Implementation and Application of an Independent Texas Synchrophasor Network

Dr. W. Mack Grady, *The University of Texas at Austin*
David Costello, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Synchronized phasor measurements are becoming widely used in wide-area networks (WANs) around the world for real-time control, monitoring, and post-disturbance analysis. While a few utilities in Texas presently employ synchrophasors in their service territories to increase overall service reliability, many challenges have prevented the development of a large-scale synchrophasor measurement network spanning the Electric Reliability Council of Texas (ERCOT) interconnection. New comprehensive analyses of data gathered from measurement units strategically placed throughout ERCOT will ultimately allow these utilities to make more informed control decisions.**

This paper discusses the ongoing development of a synchrophasor network by the University of Texas and the network applications, including modal analysis of measured angle differences between measurement locations. Understanding how high penetration levels of wind generation in West Texas affect overall system stability is of key interest. Phasor measurements in this network are taken from conventional 120 V wall outlets. Most data are sent to Austin through the public Internet.

I. Introduction

The Electric Reliability Council of Texas (ERCOT), the grid operator for most of the state, set a new hourly average usage record of 63,400 MW on July 13, 2009. Available generation resources for 2009 totaled 72,712 MW. The ERCOT target minimum reserve margin is 12.5 percent; on July 13, the reserve margin was only 12.8 percent. Less than 10 years ago, the reserve margin was 15 percent. ERCOT, like most electric power systems, is operating closer to its limits and with less reserve margin than ever before.

The state of Texas currently leads the United States with the most installed wind generation capacity. At 8,135 MW, this exceeds the goal set by the Texas legislature in 2007 of 5,000 MW by 2015; it is also on pace to exceed the legislature's goal of 10,000 MW by 2025. In fact, the Department of Energy "20% Wind Energy by 2030" benchmark [1] has already been a reality in Texas; on several days in March 2009, wind in Texas reached 20 percent of total generation. However, for planning purposes in Texas, wind generation is calculated at only 8.7 percent of installed capacity as dependable at peak [2]. The inconsistency of wind generation was on display in March 2009 when the state saw an increase, and corresponding decrease, of nearly 2,000 MW of wind generation within 1 hour! Texas is the ideal location to study this volatile energy source and its impact on grid operations.

The widespread installed base of satellite-synchronized clocks and phasor measurement units (PMUs) has made synchrophasors a ubiquitous technology. Protective relays include PMU capability as a no-cost feature. In Texas alone, there are more than 8,000 PMUs installed today. Over 2,500 of those are IEEE C37.118 message compliant, with a 30 messages-per-second or greater output rate. These units are available to be put to use today! The effort requires a communications path and an information user. The independent Texas synchrophasor network described in this paper has already shown beneficial results that others can easily emulate.

There are three aspects to this synchrophasor project. The first aspect is the deployment of clocks, PMUs, and communications. The second aspect is the establishment of the database. Every day, the network archives more than two million lines of Microsoft® Excel® comma-separated value (CSV) data. A five-step daily procedure is used to check this volume of data and screen for abnormal or interesting events. The third aspect is the processing and interpretation of the data. For this, the project uses a combination of off-the-shelf visualization, archiving, and mathematical software and custom screening and modal analysis software developed by graduate students at the University of Texas (UT).

II. Overview of Synchrophasors

A. Review of Sinusoidal Waveforms and Phasors

Recall that the sinusoidal waveform function y(t) is represented in the time domain by (1).

$$y(t) = |A|\cos(\omega t + \phi) \tag{1}$$

where:

y(t) = system voltage.

A = amplitude.

ω = angular frequency in radians per second.

t = time in seconds.

ϕ = angle shift from the peak of the waveform to time zero (or the reference).

Fig. 1 shows the sinusoid and its corresponding phasor representation. Angle ϕ is used to specify the value that y(t) has at the reference time, t = 0. The larger the angle ϕ, the farther the sinusoid moves to the left of the t = 0 reference. In the phasor plane, a larger ϕ means that the phasor is rotated farther in the counterclockwise direction from the real axis.

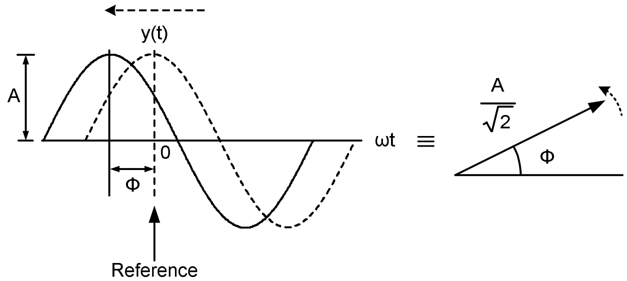

Fig. 1. Sinusoidal waveform translated to phasor representation

B. Turning Phasors Into Synchrophasors

The angle of a phasor by itself has little significance without a reference. It is common for relays to choose V_A at 0 degrees as a reference for all phasors within the device. However, comparing the angle difference of V_A voltage between two devices does not give accurate results unless both the waveforms are sampled at exactly the same moment in time.

Synchrophasors allow for precise measurement of voltage, current, phase angle, frequency, and other power system data from different PMUs with exact time stamps. This is possible when a universal time source, usually a satellite-synchronized clock, serves every PMU.

Each PMU uses the universal time source to create a phasor representation of a constant sinusoidal reference signal. This reference signal is the same across all relays in the network. The peak of the reference sinusoid is at the top of each second. A reporting instant, identified by a time tag, defines the absolute relationship between any measured signal and the reference [3] [4].

C. A Basic Synchrophasor Network

The basic equipment required for a synchrophasor network includes the following:

- Phasor measurement units.
- A phasor data concentrator (PDC) or a synchrophasor vector processor (SVP).
- Satellite-synchronized clocks for each PMU location.
- Appropriate communications equipment.
- Tools for visualization, storage, analysis, and control.

A PDC performs time alignment, data concentration, and "superpacket" data output for visualization, analysis, and control applications. An SVP consists of a PDC and a real-time IEC 61131-3 math engine. The math engine is composed of built-in functions, such as modal analysis, as well as user-defined functions created for custom applications. The SVP can send commands to connected PMUs for real-time control [5] [6].

III. Setup of the Texas Synchrophasor Network

A. Physical Overview of the Network

On November 26, 2008, engineers installed and made operational the first part of the Texas synchrophasor network. A central station consisting of a local PMU, clock, clock display, SVP, and a computer with processing and display software was installed in the power teaching laboratory at UT Austin, where it would have maximum visibility for students. A second "test remote" PMU and clock, located in the same building on campus, were also installed. This was done to verify that all devices would communicate through the Internet. Only the central station remains today. This Austin PMU is connected serially to the SVP, and its data represent a major load center.

In January 2009, engineers added the first truly remote PMU at the McDonald Observatory (Fig. 2) in Fort Davis in far West Texas. Fort Davis is about 400 miles west of Austin and represents wind country. The PMU in Fort Davis is very near several wind farms and closely approximates a PMU located on a wind farm. Establishing this location provided the precise voltage phase angle difference between remote wind generation sites and a major load center. The McDonald Observatory is owned and operated by UT, so this PMU sends data to the Austin SVP via the university internal Ethernet network. Remote engineering access facilitates monitoring and settings changes from a distance.

Fig. 2. Aerial view of McDonald Observatory in West Texas

Other PMUs have since been added in Houston and Boerne (30 miles northwest of San Antonio). Additional PMUs will soon be added at UT campuses in Arlington (near Dallas), Harlingen (South Texas), and Tyler (East Texas). These locations communicate using a variety of methods over Ethernet and the Internet. A second Austin-based PMU will soon be installed that will communicate its data serially to the SVP using line-of-sight spread-spectrum radios. These PMUs are all within ERCOT (Fig. 3).

Fig. 3. Map of ERCOT with existing and future PMU installations

PMUs in the Western Electricity Coordinating Council (WECC) were added to the network in the summer of 2009. This enabled the project to monitor WECC disturbances from points in Pullman, Washington, and Cloudcroft, New Mexico. Future plans include adding more PMU locations in ERCOT, WECC, and the Eastern Interconnection.

B. Equipment Details

None of the PMUs are installed in substations, but rather in laboratories, commercial offices, and residences. Each PMU is powered by 120 V. Most of the PMUs measure voltage and frequency from a standard wall outlet; a single-phase voltage is connected to the device power supply input. The Houston and Fort Davis PMUs are installed in buildings served by three-phase voltage, which will be used in the future.

Fig. 4 shows the major equipment needed to send remote PMU data to the SVP. Each remote measurement location requires a high-accuracy satellite-synchronized clock capable of outputting time in IRIG-B000 format with an IEEE C37.118 extension. Also, a PMU compliant with IEEE C37.118 is needed. Various clock accessories are likewise required at each site, such as a Global Positioning System (GPS) antenna; cabling to connect the antenna, clock, and PMU together; and an inline, grounded surge protector installed between the antenna and the clock to protect equipment from lightning strikes.

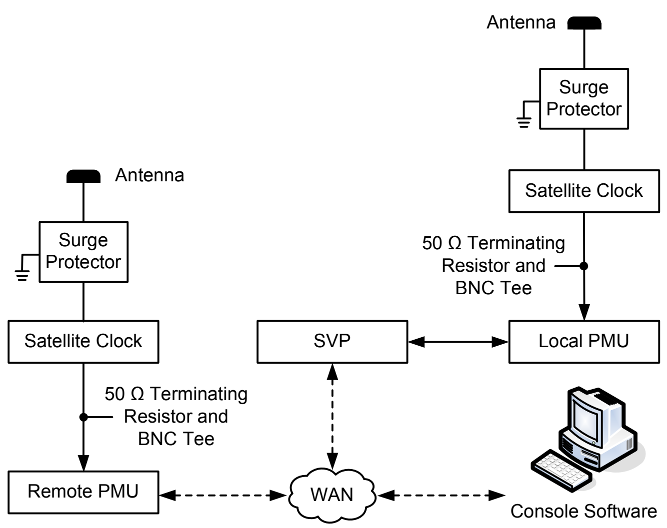

Fig. 4. Block diagram of system equipment setup

The SVP client in Austin serves as the central data station and performs several functions. First, the SVP receives local data from a serially connected PMU. Establishing this PMU server as part of the network was simple, but it adds a valuable local measurement. Second, the SVP gathers and time-aligns the PMU data from all locations and outputs the concentrated superpacket data to external IEEE C37.118 clients. The data are received by visualizing and archiving software on an external PC. Data archival allows for post-disturbance analysis. Visualization of the data demonstrates how system operators can make decisions in response to developing abnormal system conditions. Finally, the SVP is programmed to perform analysis of data and to make automatic real-time control decisions in reaction to developing abnormal system conditions. Control decisions do not operate any breakers in this system but are used for demonstration and proof of concept.

C. Device Settings

Successful synchrophasor data transmission from a PMU to the SVP depends heavily on message rate (messages per second), packet size, and communications bandwidth. Increasing the message rate or the amount of data included in the output requires an increase in bandwidth.

For serial output from a PMU to an SVP, increasing the bandwidth simply translates to increasing the serial port speed to a setting that can accommodate the packet size and message rate. The Austin PMU was set at its maximum allowable port speed, 57.6 kbps.

For Ethernet output, available bandwidth is a function of the transmission speed characteristic of the type of medium used and other traffic encountered on the network. PMUs communicating to the SVP over Ethernet are located on DSL Ethernet channels or better, but dropouts in data transmission occur occasionally when intranet traffic bottlenecks in the router that is sending data from a local-area network (LAN) to the Internet.

At the time of publication, the time-alignment algorithm in the SVP required every PMU in the network to be set to the same message rate. Higher output message rates provide better resolution for post-event analysis but also require higher bandwidth. Conversely, lower message rates sacrifice data resolution for a lower probability of encountering dropouts.

A good practice for selecting a message rate is to initially select the maximum of 60 messages per second for all devices in the network and monitor the output of each device. If the ratio of dropouts (the number of samples lost divided by the total number of samples in a given interval) is less than 5 percent, then the message rate selected is acceptable. Otherwise, the message rate should be stepped down one interval. This assumes that the message size and bandwidth are already determined for the application.

Applying this process to the system, the initial choice of 60 messages per second revealed that data transmissions from some PMUs to the SVP were riddled with dropouts, especially during peak Internet usage times. Stepping the message rate down to 30 messages per second produced considerably fewer dropouts in data and still allowed for acceptable data resolution.

D. Network Problems and Solutions

While the concept of implementing a network is simple, the actual process was complicated by the need to route Internet traffic cross-country and across networks owned by different entities. It is easy enough to assign an Internet protocol (IP) address to each PMU and the SVP. However, firewalls, routers, and other Internet traffic complicate how data are routed from Point A to Point B.

For this installation, information technology personnel were called upon to assist in configuring network parameters at each location to allow communication between the local

PMU and the SVP. This was necessary since the network was constructed in partnership with multiple entities, and security of the data and the infrastructure of each entity is critical. In a single entity-owned network, these security issues would be easier to overcome. Unchanging or "static" IP addresses must be used for communication between all devices on the network.

However, PMU data bound for an SVP outside of the LAN can only reach their destination if both of the devices, the local and remote firewalls, and the communications channels are properly configured. Well-established security mechanisms, including leased lines, virtual private networks, and encryption, exist today. This project uses Network Address Translation (NAT) to allow a device inside LAN A to send data to a device inside LAN B (Fig. 5). A private or local address belonging to the device in LAN A is first converted into a public address registered on the public Internet by an NAT router, which acts as a buffer between the LAN and the public Internet. Once out on the public Internet, the public destination IP address, contained within the message sent from the device, routes the message to the NAT router at LAN B. The public address associated with the device in LAN B by its NAT router is then translated into the local address assigned to the device awaiting the data.

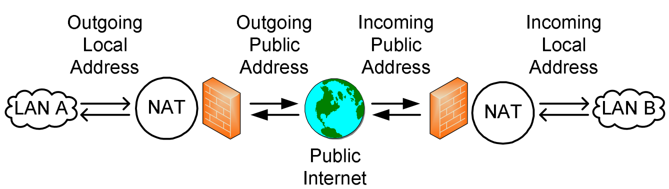

Fig. 5. Data transmission between two networks employing NAT

Additionally, firewalls are employed to secure Internet traffic from unauthorized intrusion. They are configured for proper NAT to allow the local and remote devices to send data in a two-way virtual tunnel. Permissions are set at both LANs to grant the public address of the remote device access through a specific network port. This port is specified in both local and remote devices. The combination of employing NAT and configuring firewall permissions in this manner provides very secure and efficient communication between PMUs and an SVP.

IV. Observations From the Synchrophasor Network

A. February 2009—Do Synchrophasors Provide Significant New Information About Grid Oscillations?

The ability of the power system to recover from perturbations caused by disturbances and return to an acceptable operating condition is called transient stability. Modal analysis describes system transient response in terms of mode shapes, amplitudes, frequencies, and damping characteristics. It is beyond the scope of this paper to discuss stability studies in any detail. References [7] and [8] are recommended.

Consider Saturday, February 21, 2009. It was a typical late winter day in Texas—sunny, windy, and cool. The ERCOT peak load was about 30 GW. The day began with a strong wind generation penetration level of 13 to 14 percent of the total (Fig. 6). Wind generation gradually subsided during the day, finishing at less than 1 percent penetration.

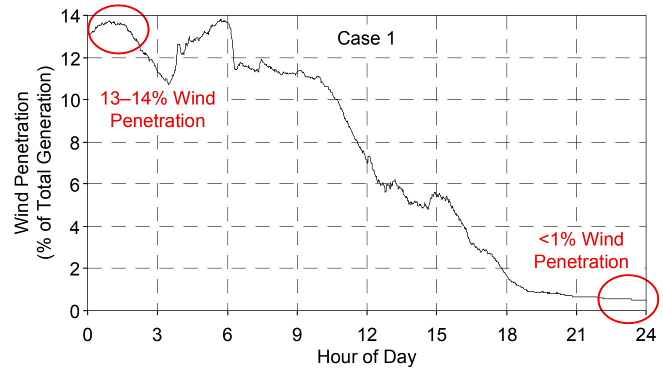

Fig. 6. Wind penetration in ERCOT, February 21, 2009

The impact of different wind penetration levels on the same day was explored. The first period of analysis is between 12 midnight and 1 a.m., and the second period is between 11 p.m. and 12 midnight. The modal analysis results for both hours are scatter-plotted next (Fig. 7 and Fig. 8). The modes are computed on the McDonald Observatory voltage phase angle with respect to UT Austin. The 0.7 Hz mode always exists, but the 2.0 Hz mode is not always present; the 2.0 Hz mode may be attributed to high wind penetration.

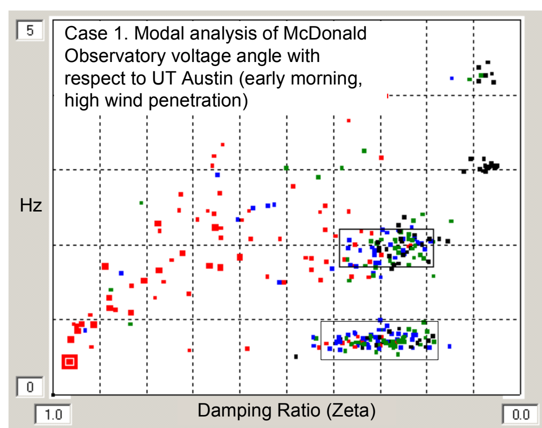

Fig. 7. Modal analysis for the 13 to 14 percent wind penetration period

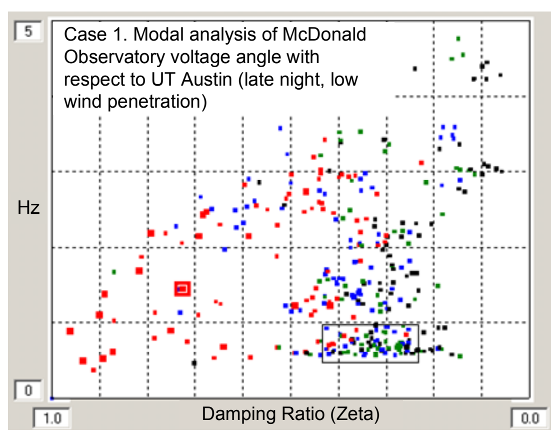

Fig. 8. Modal analysis for the < 1 percent wind penetration period

Next, consider Monday, February 23, 2009. A generator trip occurred, and a 5-minute frequency excursion was recorded by a monitoring station in San Angelo, Texas. This is a separate station that has been operating for about 5 years. It is not a PMU and is not GPS time-synchronized.

The frequency measurements from the older station and the new PMUs are shown in Fig. 9. Note that the frequency data are almost identical. This early result provided validation and a high degree of confidence in the new data.

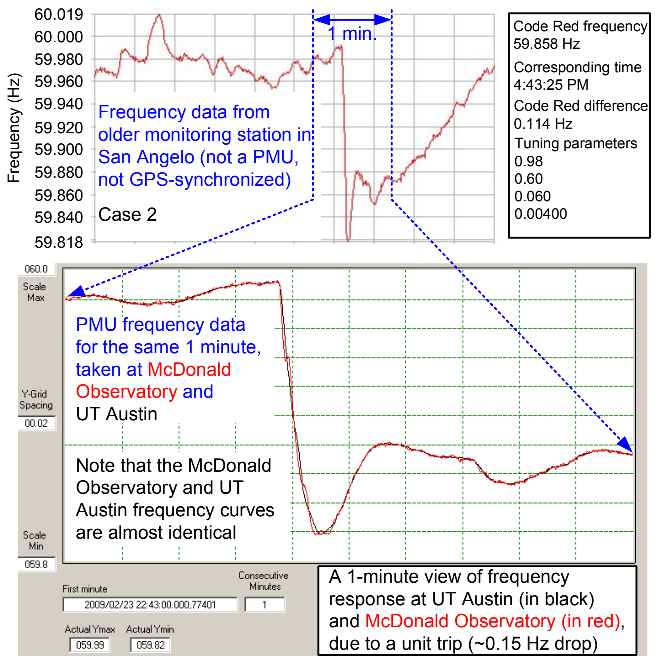

Fig. 9. Frequency data from older station matches PMU data, February 23, 2009

The validity of the frequency data is useful, but the synchrophasor data provide additional and non-overlapping information. The voltage phase angle at McDonald Observatory with respect to Austin is shown in Fig. 10. Over the full 1-minute window, the voltage phase angle difference drops by 3.5 degrees. This is an indication that the unit trip occurred in West Texas. More importantly, we are able to see the induced system oscillation brought about by a "step change" event, such as a large unit trip. Here, we observe a lightly damped 0.65 Hz oscillatory response.

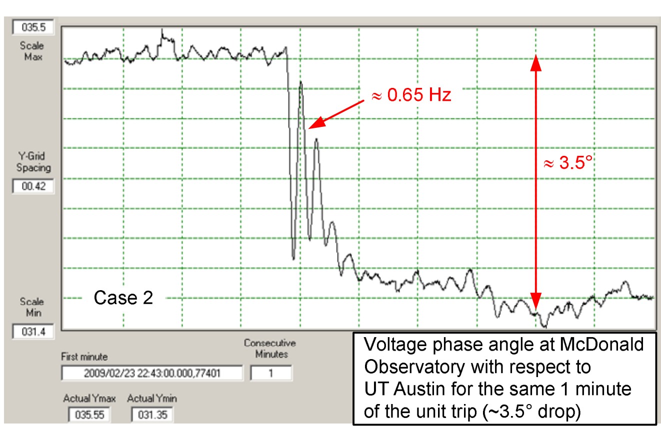

Fig. 10. Voltage phase angle change during generator trip

The ability to observe the system response to sudden events provides the opportunity to fine-tune stability models by matching simulations with field measurements. We can also determine the types of responses that are normal or abnormal for a grid.

Remember, the data used for this analysis were provided by two PMUs recording wall outlet voltages [9] [10].

B. 20 Percent Wind by 2030—Why Wait So Long?

On March 7, 2009, wind reached 20 percent of total generation in Texas (Fig. 11).

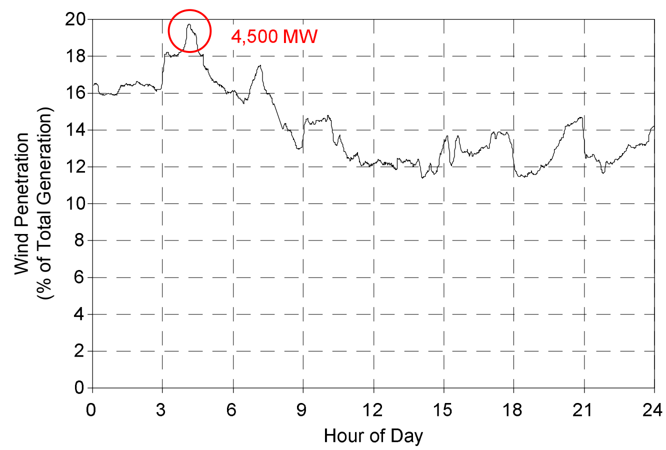

Fig. 11. ERCOT achieves 20 percent wind penetration on March 7, 2009

During a 5-minute window corresponding to the peak wind generation, the voltage phase angle in West Texas with respect to Austin reached nearly 60 degrees (Fig. 12). The phase angle is typically in the 30-degree range.

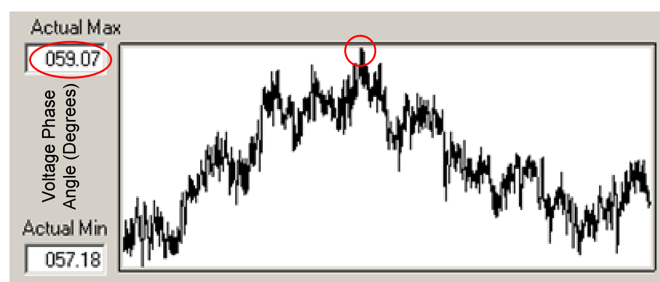

Fig. 12. West Texas phase angle with respect to Austin during peak wind penetration on March 7, 2009

Modal analysis of the 1-hour window corresponding to the peak of wind generation is shown in Fig. 13. Note the 2.0 Hz mode in addition to the usual 0.7 Hz mode. The 2.0 Hz mode may be attributed to high wind penetration. The modes are computed on the McDonald Observatory voltage phase angle with respect to Austin.

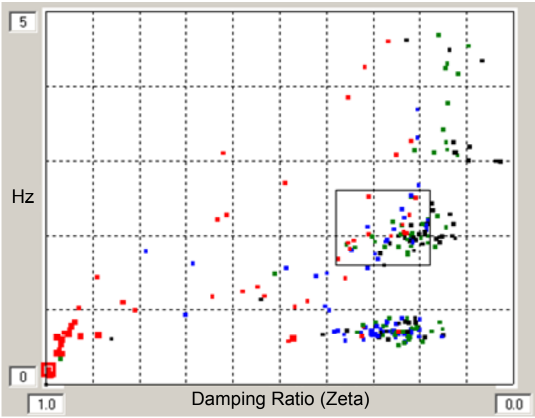

Fig. 13. Modal analysis for the 20 percent wind penetration period

C. Grid Response to a Second Single Generator Trip

Consider Friday, March 6, 2009. A generator trip occurred, and the ERCOT frequency is shown in Fig. 14, as measured by the separate monitoring station in San Angelo, Texas. Wind generation at the time of the trip was approximately 15 percent of total.

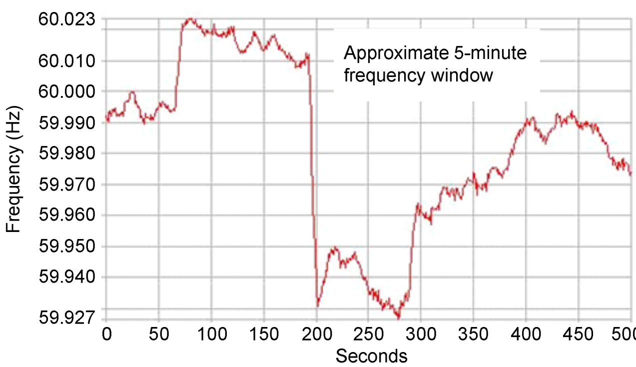

Fig. 14. Frequency excursion due to generator trip on March 6, 2009

The frequency information was readily available before synchrophasors. From the PMU data, however, we can view the voltage phase angle response to the generator trip (Fig. 15). Note the damped system response to the step change.

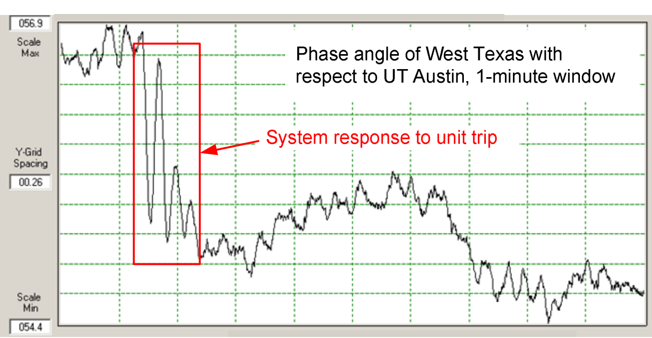

Fig. 15. Voltage phase angle oscillation due to generator trip

D. A Large Generator Trip With Slow System Recovery

A large generator trip was observed on March 10, 2009. A 5-minute window (Fig. 16) shows the frequency data from UT Austin (red) and the McDonald Observatory (black). The graphs are virtually indistinguishable. Thus, it is difficult or impossible to observe the response of West Texas with respect to UT Austin from frequency data alone.

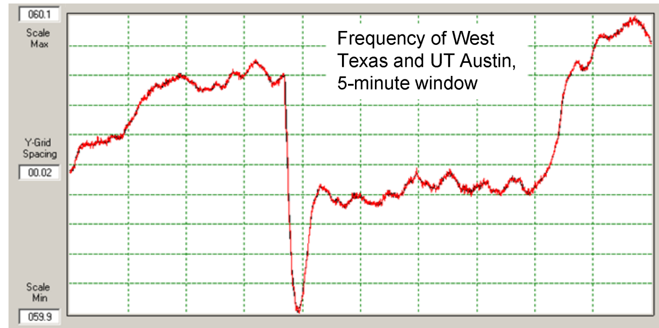

Fig. 16. Frequency at McDonald Observatory and UT Austin (identical)

However, a 2-minute detail of the voltage phase angle of the McDonald Observatory with respect to UT Austin using PMU data is shown in Fig. 17. The phase angle clearly shows the damped resonant system response.

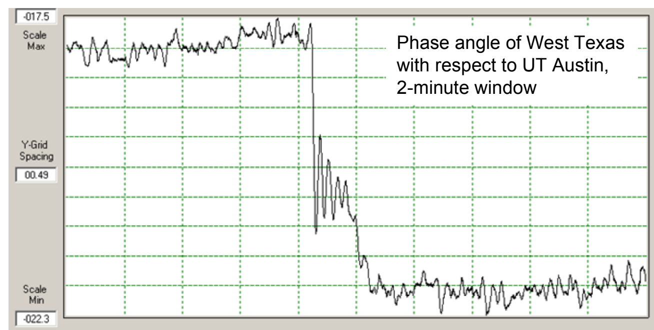

Fig. 17. Voltage phase angle response to generator trip

E. The Volatility of Wind Generation

On March 10, 2009, a sudden increase (about +1 MW/s) in wind generation occurred (Fig. 18). This was followed by an equally sudden decrease. The duration of the impulse was approximately 1 hour.

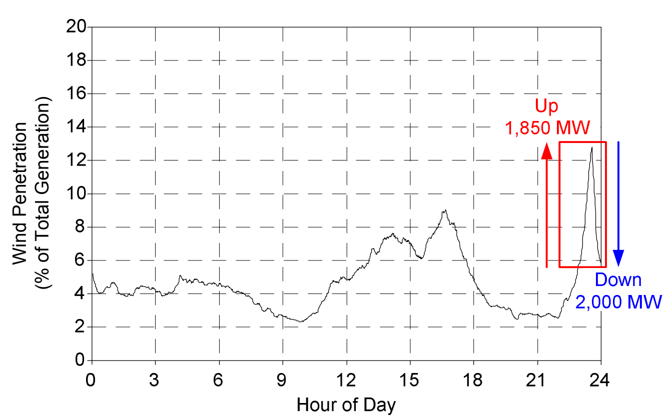

Fig. 18. Wind generation in ERCOT on March 10, 2009

The resulting voltage phase angle change of West Texas with respect to Austin showed an increase of 36 degrees in 30 minutes, followed by a decrease of 43 degrees in 30 minutes (Fig. 19).

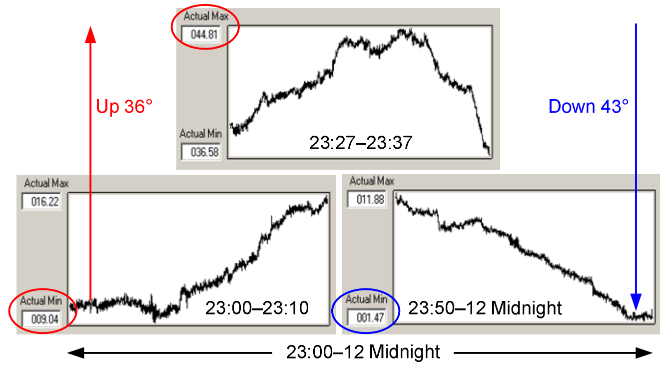

Fig. 19. Voltage phase angle changes during spike in wind generation

F. Wind Generation Exceeds 20 Percent of Total Again

On March 18, 2009, wind generation was greater than 20 percent (Fig. 20). The voltage phase angle reached +65 degrees and fell to −23 degrees (Fig. 21 and Fig. 22).

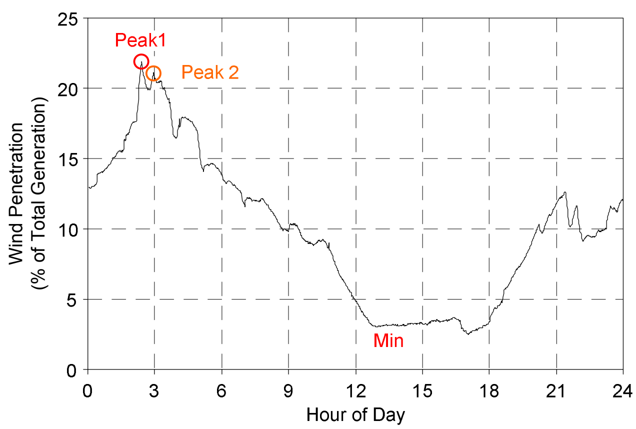

Fig. 20. Wind generation in ERCOT on March 18, 2009

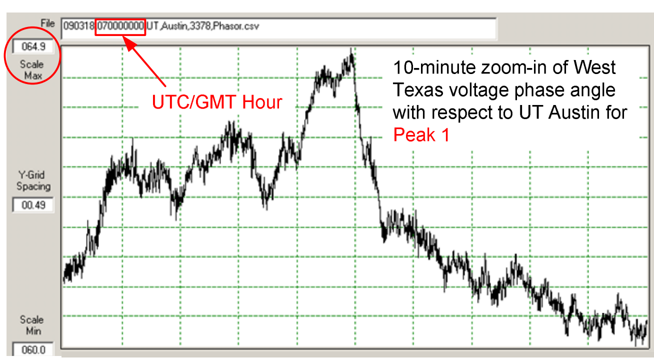

Fig. 21. Voltage phase angle difference during Peak 1 on March 18, 2009

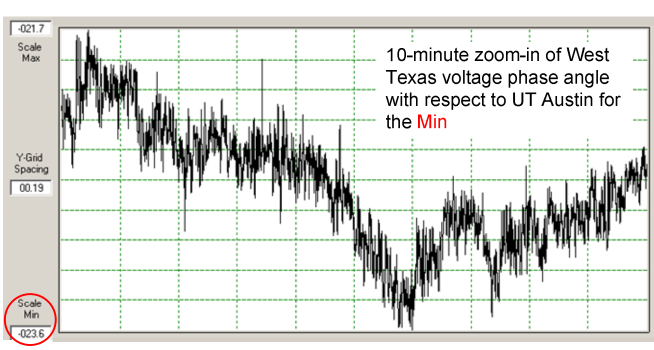

Fig. 22. Voltage phase angle difference during Min on March 18, 2009

G. Wind Generation Affects Modal Results

With respect to total ERCOT load, compare the early morning time period of March 18 (Fig. 20) to a similar period on March 12, which had practically no wind generation (Fig. 23).

The modal graphs (Fig. 24 and Fig. 25) represent the 2 a.m. to 3 a.m. period on both days (computed on the McDonald Observatory phase angle with respect to UT Austin). On March 12, the wind generation was 2 percent of total. The 2.0 Hz cluster is well absent (Fig. 25).

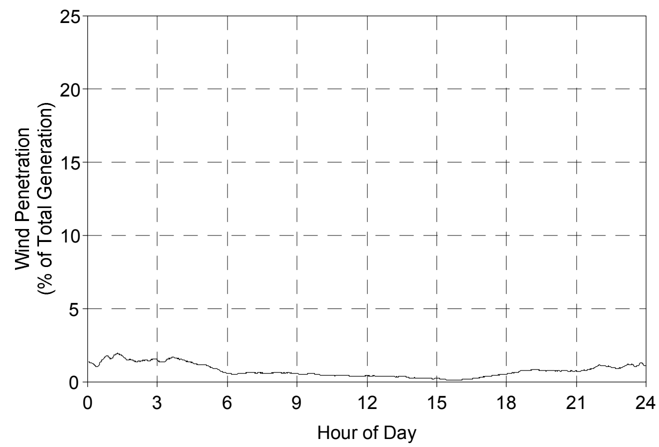

Fig. 23. Wind generation in ERCOT on March 12, 2009

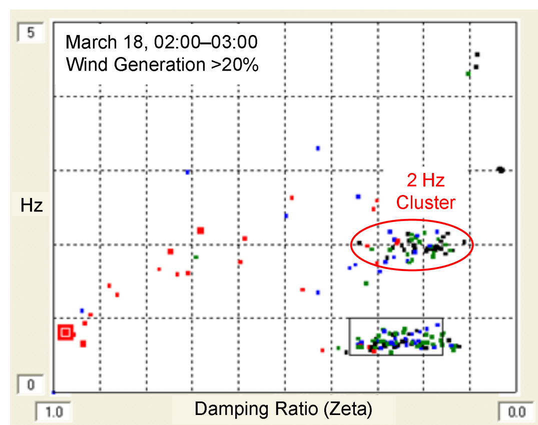

Fig. 24. Modal analysis for March 18, 2009

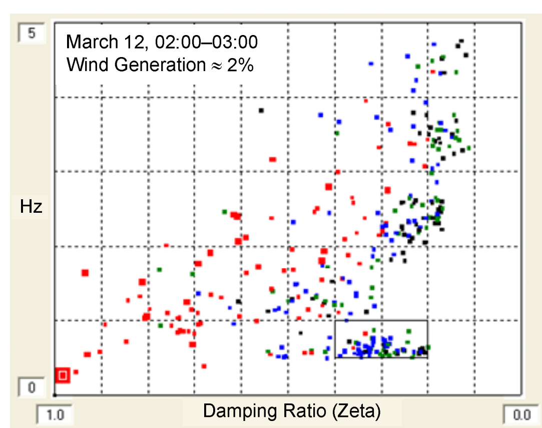

Fig. 25. Modal analysis for March 12, 2009

H. Event of Interest on March 26, 2009 (Unknown Cause)

An event of interest occurred on March 26 at 12:45 in the afternoon. Wind generation was approximately 10 percent of total, and the West Texas phase angle led UT Austin by a modest 22 degrees. The corresponding 120-second window of West Texas voltage phase angle with respect to UT Austin is shown in Fig. 26. Window A is pre-event. Window B is during the event and has a strong and sustained oscillation.

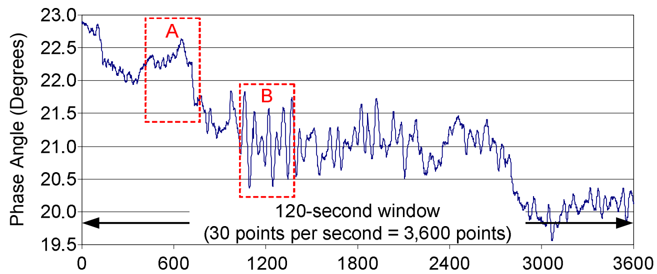

Fig. 26. Voltage phase angle oscillations on March 26, 2009

Closely examine the situations in A and B. A 12-second detail of Window A (Fig. 27) reveals a weak 1.0 Hz oscillation.

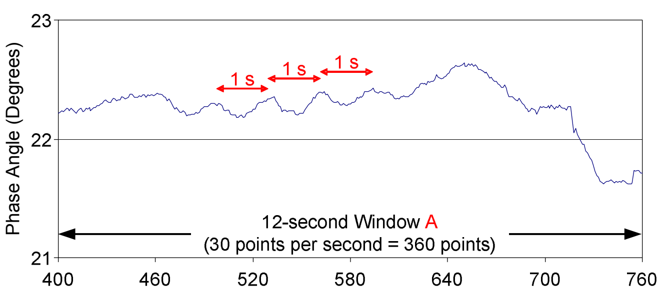

Fig. 27. Window A oscillations, March 26, 2009

Examine a 12-second detail of Window B (Fig. 28). The time period between peaks in B has increased such that the oscillation frequency becomes 0.7 Hz instead of 1.0 Hz. The magnitude of the oscillations in Window B is about five times greater than that in Window A. During the pre-event Window A, there is a weak 1.0 Hz oscillation, but little or no 0.7 Hz oscillation. During the event Window B, there is a strong 0.7 Hz oscillation, but little or no 1.0 Hz oscillation. The cause of the event is unknown at the time of publication.

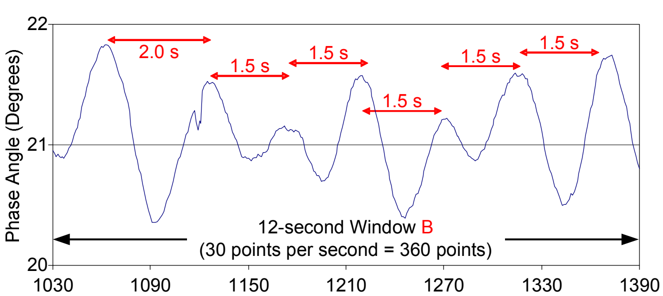

Fig. 28. Window B oscillations, March 26, 2009

I. April 2009—Three New PMUs Added to the Network

Additional data began to stream in from Boerne and Houston in ERCOT and Pullman in WECC at the beginning of April 2009. More than 100,000 lines of data were now streaming in every hour.

One significant event occurred in ERCOT at this time, and the recordings are shown in Fig. 29. The top graph is a 1-minute frequency window beginning at 7:09 a.m. on Sunday, April 5. The bottom graph is a 6-second detail of the top graph, centered around the frequency dip.

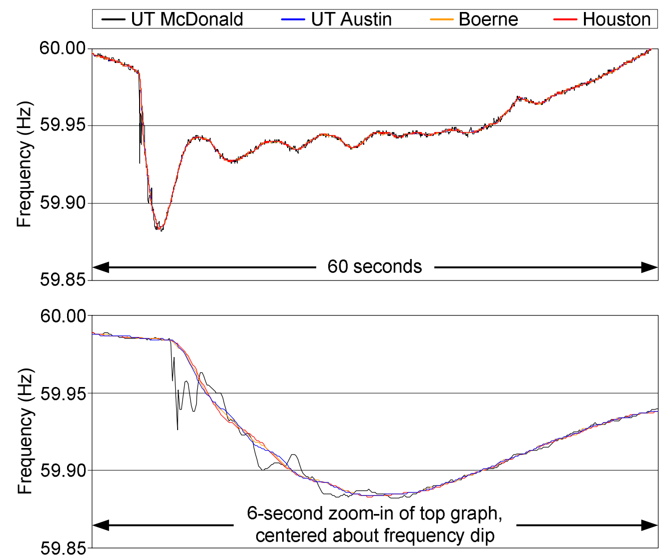

Fig. 29. ERCOT frequency response, April 5, 2009

Note that the frequency responses at Austin, Boerne, and Houston are essentially the same, but the McDonald PMU (in far West Texas) has a more dramatic response.

Plots of the corresponding phase angles (relative to UT Austin) for the 6-second window are shown in Fig. 30. The drop in West Texas phase angle indicates that the unit trip was likely in West Texas.

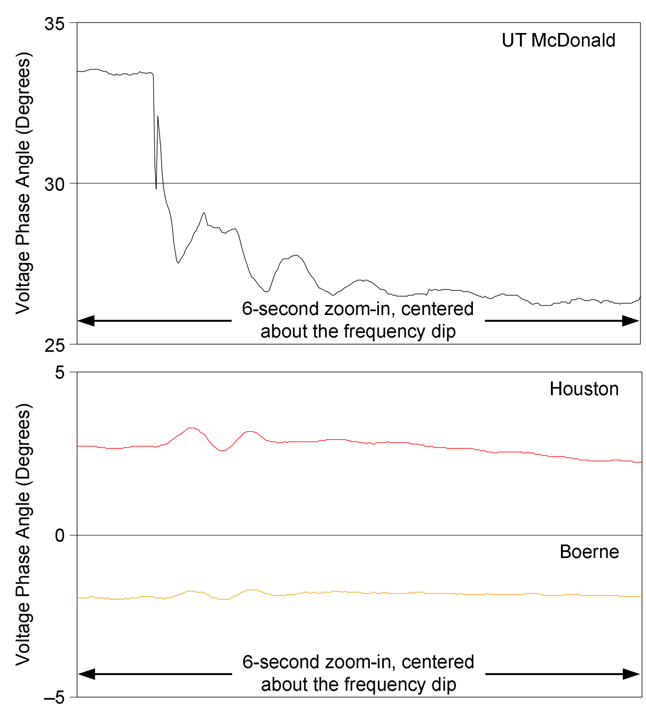

Fig. 30. ERCOT phase angles with respect to UT Austin, April 5, 2009

A 6-second detail of phase angles with respect to UT Austin is shown after the system frequency has recovered to a new steady state (Fig. 31). The residual peak-to-peak variation for West Texas is about 0.3 degrees. For Boerne and Houston, the residual peak-to-peak variation is one-fifth of that (about 0.06 degrees). This is an indication that the noise between PMUs at UT Austin, Boerne, and Houston is most likely less than 0.06 degrees (i.e., negligible).

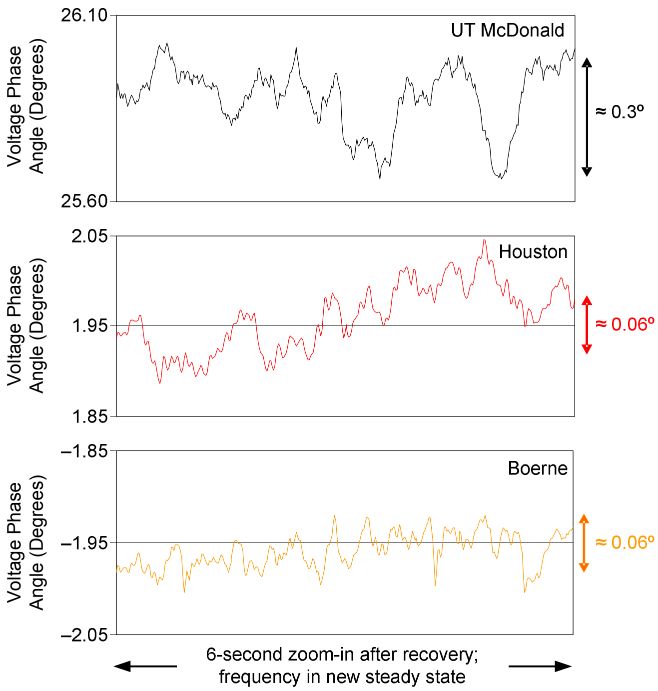

Fig. 31. Steady-state ERCOT phase angles with respect to UT Austin, April 5, 2009

J. *How Appropriate Are Wall Outlet Voltages?*

Up to this point in the project, all data have come from 120 V wall outlets or building supply voltages. Obviously, 120 V wall outlet data are not as high in quality as what we would expect from PMUs connected directly to a transmission grid through substation instrument transformers.

Distribution feeders and building loads contain noise. The harmonic content of a wall outlet circuit feeding a BlackBerry® charger with the device plugged in and charging is shown in Fig. 32.

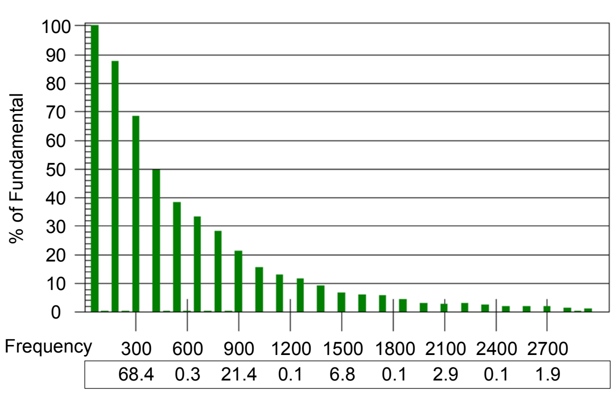

Fig. 32. Harmonic analysis of a BlackBerry charger

Fig. 33 shows about 1 second of noise on the Pullman PMU that was observed infrequently after the PMU was moved to a new location. The new location included a unique load, a thermocouple circuit in an oven used for ongoing reliability testing of relays. The thermocouple circuit monitors and maintains a temperature of 90°C for extreme temperature tests. When the oven cycled on or off, the PMU saw noise because of the influence of this load.

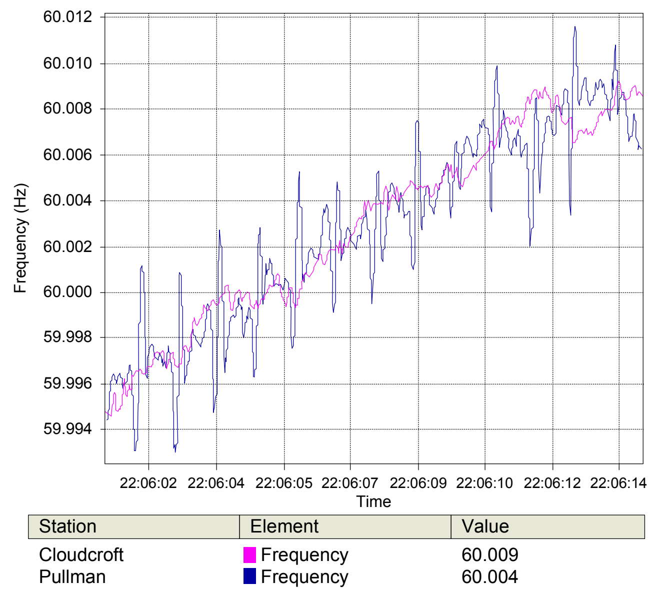

Fig. 33. Frequency noise during the cycling of a thermocouple

All of this noise, however, tends to be well above the 0.5 to 5 Hz range of interest for synchrophasor applications and can be filtered out of the analysis. Additionally, the PMUs use digital filtering designed to perform flawlessly in electrically noisy environments [11] [12].

There is some load-related phase angle shift through substation transformers and along feeders, beyond that due to wye-delta transformers. Experience with harmonic studies on distribution feeders indicates that this additional phase shift is less than 3 to 4 degrees over the entire load range (i.e., "no load" to "full load"). Over periods of minutes or even hours, this extra shift is rather constant and thus has little or no impact on observed system oscillation modes and damping rates.

An engineer must always determine how many net 30-degree phase shifts exist between locations. Fortunately, it is not difficult for an engineer familiar with the system to adjust the synchrophasor readings accordingly.

By the middle of April 2009, five PMUs were installed in ERCOT (plus a sixth in WECC). With more PMUs came better data to address the question of the quality of 120 V wall outlet data for synchrophasor applications. Phase angle differences between Austin, Houston, and Boerne are usually small. Therefore, we can assess the quality of 120 V data by comparing the angles of Austin, Boerne, and Houston to that of the McDonald Observatory.

Consider the 2-minute interval shown in Fig. 34, which occurred shortly before midnight on April 9. The three graphs are the relative angles of the McDonald Observatory with respect to Austin, Boerne, and Houston.

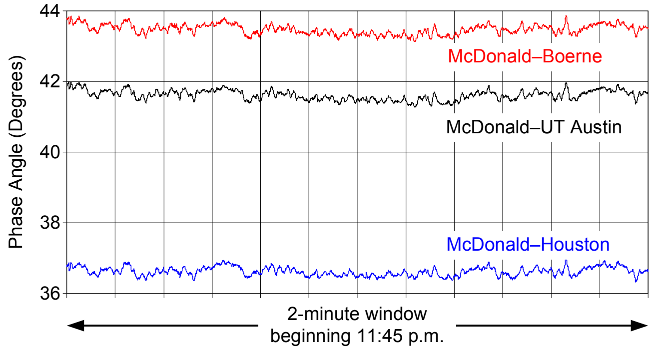

Fig. 34. McDonald Observatory phase angles with respect to UT Austin, Boerne, and Houston on April 9, 2009

Wind generation was about 17 percent of total generation at the time. The phase angles are relatively constant across the 2-minute interval. Data stream in at 30 points per second; thus, each graph contains 3,600 points. The horizontal axes span 2 degrees, and the vertical grid lines are spaced 10 seconds apart. It is clear that the three graphs are essentially the same except for their average values. Using the built-in Microsoft Excel correlation function shown in (2), the correlations between all three pairs of phase angle curves were computed and are given in Table I. The correlations are very strong, which means that from the vantage point of the McDonald Observatory, the waveshapes of the UT Austin, Boerne, and Houston angle variations are essentially identical except for their average values and possible scale factors.

$$\text{Correl}(X,Y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \quad (2)$$

TABLE I
CORRELATION OF PHASE ANGLE DATA MEASURED AT WALL OUTLETS

Vector X	Vector Y	Correlation
McDonald–UT Austin	McDonald–Boerne	0.98
McDonald–Boerne	McDonald–Houston	0.91
McDonald–Houston	McDonald–UT Austin	0.92

Now, examine the scatter plot (Fig. 35). The x- and y-axes span 1 degree. A diagonal line is drawn at 45 degrees to assist in interpreting the plot. The scatter plot appears to have a 45-degree slope. This indicates that from the McDonald PMU viewpoint, UT Austin and Boerne angles vary with almost exactly the same magnitude. This is logical because UT Austin and Boerne are only 80 physical miles apart, yet very far from the McDonald Observatory.

These observations and analyses do not prove that 120 V wall outlets are always suitable for synchrophasor applications. However, these data lead us to believe that 120 V wall outlets are suitable for many, and perhaps most, synchrophasor applications. Small errors, Internet dropouts, and noise in 120 V wall outlets seem to be completely compensated for by the large numbers of repetitive readings streaming in and being archived. The readings quickly form clusters of points that can be averaged and statistically processed to compute confidence intervals.

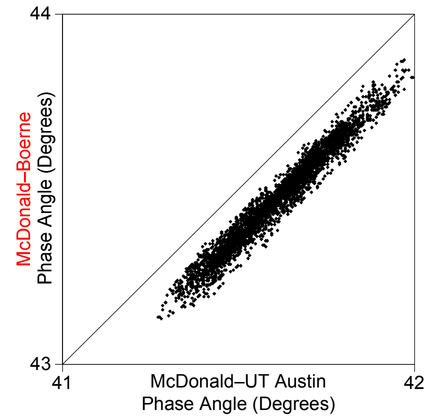

Fig. 35. Scatter plot of phase angle data correlation

K. The Matter of Dropouts on the Public Internet

Most of the PMU data stream to Austin through the public Internet. Naturally, some data are lost due to Internet dropouts and are recorded as zeros. Most hours have very few dropouts (i.e., less than 0.05 percent of total data). Some hours have many dropouts (i.e., a few percent of total). We consider dropout rates less than 1 percent to be "low."

Consider the 5-minute window shown in Fig. 36. The window begins at 4:33 p.m. on April 13, 2009. Frequency data streaming in from the McDonald Observatory and Houston are plotted. This graph shows one of the worst dropout periods, with 88 Houston dropouts in the 5-minute window. At 30 readings per second, there are normally 1,800 readings per minute, which corresponds to 9,000 readings in 5 minutes. Thus, the dropout rate for the Houston PMU in this window is 88/9,000 ≈ 1 percent. By comparison, McDonald Observatory in far West Texas had no dropouts during the 5-minute window and only 23 dropouts during the entire hour (i.e., a dropout rate of 0.02 percent).

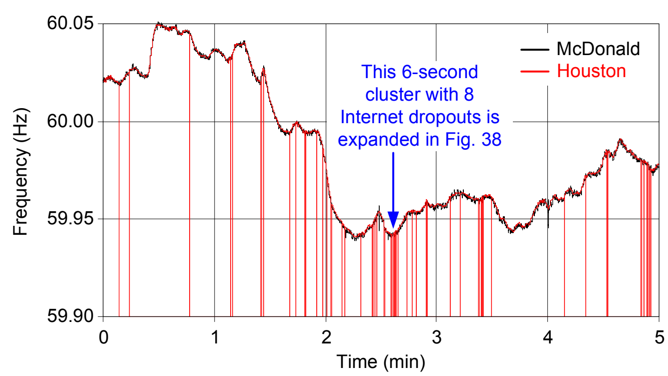

Fig. 36. Five-minute window with Houston dropouts

The Houston situation does not look so bad when the same data are plotted without dropouts (Fig. 37).

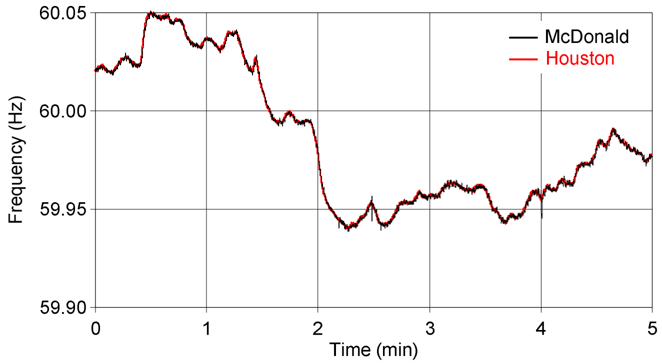

Fig. 37. Five-minute window without Houston dropouts

If we zoom in on the 6-second dropout cluster (Fig. 38) identified in Fig. 36, and again on a 1-second portion of that cluster (Fig. 39), we can see that dropouts are not the same as errors. Dropouts are recorded as zeros. We can skip over them and continue with the analysis. The sheer volume of data streaming in at a rapid rate appears to completely overshadow any practical difficulties created by dropout rates of a few percent or less. This is especially true if dropouts are randomly distributed. Even 15 valid data points per second (i.e., a dropout rate of 50 percent), uniformly spaced, will provide most of the information we need.

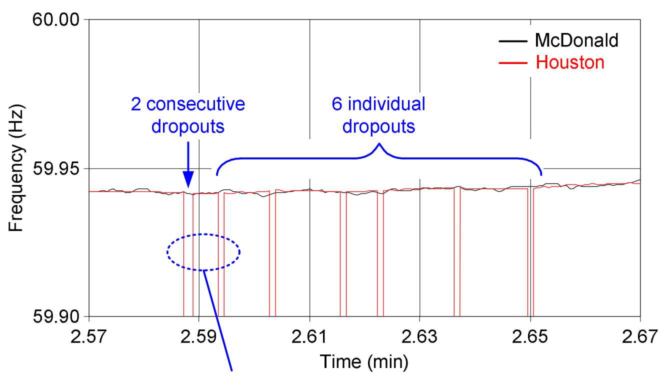

Fig. 38. Six-second zoom-in of the Houston dropout cluster

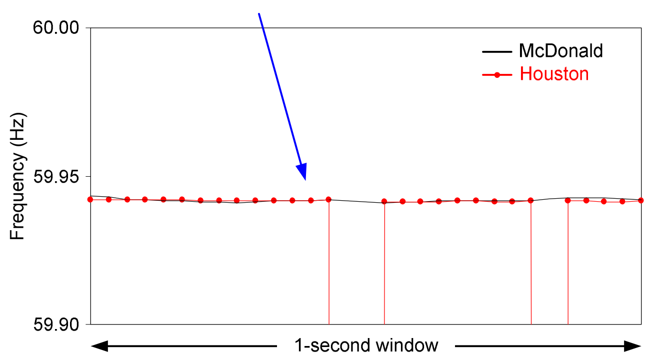

Fig. 39. One-second zoom-in shows 3 dropouts out of 30 points

L. *Deep Triple-Voltage Dip at McDonald Observatory*

The McDonald Observatory is at the end of a long 12.47 kV distribution feeder. The feeder winds from the historic town of Fort Davis through a mountainous area to the 6,500-foot elevation observatory. On April 12, 2009, the 120 V single-phase PMU reported a series of root-mean-square voltage sags, shown in Fig. 40. The total time span of the window is 40 seconds.

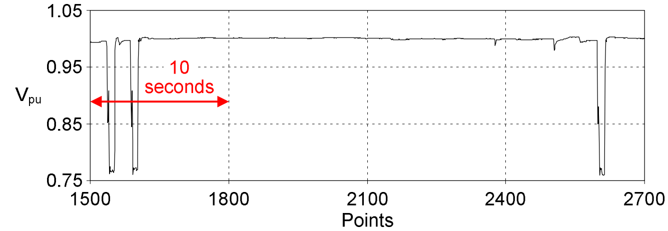

Fig. 40. McDonald Observatory voltage sags, April 12, 2009

Fig. 41 is a detail of the first two voltage sags. The sags are remarkably similar.

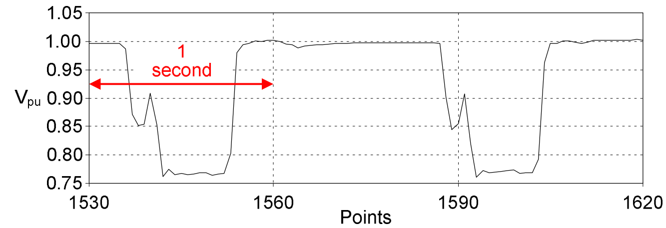

Fig. 41. Detail of first two McDonald Observatory voltage sags

After conferring with several utility engineers, we believe the event was a fault and recloser operation on an adjacent distribution feeder. The voltage phase angles during this sequence of events are shown in Fig. 42, where phase angle with respect to UT Austin is plotted for the 40-second period.

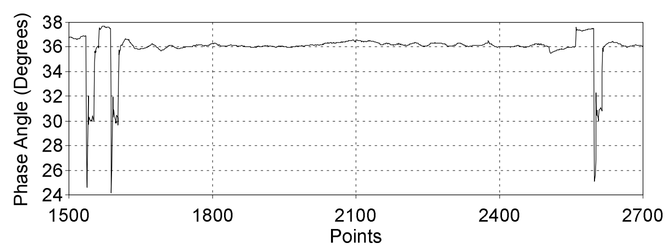

Fig. 42. Phase angle with respect to Austin during distribution fault

There is a 12-degree phase angle drop at the onset of each sag, followed by a quasi-steady state. Otherwise, the measured phase angle is hardly affected. We consider the impact of this distribution voltage sag event on synchrophasors to be minor. PMUs report phase angle and voltage. When there is a sudden change in phase angle, a simple check of voltage can determine if the points involved are valid or due to nearby faults.

M. *September 3, 2009—Major WECC Event Captured*

By the end of summer, the network was able to monitor disturbances in WECC from two monitoring points, Pullman and Cloudcroft. The frequency and voltage phase angle plots for an event on September 3 are shown in Fig. 43 and Fig. 44. The root cause is unknown at the time of publication.

Independent entities employing synchrophasor data can easily validate events. Engineers working with data from a separate network in WECC have quickly confirmed event data captured by the PMU in New Mexico. If a grid event is witnessed in one state, it is possible to find substantiating data without any significant effort.

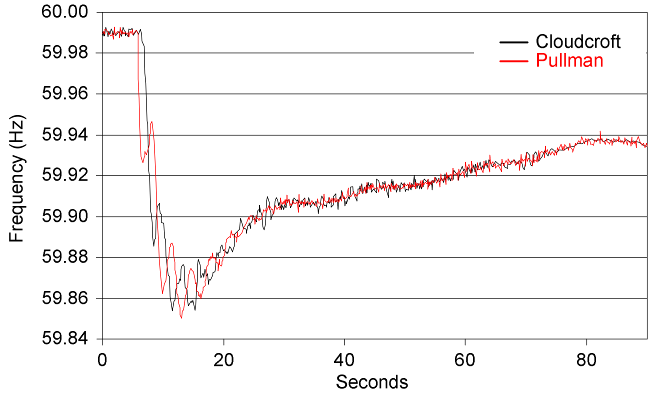

Fig. 43. Frequency at Cloudcroft and Pullman during WECC event

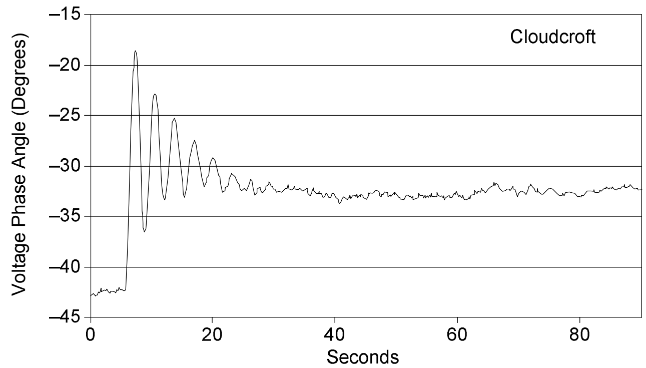

Fig. 44. Cloudcroft voltage angle with respect to Pullman during WECC event

V. Conclusions

Thus far, the project focus has been on large-scale wind integration and its impact on grid operations in ERCOT. The hope is that grid stability will be improved through new automated control systems. Research plans include implementing new algorithms for estimation of the damping coefficient and frequency of power system oscillations.

The project has proven that PMUs can be connected to wall outlets and that they provide extremely valuable data. Practical solutions validate the data and overcome data dropouts.

VI. Acknowledgements

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VIII. Biographies

W. Mack Grady, Ph.D., P.E., is a professor and the Associate Chairman of Electrical & Computer Engineering at the University of Texas at Austin. He is the Jack S. Josey Centennial Professor in Energy Resources at the Cockrell School of Engineering. Dr. Grady received his BSEE from the University of Texas at Arlington in 1971, and his MSEE (1973) and his Ph.D. (1983) from Purdue University. He is a registered professional engineer in Texas. In 2000, Dr. Grady was elected an IEEE Fellow. He holds a security clearance and works on power grid and power distribution issues for the Scientific Applications and Research Associates (SARA) team on Department of Defense (DOD) Defense Threat Reduction Agency projects.

David Costello graduated from Texas A&M University in 1991 with a BSEE. He worked as a system protection engineer at Central Power and Light and Central and Southwest Services in Texas and Oklahoma. He has served on the System Protection Task Force for ERCOT. In 1996, David joined Schweitzer Engineering Laboratories, Inc. He is a senior member of IEEE, a member of the planning committee for the conference for Protective Relay Engineers at Texas A&M University, and a recipient of the 2008 Walter A. Elmore Best Paper Award.

Previously presented at the 2010 Texas A&M
Conference for Protective Relay Engineers.

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