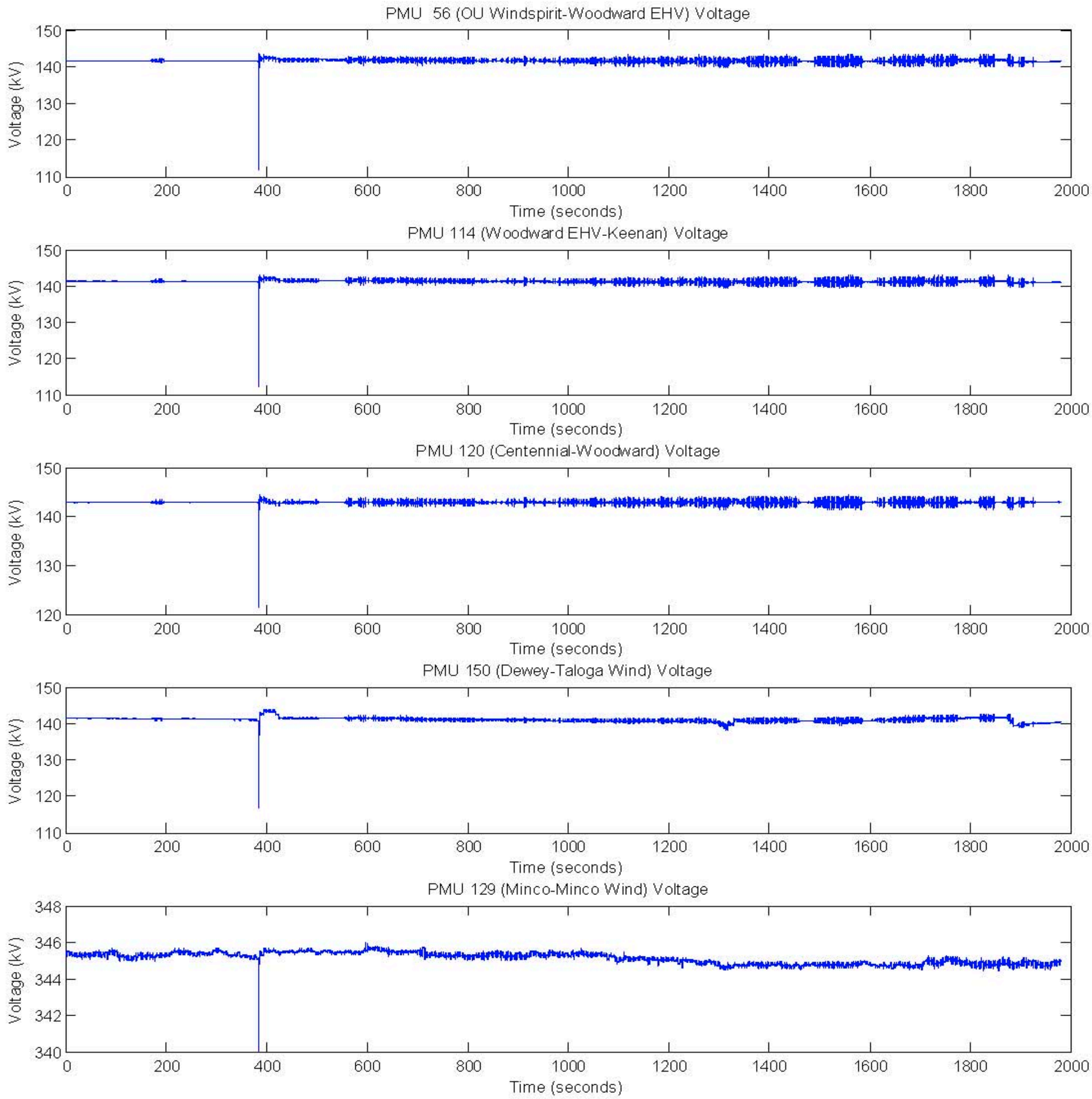

Figure 17. Voltage oscillations at WPPs.

Voltage oscillation was seen in four out of the five WPPs during this 33-min period. Only Minco WPP, which is connected to 345 kV line, did not experience voltage oscillation during this time. Oscillations at OU WindSpirit and Keenan WPPs had higher amplitude–3.0 kV peak-to-peak or 2.2% of the nominal voltage. As shown, there was a voltage transient at 12:33:23.333 UTC. This particular voltage transient was observed throughout the OG&E system except for the very east end, where it is interconnected with Entergy at a 500/345 kV substation at the Oklahoma/Arkansas border. Physically, OU WindSpirit, Keenan, and Centennial WPPs are closer together and are further northwest in relation to the location of Taloga WPP. The Minco WPP is further south in relation to Taloga. The amplitudes of voltage oscillation became smaller the further south the WPPs are located. The southernmost WPP connected to a 345 kV line did not experience voltage oscillation. Figure 18 shows the real power profiles of these five WPPs during this time. The voltage transient showed up in output power of the four WPPs connected at

138 kV, but not the output power of Minco WPP. Similar to the oscillation event discussed in the previous section, WPP output power levels were also high in this event. During this period, output at OU WindSpirit was about 82% of its installed capacity; Keenan was at 87% of its installed capacity; Minco WPP was higher, at 94% of its installed capacity; Taloga WPP was at 90% before the sudden drop; and only Centennial WPP was at a relatively lower level of 33% of its installed capacity.

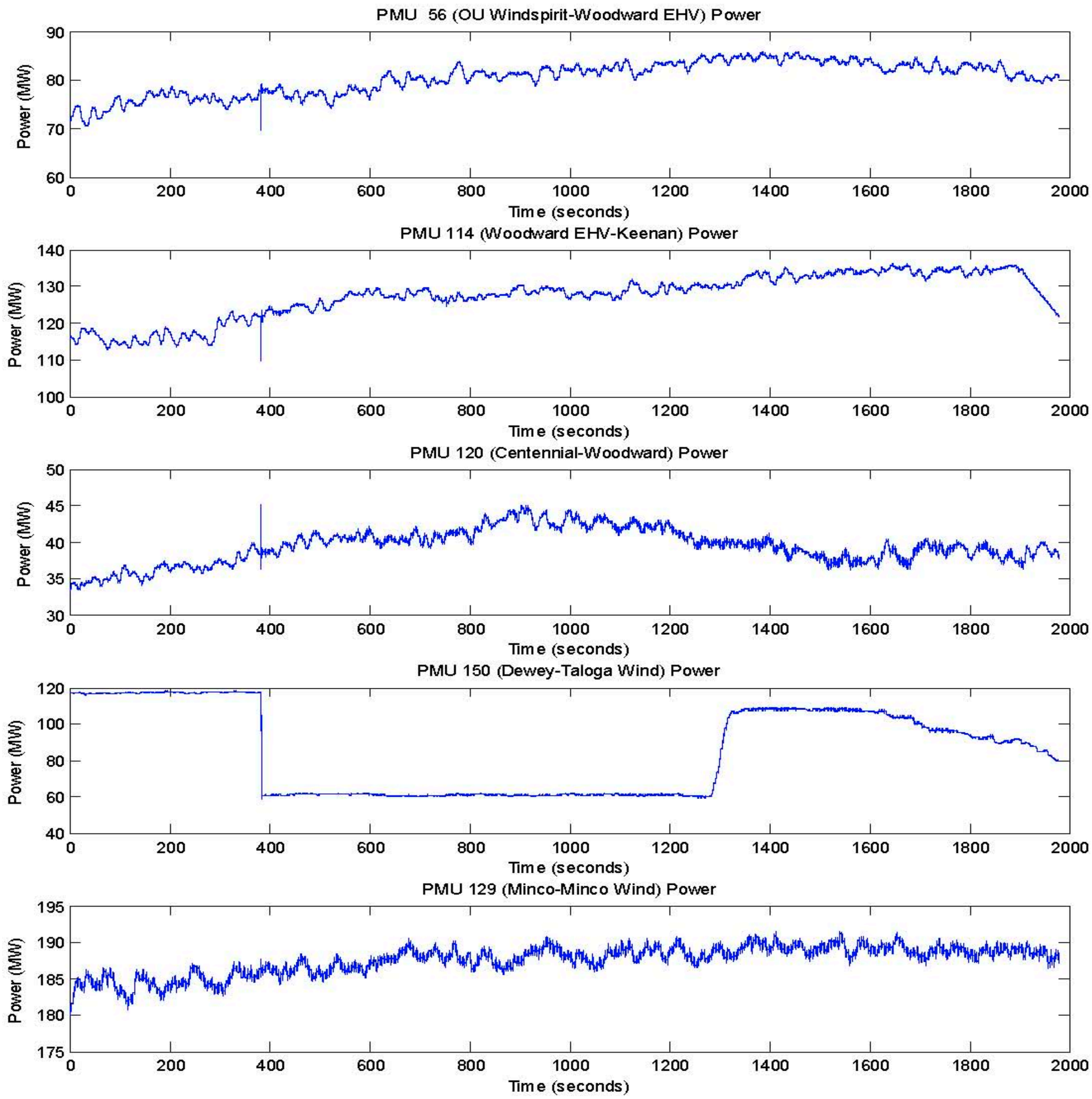

Figure 18. Wind plant output power profiles (12:27–13:00 UTC).

The voltage transient did not appear to have a noticeable effect on the power trace of Minco WPP, which is connected to the grid at 345 kV, but it showed up in the power traces of four other WPPs connected to the grid at 138 kV, and it actually triggered the shutdown of half the turbines at Taloga WPP. The Taloga WPP was generating at about 117 MW when the transient occurred. After the start of the transient, Taloga WPP output dropped to about 59 MW in 2 s (almost exactly half the level before transient). It was obvious the transient caused the output drop (and not the other way around) because of the 2-s delay in power drop. Figure 19 shows the voltage profile of the four 138-kV connected WPPs in a 4-s window to show more details. The very short duration of the voltage transient suggests that the transient was likely caused by a lightning strike on the transmission line. It was noted that voltage profiles of the four WPPs during the transient were very similar, including the oscillation behavior.

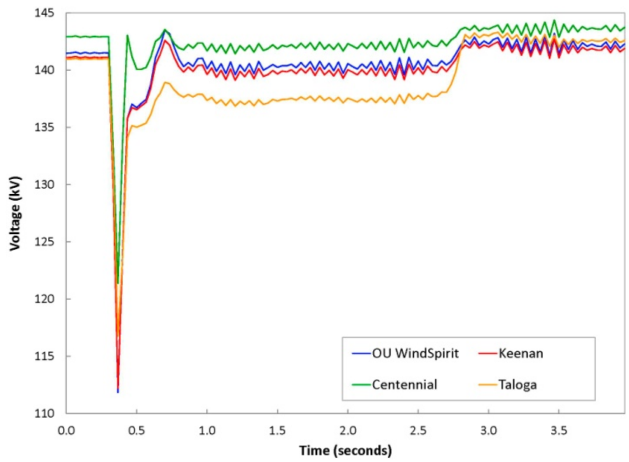

Figure 19. WPP voltage profiles during transient.

Figure 20 shows the real and reactive power profiles of the four WPPs in detail. The P and Q plots showed turbines by different manufacturers had different responses to a system transient despite the similarity in their voltage profiles. When voltage at a WPP begins to drop, the normal response for the turbines is to increase reactive power output in an attempt to hold up the voltage. There may be minor variations in how manufacturers implement this basic scheme. At the OU WindSpirit and Keenan WPPs (both have Siemens turbines), the reactive power initially dropped (in this case drawing more reactive power from the grid) along with the real power before it picked up. Reactive power at Centennial (with GE turbines) and Taloga (with Mitsubishi turbines) began to increase as soon as the voltage began to drop. The differences in reactive power were also reflected on the voltage profiles shown in Figure 17. Both Keenan and OU WindSpirit WPPs experienced a voltage drop of 21% in magnitude (compared to the before-transient value); whereas Centennial WPP experienced a 15% voltage drop and 17% at Taloga WPP. The voltage transient event did not cause the WPPs to go off-line, and the oscillations were stable.

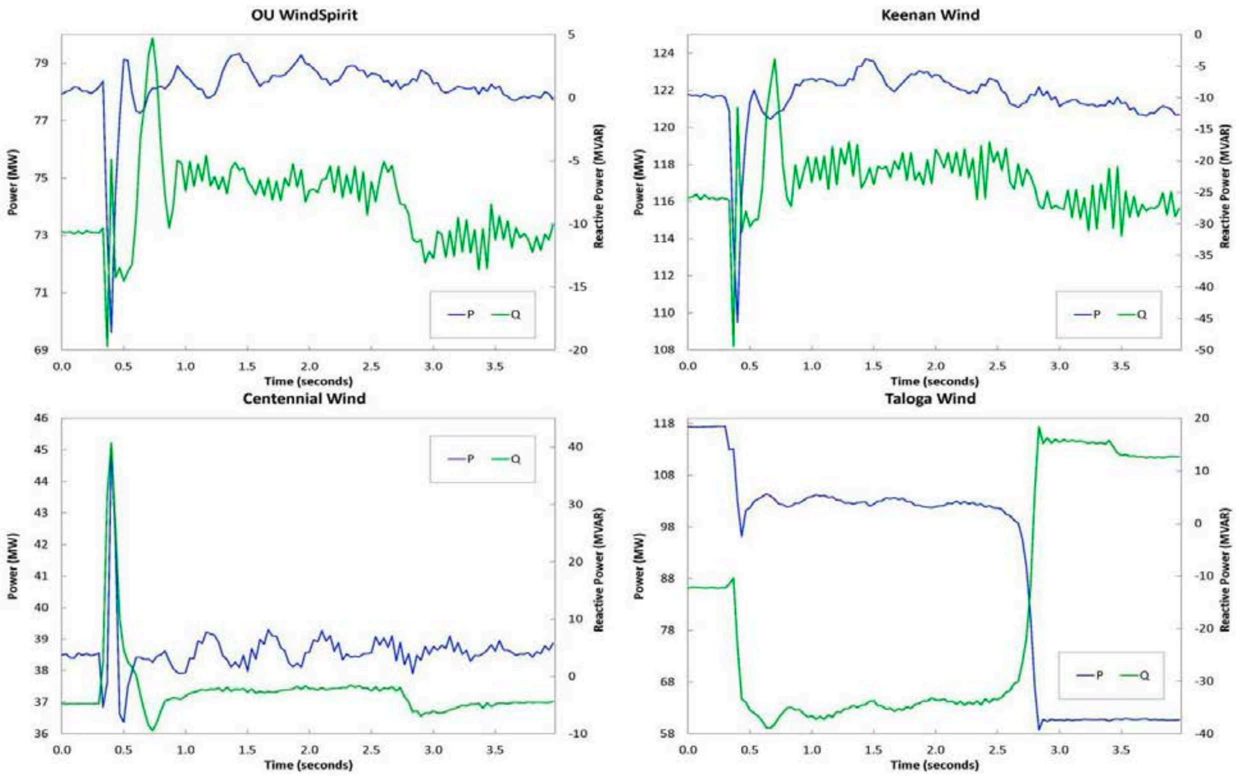

Figure 20. Real and reactive power profiles during voltage transient.

Figure 18 and Figure 19 showed the voltage oscillations after the transient event. Smaller voltage oscillations actually appeared before the transient, and the oscillations became more prominent and lasted longer after the transient. The reactive power also displayed oscillation behavior because it was closely linked to voltage. Figure 21 plots the results of spectral analysis of WPP voltage signals during the 33-min window shown in Figure 17.

There were several prominent subsynchronous frequencies in the voltage signals of these four WPPs. The most noticeable group of higher frequency components in Figure 21 were 13.33 Hz, 14 Hz, and 14.67 Hz. The frequencies of 14.67 Hz and higher were the artifacts of aliasing of fast Fourier transformation calculation. The 13.33-Hz oscillation, which was present during the event discussed in the previous section, showed up again in this event. After the April 5, 2011, oscillation incident, the turbine manufacturer modified the turbine controller to damp the 13.3 Hz oscillation. However, under similar wind conditions (high WPP outputs), the voltage still oscillated at this frequency, albeit at a lower amplitude. The difference between the April 5 event and this event was the voltage transient, which seemed to excite the generators to oscillate at 13.33 Hz and 14 Hz. Additional data and research will be needed to determine why WPPs oscillate and how the oscillations were damped.

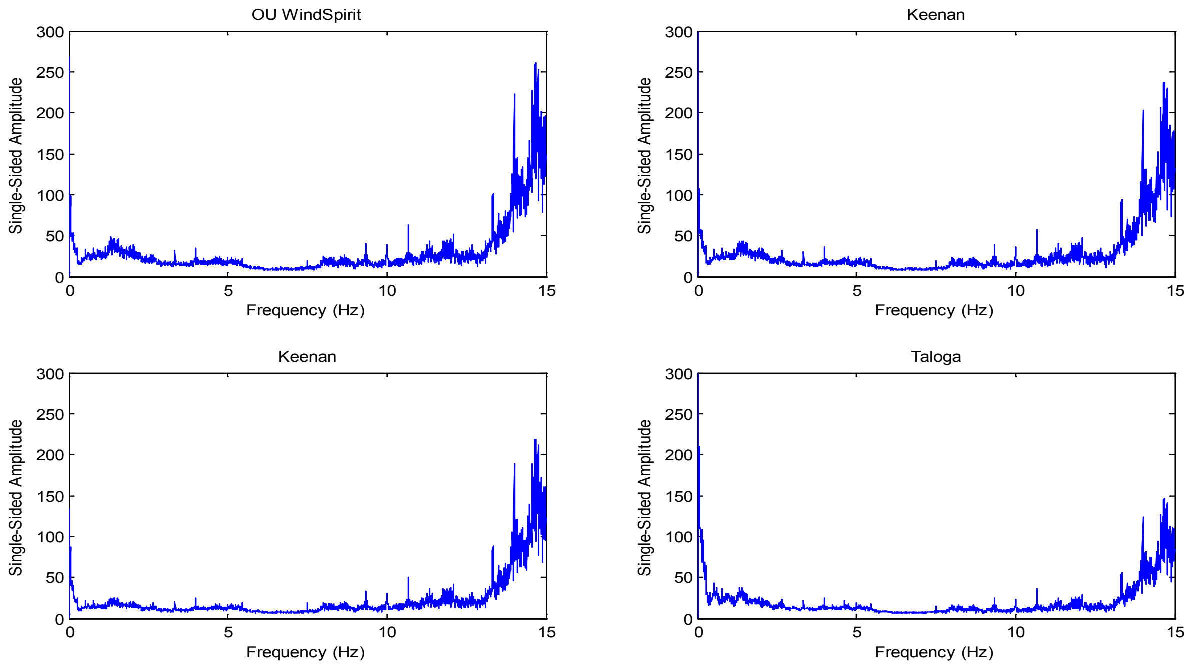

Figure 21. Frequency components of voltage oscillations.

Frequency analysis of the voltage signals before the transient and oscillation again showed familiar subsynchronous frequency components, such as 8 Hz, 10 Hz, 12 Hz, and 14 Hz. Figure 22 plots the voltage profiles and their spectral components of the five WPPs for the 12-min period from December 14, 2011, 13:15 to 13:30 UTC (before the start of the voltage oscillation). The four WPPs connected to the grid at 138 kV (OU WindSpirit, Keenan, Centennial, and Taloga) had very similar frequency spectrums. The Minco WPP, which connected to the grid at 345 kV, had a significantly different frequency spectrum. It is also shown that the spectrum of the voltage signals of OU WindSpirit and Keenan were very similar to that shown in Figure 16.

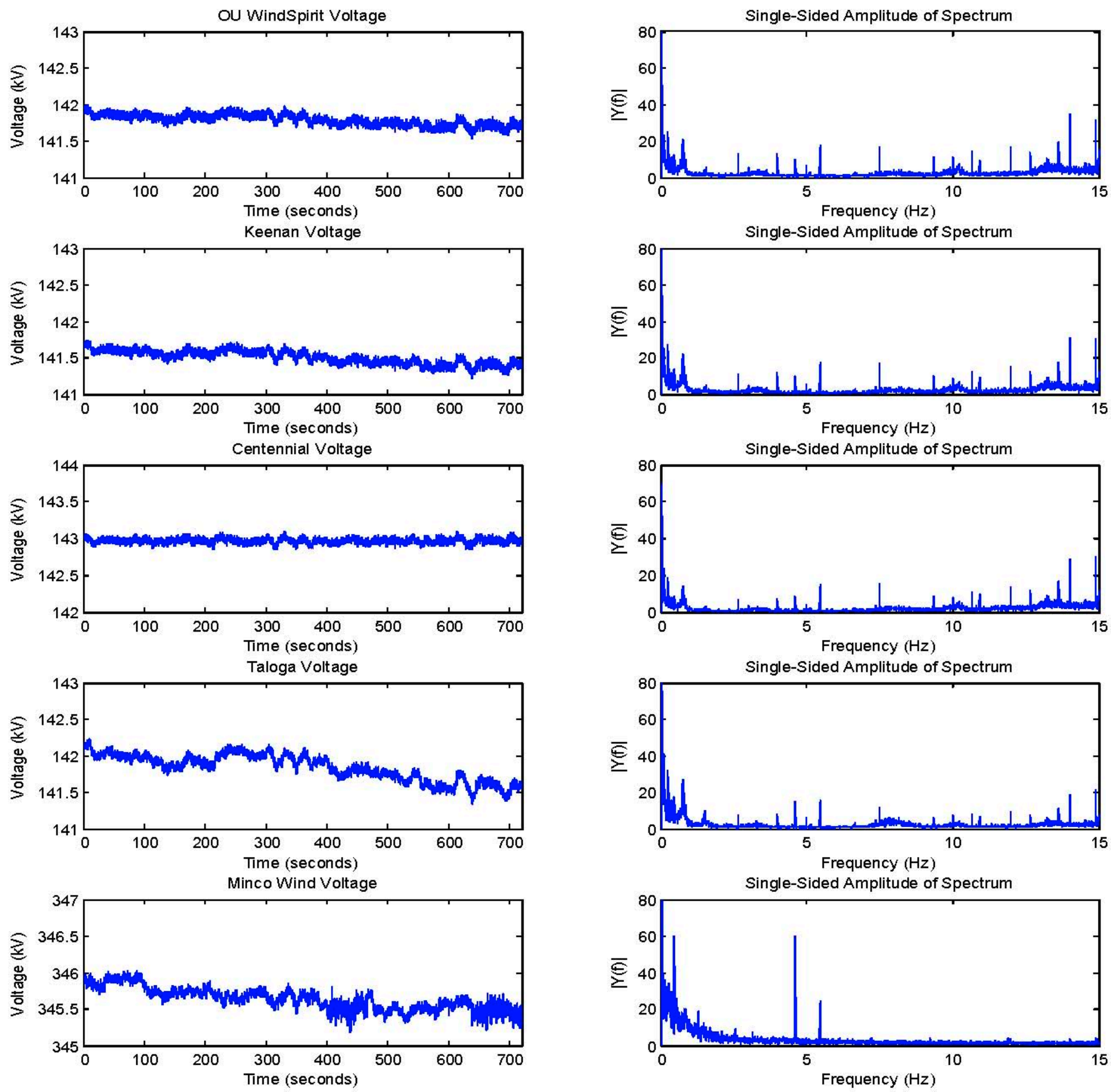

Figure 22. WPP voltage and spectrum prior to oscillation.

Figure 22 reinforces the observations from WPP PMU data that several subsynchronous frequencies are inherent to wind turbines installed at these WPPs. Three turbine manufacturers (Table 1) are present here, but only two types of turbine designs: Type 3 wind generators with doubly-fed induction generators and power converters by GE and Mitsubishi and Type 4 wind generators with variable-speed generators and full AC-DC-AC conversion by Siemens. The subsynchronous frequencies that originated from Minco WPP were less prominent because of the inherent strength of the 345 kV EHV transmission grid. At the 345 kV level, the pair of subsynchronous frequencies around 5 Hz became prominent.

4.2.4 Subsynchronous Frequencies From WPPs

Figure 23 shows the voltage profiles and frequency components of six WPPs in the OG&E system under normal conditions. The original voltage signals are from the 15-min window beginning December 6, 2011, 23:30 UTC (December 6, 2011, 5:30 PM CST). During that time, all six WPPs were online but at very low power level, between -1 MW (drawing power from grid) to +0.1 MW (generating barely enough power to overcome its own losses). These low power levels indicate that the power converters (most likely sources of subsynchronous frequencies) of the turbines were active. Another factor for selecting data from this period is that there were no grid transient events or breaker operations. The purpose here is to establish a baseline pattern of subsynchronous frequencies from WPPs.

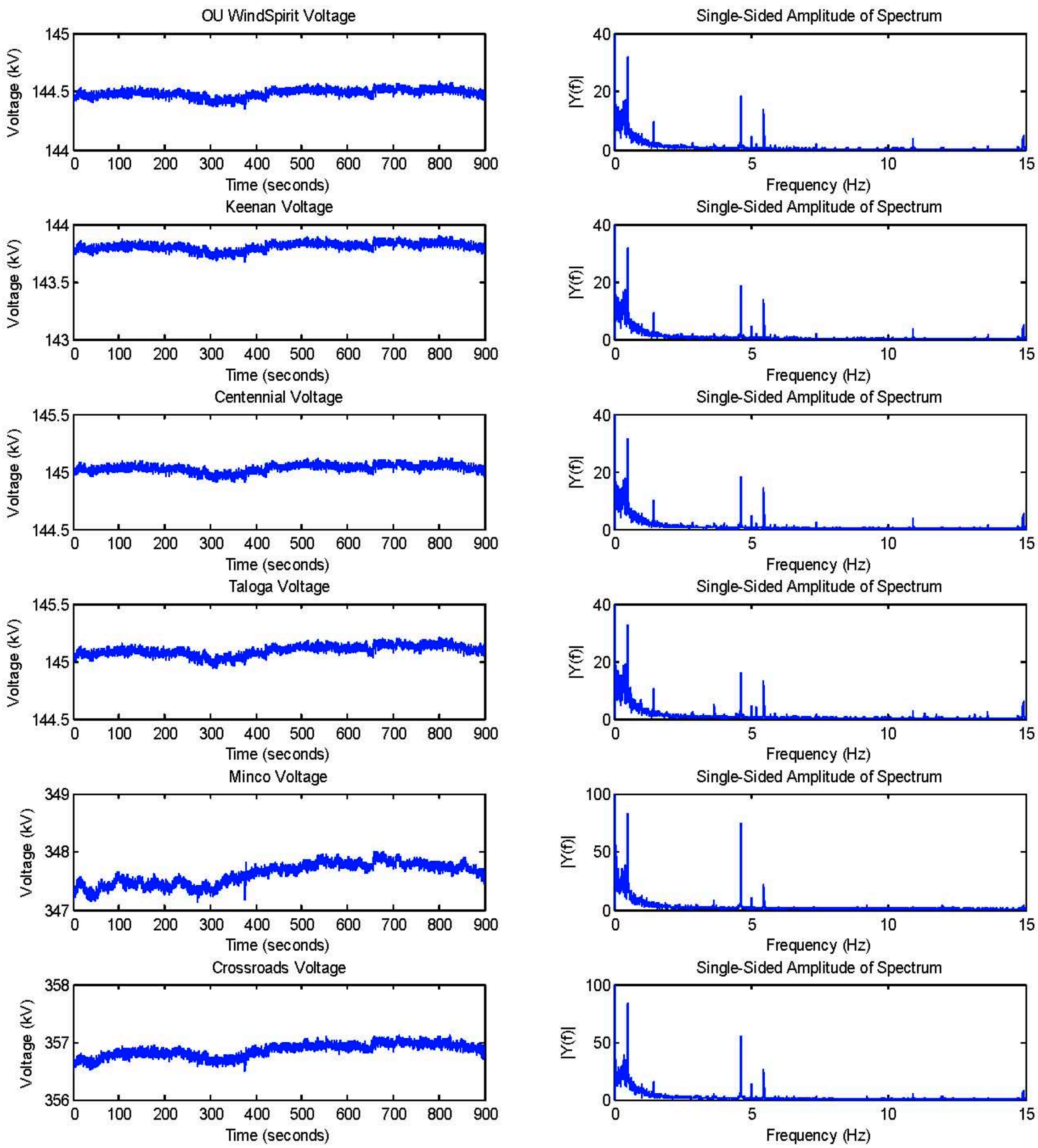

Figure 23. Subsynchronous frequencies at WPP during low wind speed.

During low wind speed periods, the inter-area oscillation mode frequencies from the grid dominated the spectrum. The most obvious was 0.48 Hz, which is typical of inter-area power oscillations and the frequencies around 5 Hz that are associated with VFD motors. Although very small, the 11-Hz and 12-Hz components associated with WPP can still be detected in Figure 23.

As the WPP output power increased, the subsynchronous frequencies from turbines began to appear, as shown in Figure 24. It shows voltages and their frequency spectrums during a 15-min period of moderate wind speed, which in this case was defined as the time the WPP outputs were at about 26% of their installed capacity. As shown, the subsynchronous frequencies associated with inter-area oscillations and VFD motors were still present, but the 10- to 12-Hz components became more obvious.

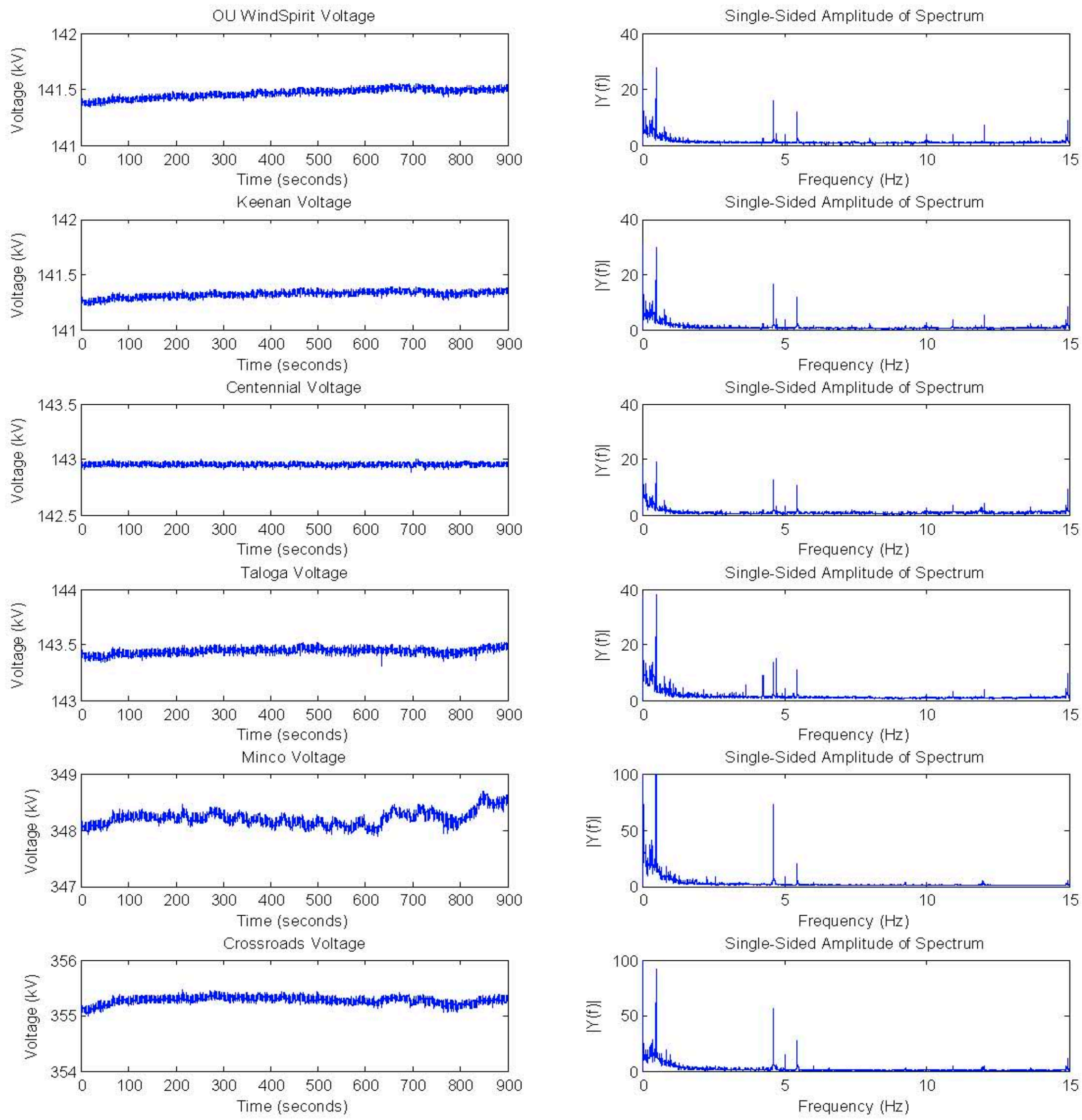

Figure 24. Subsynchronous frequencies at WPPs during moderate wind speed.

At higher wind speed and higher plant output levels, the above-10-Hz frequency components become even more prominent. Figure 25 shows WPP voltages and frequency spectrums during a 15-min period when plant outputs were more than 80% of installed capacity. In addition to 10-, 11-, and 12-Hz components, the 14-Hz component also appeared. The spikes in the voltage traces of the four WPPs at 138 kV appear to have been the result of a transformer tap change somewhere in the system; however, unlike the cases discussed in the two previous sections, outright voltage oscillations did not occur in this case.

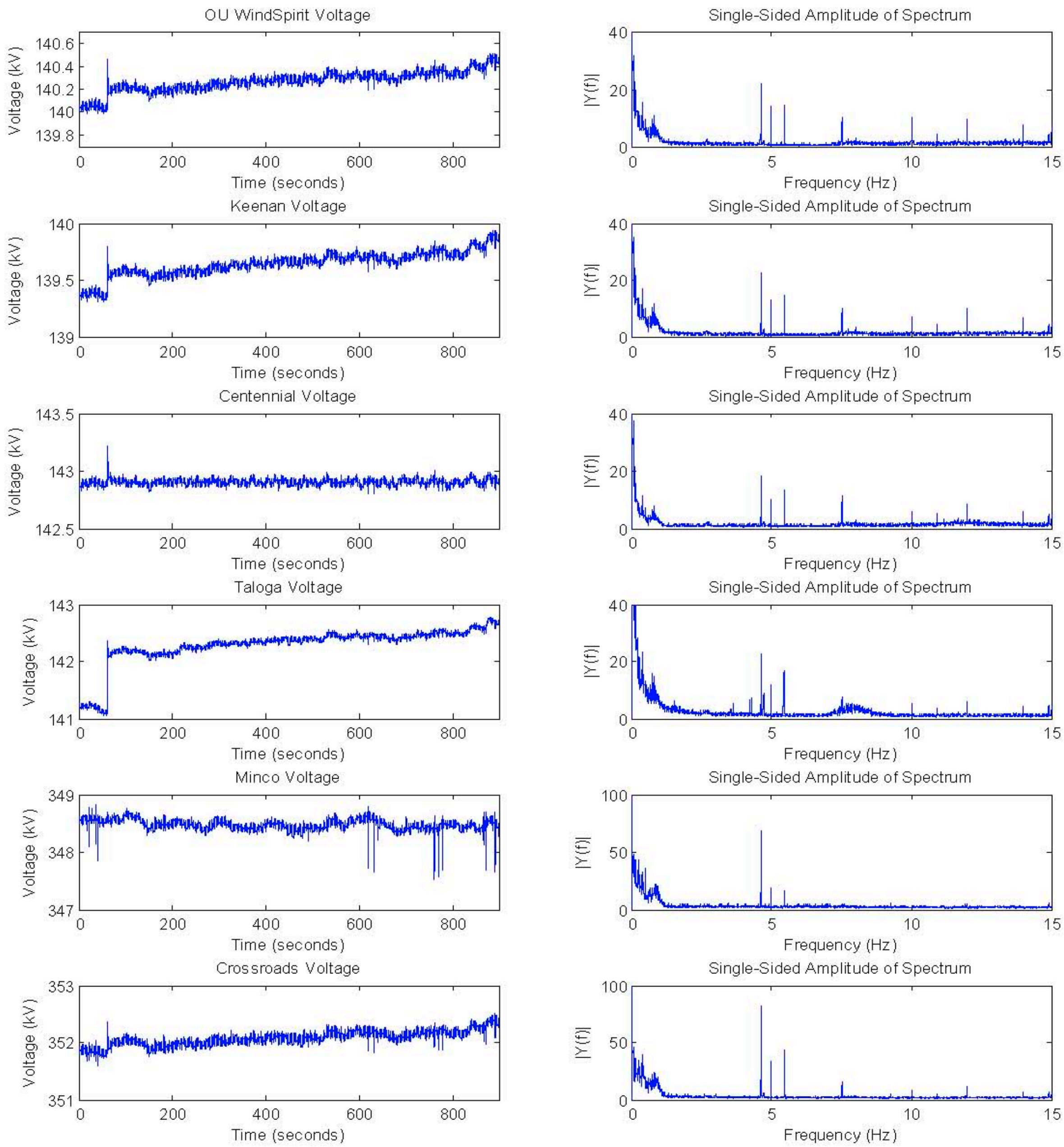

Figure 25. Subsynchronous frequencies at WPPs during high wind speed.

The three examples of WPP voltages and their spectrums in this section showed that subsynchronous frequency components were present at WPPs, and their amplitudes would increase along the plant outputs. It is also clear from the available data that when a WPP is connected to the grid at 345 kV, it is less likely to experience voltage oscillation. Under exactly what conditions those subsynchronous frequencies will develop into voltage oscillation is not clear. This will be an area for further research.

4.2.5 WPP Behavior During Grid Contingencies

One of the objectives of collecting PMU data from WPPs is to study the behaviors of WPPs during grid contingencies such as a loss of a major generation and loss of a major system component (transformers, EHV lines, etc.). The available data so far does not contain an event of major generation loss (i.e., an entire large generating plant tripping off-line). It does contain many incidents of individual generating units of a plant tripping off-line and outages of EHV lines. Two such events are analyzed in this section to illustrate if such so-called N-1 contingencies affect WPP operations.

The first case was an example of EHV-line outages during a thunderstorm (with tornados reported) that occurred on May 24, 2011, around 17:00 CDT. The thunderstorm caused many outages in the OG&E transmission system in the area. In addition to the outages of lower voltage transmission lines, OG&E records show that three EHV line segments in relatively close vicinity suffered some damages and tripped open within 17 min of each other. Figure 26 shows the voltage profiles of the three line segments and a reference line segment that is 80 miles away within a 20-min window. The first 345-kV line segment opened at 16:48:50.167 CDT; the second 345-kV line segment opened 5 min later, at 16:53:23.343 CDT, after a failed reclose attempt (the scale of Figure 26 cannot display the reclose operation); and 10 min later, at 17:03:5.063 CDT, the third 345-kV line segment opened, following a failed reclose attempt. The outages of these three line segments produced noticeable but relatively minor voltage sags on the reset of the transmission system. The voltage profile of the reference Draper-Seminole line in Figure 26 is an example.

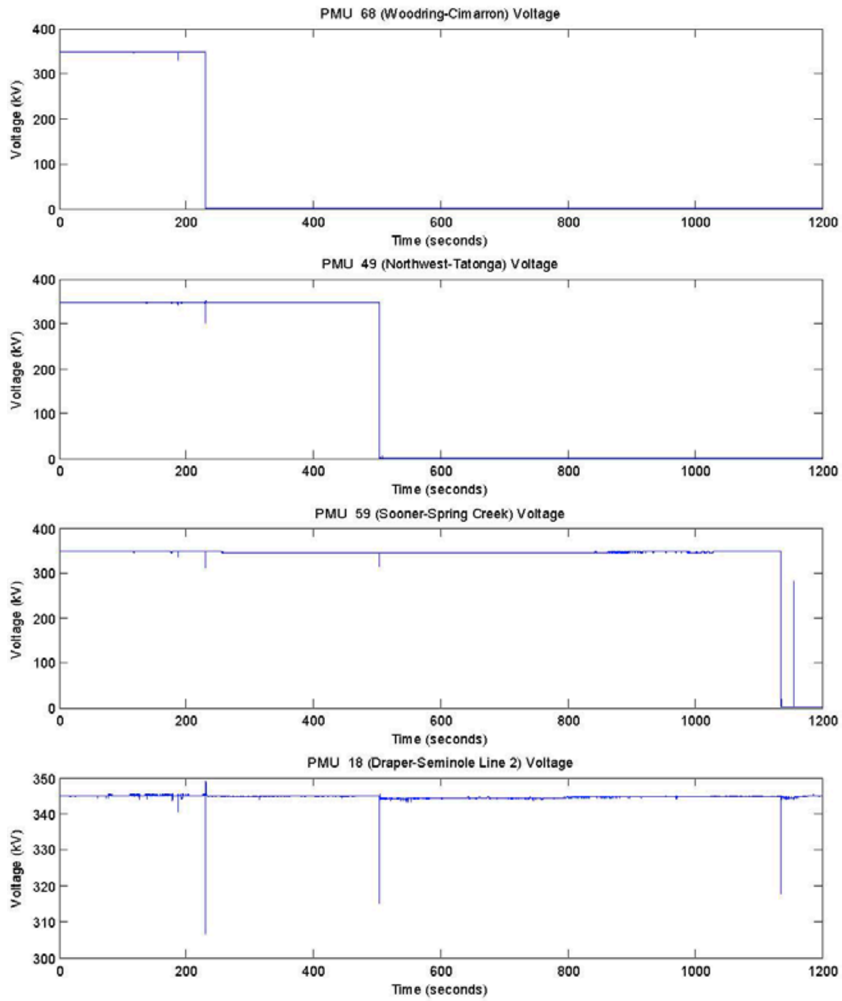

Figure 26. EHV line voltage profiles showing line outages.

During this time, all WPPs were online and were producing at moderate levels ranging from 27% of the installed capacity at Minco WPP to 68% of the installed capacity at Centennial WPP. Figure 27 shows the voltage profiles of the four WPPs during the same 20-min window.[3] WPPs did experience voltage transients when EHV lines were opened, but their operations were not adversely affected.

[3] Wind plant PMU data quality during this particular 20-min window was somewhat suspicious—e.g., data from PMU 114 and 115 were almost (but not exactly) identical. However because data streams before and after this period appeared to be normal, data from this period was considered adequate.

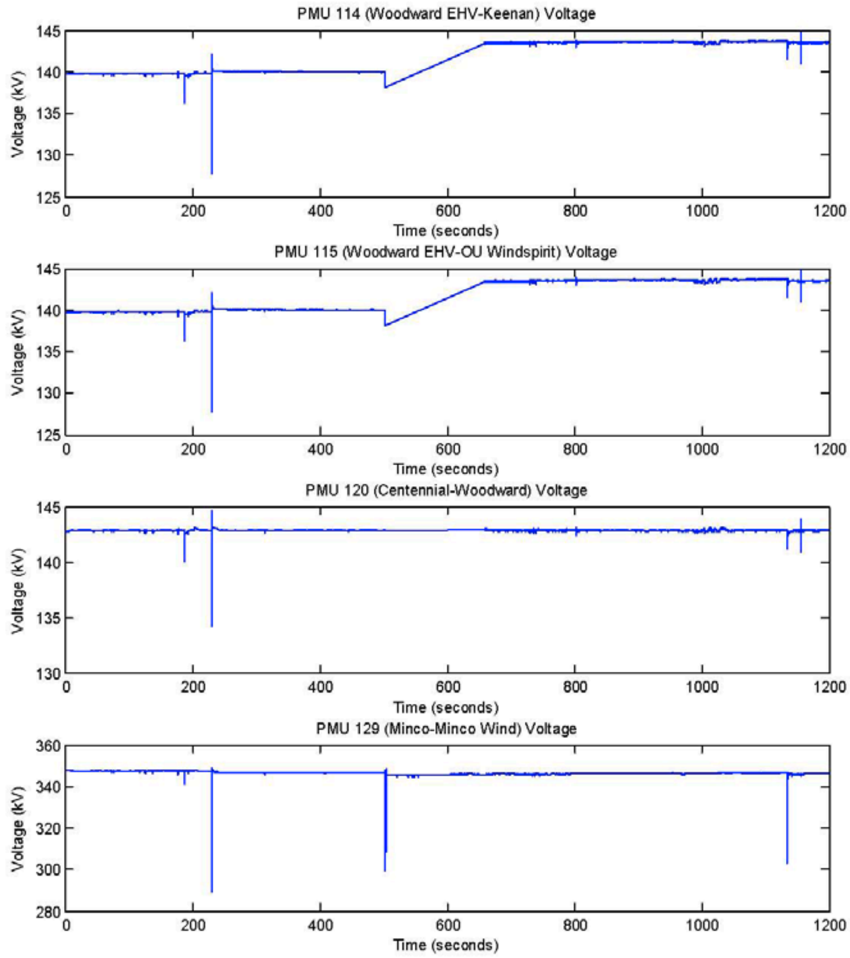

Figure 27. WPP voltage profiles during grid disturbance.

Although there were many breaker operations during this period that resulted in EHV transmission line outages, it appeared that those outages did not depress the voltage profile enough and the transmission system was not seriously stressed to the point to really test the LVRT capability of the wind turbines. As shown in Figure 27, the grid contingency caused the voltage at the WPP to drop to 84% of the nominal level. It was outside the normal operation range, but it was far from the required LVRT level, which is 0.[4]

The available data contained several events of loss of generation. The second case analyzed was an example of this. A significant event occurred on April 27, 2011, at 21:36 UTC, when all three units at Browns Ferry nuclear plant were tripped because loss of external power resulted from damages to power lines by a tornado. This event, although severe, was remote (in Alabama); therefore, its impact on the WPPs within the OG&E system was relatively minor. The event showed up on frequency and voltage signals at the WPPs, but the plant operations apparently were not affected. Figure 28 shows the frequency, voltage, and power traces of the three WPPs where PMU data were available at the time. The frequency in these parts of the system dropped 0.1 Hz by this event, and it took more than 200 s for the system frequency to recover. A

[4] Joos, G. "Wind Turbine Generator Low Voltage Ride Through Requirements and Solutions." IEEE Power and Energy Society General Meeting, July 20–24, 2008.

momentary voltage dip was also evident. However, WPP output power was not affected by this event. Power output from the WPPs did not respond to system frequency changes, which was expected because of current state-of-art turbine technologies.

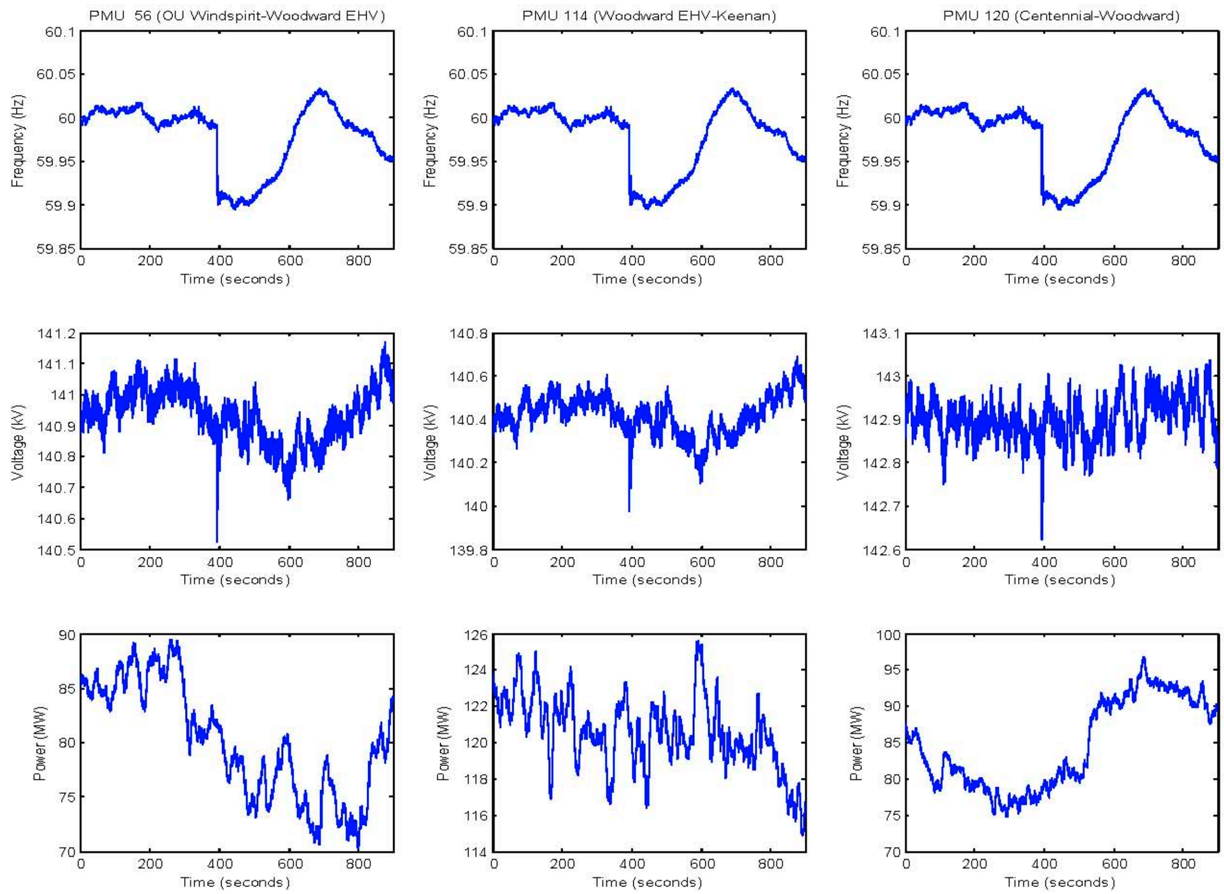

Figure 28. WPP responses to loss of generation.

There were other loss-of-generation events in the available PMU data, but all of them were minor in terms of the amount of generation lost compared to the system load and available generation on-line. Consequently, the responses of WPPs were the same as that of this event.

5 Summary and Conclusions

The availability of synchronized phasor data from PMUs offers unprecedented opportunity for observing and analyzing the WPP operations under normal and grid-contingency conditions. The analyses of PMU data from OG&E provided several noteworthy results.

The most noticeable finding is the tendency of certain WPPs to oscillate. The data suggests that certain subsynchronous frequencies may be present in such WPPs all the time, and grid disturbances may excite one or a group of these subsynchronous frequencies to begin to oscillate during high-wind periods. It appears that Siemens turbines have a higher tendency to oscillate, but GE and Mitsubishi turbines are not totally immune from this behavior. It is not clear from the available PMU data why this is the case. It is also not clear if this is unique to WPPs in the OG&E system because we do not have PMU data from other WPPs outside the OG&E system.

Results show that the WPPs will routinely ride through grid disturbances as designed. Lightning strikes, line outages, and loss of generation will cause WPP voltage to sag and swing in a way not very much different from the responses of other types of generators. There was a case in the data set in which one of the WPPs tripped off-line during a high-wind period; however, the OG&E disturbance list did not indicate any breaker operations or grid event at the time and there was no oscillation. No conclusion could be drawn from that event. The other events included in the available data set were not severe enough (in terms of magnitude of voltage drop and duration) to really show how WPPs will perform under more severe conditions. Additional data and analyses are needed to provide a more quantitative answer.

The results also point to the critical need for accurate WPP models and the knowledge of turbine controller logic and controls. The PMU data showed how WPPs behave under different conditions, but to know why WPPs behave in these ways we need good WPP models to tell us. The ultimate goal of analyzing WPP PMU data is to improve WPP dynamic performance under normal and grid contingency conditions. Using PMU data to better understand WPP behavior is only the first step in this process. We will also need to work with turbine manufacturers on this aspect.

Future work will include analyzing additional PMU data to identify more severe events under different situations. The example in Section 4.2.1 serves as a good example of how much information can be obtained from the PMU data. We will also try to obtain PMU data from other WPPs in other regions and of turbines by different manufacturers to broaden our database and to further our understanding of WPP oscillations.