Overview. This report covers 17 days starting Thursday, Jan. 12, and ending Saturday, Jan. 28. By ERCOT standards, these 17 days were rather “tame.” There was only one serious unit trip, that being a drop to 59.81 Hz on Tuesday, Jan. 24. There were no new peaks in wind generation or load. Wind generation did rise above 45% of total generation for some hours on three days, and West Texas voltage phase angle reached 70 degrees (relative to Austin) three times. Angle spread between West Texas and the Rio Grande Valley reached 100 degrees. McDonald Observatory (West Texas) had two days with synchronization problems, which coincided with low voltages. We normally would not expect synchronization and low voltages to be related.

For the first time, we are able to present some phase angle observations for the Eastern grid. In addition to the DC area station we have had for some time, we are delighted to now have a PMU operated by Empire District Electric Company in Joplin, Missouri. Some Eastern results from the past week are shown, starting on page 25.
West Texas Phase Angle Variation with Wind Generation.

ERCOT Wind Generation
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

Average Voltage Phase Angle Relative to Austin
McDonald Observatory, Waco, UT Rio Grande
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

McDonald Observatory synchronism problems
Wind Generation, Net DC Tie Export, and Capacity-to-Load Ratio.

ERCOT Wind Generation
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

ERCOT DC Tie Export
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

ERCOT Capacity to Load Ratio
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC
Frequency and Voltage.

**Austin Average and Minimum Frequency**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

**McDonald Observatory Average and Minimum Frequency**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

**UT Rio Grande Valley Average and Minimum Frequency**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC
Frequency and Voltage, continued.

**Austin Average and Minimum Voltage**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

**McDonald Observatory Average and Minimum Voltage**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

**Waco Average and Minimum Voltage**
1-Minute Intervals, Thursday, Jan. 12, 2017, through Saturday, Jan. 28, 2017, 00:00 UTC

Are synchronization problems and low voltages related?
Event 01. January 13, 2016, 05:54 (UTC). Three Minute Window

A unit trip occurs, causing Waco angle to fall, and Rio Grande Valley angle to rise. Little change at McDonald. The tripped unit is north or northeast of Waco.

An onset of ringing at all stations relative to Austin coincides with a small unit trip. A larger unit trip follows 20 seconds later. Waco sees an unusually large ring in voltage magnitude.
Event 03. January 14, 2016, 15:51 (UTC). Twenty Second Window

Small unit trip occurs with fast recovery. There is no change in steady-state angle. This could be the opening and reclosing of a DC connection feeding ERCOT.
Event 04. January 15, 2016, 07:36 (UTC). One Minute Window

An unusually sharp drop, then rise, in frequency. Clearly an event has shaken the grid, as noted by erratic angle and frequency.

Onset of ringing at UT Rio Grande Valley, which is visible across ERCOT. McDonald phase angle falls in steps. As seen by the phasor diagram below, McDonald angle lags. Thus, there is little or no wind generation in West Texas.
Event 05, continued,

Oscillation resumes seven minutes later. This time, McDonald angle recovers.
Event 06. January 16, 2016, 00:32 (UTC). One Minute Window

Next day sees more ringing. The ring magnitude is exaggerated a bit by the y-axis scale, but is still about the same magnitude as Event 05.
Event 07. January 16, 2016, 03:54 (UTC). One Minute Window

Frequency jumps suddenly to nearly 60.06 Hz. Steady-state phase angles change. Waco sees a voltage swell. This could be a sudden loss of DC tie load.
Event 8. January 22, 2016, 16:14 (UTC). One Minute Window

Four large voltage dips at McDonald are followed by what appears to be a small unit trip. The event is encompassed by high-frequency voltage magnitude ringing at McDonald. Time of the event is shortly after midnight (local time), thus the ringing is not due to PV generation.

Rio Grande is exporting power. A unit trip, and Rio Grande angle falls. The tripped unit is in South Texas.

A simultaneous fault and unit trip near UT Rio Grande Valley. Rio Grande angle falls, indicating that the tripped unit is nearby.

A unit trip, with McDonald most affected. McDonald phase angle begins to fall slightly. The tripped unit is nearby.

This appears to be two consecutive faults near UT Rio Grande Valley.

A major unit trip, 813 MW. Frequency drops to 59.81. Angle drops at Waco, wind generation is up in West Texas. All PMU voltages experience a dip. The tripped unit is north of Waco, and probably near the NE edge of ERCOT where there is significant generation.

Similar to Event 04.

Two unit trips occur, but their locations are not obvious. McDonald ringing begins. Unrelated? The time is 11:32 am (local).

A unit trip and voltage drop in West Texas appears to stop the high-frequency ringing there. A coincidence? The time is shortly before noon (CST).
Event 17. January 28, 2017, 01:23 (UTC). One Minute Window

An abrupt rise in frequency coincides with a large voltage angle and magnitude increase at McDonald. The time is 7:23 pm local (dark). It appears that additional generation was suddenly turned on near McDonald, and then turned off about 20 seconds later.
Event 18. January 28, 2017, 01:50 (UTC). One Minute Window

A unit trip. Phase angles show almost no transfer of power over long distances. Austin and Waco see voltage dips. Waco see an angle dip. The tripped unit is likely near Austin.
Observations from the Eastern Grid

DC_AREA Phase Angle Relative to JOPLIN, Jan. 22-28, 2017, 00:00 UTC

DC_AREA Average and Minimum Frequency
1-Minute Intervals, Jan 22-28, 2017, 00:00 UTC

JOPLIN Average and Minimum Frequency
1-Minute Intervals, Jan. 22-28, 2017, 00:00 UTC
Observations from the Eastern Grid, continued

**JOPLIN Average and Minimum Voltage**
1-Minute Intervals, Jan. 22-28, 2017, 00:00 UTC

**DC_AREA Average and Minimum Voltage**
1-Minute Intervals, Jan. 22-28, 2017, 00:00 UTC
Observations from the Eastern Grid, continued
Sustained Ringing Frequencies Observed at McDonald Observatory Relative to Austin
Texas Synchrophasor Network, Prof. Mack Grady and Mr. David Jonsson, Baylor University

Magnitudes of the Ringing Frequencies
Texas Synchrophasor Network, Prof. Mack Grady and Mr. David Jonsson, Baylor University
Hourly Distribution of Minutes with Ringing Frequencies
Sept. 1, 2016, through Jan. 25, 2017 (Central Standard Time)
Texas Synchrophasor Network, Prof. Mack Grady and Mr. David Jonsson,
Baylor University
Overview. ERCOT had three strong wind days, and wind generation was almost perfectly out-of-phase with load. It is clear from the middle graph on page 3 that some excess wind energy was sold through HVDC ties.

Six events are presented for ERCOT, and four events are presented for the Eastern Grid. Two of the Eastern events are from January 27, which were not included in the last report.

Our new Eastern grid unit at Conroe, TX, (near Houston) came on-line January 30.
West Texas Phase Angle Variation with Wind Generation.

ERCOT Wind Generation, Percent of Load
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

Average Voltage Phase Angle Relative to Austin
McDonald Observatory, Waco, UT Rio Grande
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC
Wind Generation, Net DC Tie Export, and Capacity-to-Load Ratio.

ERCOT Wind Generation
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

ERCOT DC Tie Export
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

ERCOT Capacity to Load Ratio
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC
Frequency and Voltage.

Austin Average and Minimum Frequency
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

McDonald Observatory Average and Minimum Frequency
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

UT Rio Grande Valley Average and Minimum Frequency
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

Event 01
Frequency and Voltage, continued.

**Austin Average and Minimum Voltage**
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

**McDonald Observatory Average and Minimum Voltage**
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

**Waco Average and Minimum Voltage**
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC
Event 01. February 01, 2017, 10:03 (UTC). One Minute Window.

A unit trip. Voltage angle falls for 15 seconds in West Texas. Waco angle falls, indicating that net power flow from north-to-south ERCOT drops. Rio Grande Valley angle rises to support the loss of generation. The tripped unit is north or northeast of Waco.
Event 02. February 02, 2017, 00:41 (UTC). Two Minute Window.

A sudden onset of ringing across ERCOT lasts for 1.5 minutes. There appear to be slight voltage sags at Austin, Waco, and McDonald when the ringing starts. There is no obvious change in steady-state voltage angles. Any suggestions?
Event 03. February 02, 2017, 08:00 (UTC). One Minute Window.

A unit trip appears to trigger ringing across ERCOT. Then a second, smaller unit trip occurs. Ringing soon stops. There is no significant change in steady-state voltage angles.
Event 04. February 02, 2017, 17:01 (UTC). Two Minute Window.

Frequency and Rio Grande Valley voltage phase angle rise simultaneously. Prior to this, we see from the phasor diagram that Rio Grande Valley is importing. Afterward, Rio Grande Valley imports less. This appears to be a sudden loss of load in the Rio Grande Valley.

A classic unit trip, with a strong ringdown in Rio Grande Valley phase angle. Export from Rio Grande Valley northward drops. The tripped unit is very near UT Rio Grande Valley.
Event 06. February 03, 2017, 22:05 (UTC). One-Minute Window.

A unit trip, with voltage dips visible across ERCOT. Angles fall at McDonald and Waco. Angle rises at Rio Grande Valley. The tripped unit is north and probably west of Waco.
Observations for the Eastern Grid. Frequency.

**JOPLIN Average and Minimum Frequency**
1-Minute Intervals, Jan. 29 - Feb. 04, 2017, 00:00 UTC

**DC_AREA Average and Minimum Frequency**
1-Minute Intervals, Jan. 29 - Feb. 04, 2017, 00:00 UTC

**CONROE Average and Minimum Frequency**
1-Minute Intervals, Jan. 29 - Feb. 04, 2017, 00:00 UTC

Eastern Event 04
Observations for the Eastern Grid. Across-Grid Phase Angle, and Voltage for One Station.

DC_AREA Phase Angle Relative to JOPLIN, Jan. 29 - Feb. 04, 2017, 00:00 UTC

DC_AREA Average and Minimum Voltage
1-Minute Intervals, Jan. 29 - Feb. 04, 2017, 00:00 UTC

Strong ringing at ALEXLA (Alexandria, Louisiana) and DC_AREA, relative to JOPLIN, precedes a unit trip. If the reference (JOPLIN) had a large ringing in voltage, it would cause artificial ringing to appear at all other stations. However, you can see in the lower dashed-red box that JOPLIN voltage starts with little ringing, then displays a stronger ringing later. Thus, this is a true ringing event at ALEXLA that eventually reaches JOPLIN. As JOPLIN voltage begins to ring in the lower red box, it creates artificial ringing at DC_AREA in the top red box. The changes in steady-state angles at ALEXLA and DC_AREA in the black box are real and correspond to the unit trip seen in the frequency plot. ALEXLA has the earliest frequency drop, and its angle falls, so the tripped unit is likely near ALEXLA.

A fault on the transmission system occurs, with visible voltage sags at ALEXLA and, to a lesser extent at JOPLIN. DC_AREA steady-state angle is unchanged. From the phasor diagram, ALEXLA angle lags JOPLIN, thus power is moving from north to south. ALEXLA angle then drops more. This event is a fault clearing on a transmission line somewhere between JOPLIN and ALEXLA, with no reclosure.
EASTERN Event 03. February 02, 2017, 23:23 (UTC). Two Minute Window

A unit trip occurs, and DC_AREA steady-state angle falls to maintain DC_AREA power import from the west. The tripped unit is near DC_AREA.
EASTERN Event 04. February 03, 2017, 20:45 (UTC). One-Minute Window

A unit trip occurs, followed by angle drops at ALEXLA and CONROE (near Houston). DC_AREA is unaffected. CONROE and ALEXLA are sending power north. After the trip, less power is sent north. Thus the tripped unit is most likely in southern Louisiana or southeast Texas.
Frequency on the Three U.S. Power Grids on Super Bowl Sunday, 5pm – 10pm, CST

Austin Frequency, One-Minute Averages

Washington D.C. Area Frequency, One-Minute Averages

Oregon State University Frequency, One-Minute Averages

Texas Synchrophasor Network
Baylor University, Waco, TX
Sponsored by Schweitzer Engineering Labs
Overview. The most interesting occurrences in ERCOT this week were

1. A 135 degree peak-to-peak change in phase angle between McDonald Observatory in West Texas and UT Rio Grande Valley, and
2. A large regional price swing that preceded a large reversal of phase angle between West Texas and UT Rio Grande Valley.
Wind Generation and Voltage Phase Angle Variations.

**ERCOT Wind Generation**
1-Minute Intervals, Sunday, Jan. 29, 2017, through Saturday, Feb. 04, 2017, 00:00 UTC

**Average Voltage Phase Angle Relative to Austin**
McDonald Observatory, Waco, UT Rio Grande
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC

**ERCOT 15-Minute Load Zones**
Houston, North TX, and West TX
Real-Time Settlement Point Prices
Frequency and Voltage.

**Austin Average and Minimum Frequency**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC

**McDonald Observatory Average and Minimum Frequency**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC

**UT Rio Grande Valley Average and Minimum Frequency**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC
Frequency and Voltage, continued.

**Austin Average and Minimum Voltage**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC

**McDonald Observatory Average and Minimum Voltage**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC

**Waco Average and Minimum Voltage**
1-Minute Intervals, Sunday, Feb. 05, 2017, through Saturday, Feb. 11, 2017, 00:00 UTC
Event 01. February 09, 2017, 04:22 (UTC). One Minute Window.

![Image of PMU Waveform Analyzer](image_url)
Event 02. February 09, 2017, 13:23 (UTC). One Minute Window

[Image: PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, V170205]

- PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, V170205
- Event_C_ERCOT_170209_1300000000_Min_23_AUSTIN_CAT1_01_MCDONALD.c
- Selected Minute = 2017/02/09 13:23:00.000
- 1 Minute Window

- Voltage Phase Angle, Reference PMU = AUSTIN
- Vangle
  - Max: 0.034
  - Min: 0.000
- Frequency
  - Max: 60.04
  - Min: 60.01
- Voltage Magnitude
  - Max: 0.013
  - Min: 0.98
- FFT Hz
  - FFT Mag of Voltage Phase Angle, PMU = MCDONALD
  - FFT Min = 0.0000
  - FFT Max = 0.642
  - Freq of FFT Max = 0.4
Event 03. February 10, 2017, 17:00 (UTC). Twenty-Second Window
Overview. The Eastern Grid had three periods of frequency at or below 59.95 Hz. Six interesting grid events are presented.
EASTERN Event 01. February 05, 2017, 15:55 (UTC). One Minute Window
A transmission line fault occurs near CONROE. Breakers open. No reclose shown. Angles fall at CONROE and ALEXLA. The fault is nearest CONROE.
EASTERN Event 02. February 06, 2017, 09:49 (UTC). One Minute Window
A transmission fault occurs near DC_AREA. The slight downslope in frequency that started before the angle swing suggests a unit trip. DC_AREA steady-state angle falls slightly as a result of the line trip and the unit trip (if there was a unit trip).
EASTERN Event 03. February 08, 2017, 09:31 (UTC). One Minute Window
An unusual “rainbow” frequency curve. The abrupt change in frequency slope, and angle rise at DC_AREA suggest load shedding (or HVDC drop in export) closest to DC_AREA.
EASTERN Event 04. February 08, 2017, 16:39 (UTC). One Minute Window
A unit trip, with CONROE angle most affected. ALEXLA angle drops along with CONROE. DC_AREA angle rises. The tripped unit is nearest CONROE.
EASTERN Event 05. February 09, 2017, 09:07 (UTC). Two Minute Window
A unit trip, with all angles rising relative to JOPLIN. The tripped unit is nearest JOPLIN.
EASTERN Event 06. February 11, 2017, 10:57 (UTC). Five Minute Window
Frequency rise corresponds to angle rise at DC_AREA. Apparently the added generation is nearest DC_AREA.
Overview. The Eastern Grid had a number of unit trips and frequency dips below 59.95 Hz. Fourteen events are presented.
EASTERN Event 01. February 13, 2017, 05:35 (UTC). One Minute Window
EASTERN Event 02. February 14, 2017, 05:09 (UTC). Fifty-Second Window
EASTERN Event 03. February 15, 2017, 04:17 (UTC). One Minute Window
EASTERN Event 04. February 15, 2017, 11:36 (UTC). One Minute Window
EASTERN Event 05. February 20, 2017, 07:56 (UTC). One Minute Window
EASTERN Event 06. February 21, 2017, 17:31 (UTC). One Minute Window
EASTERN Event 07. February 22, 2017, 03:30 (UTC). One Minute Window
EASTERN Event 08. February 22, 2017, 12:19 (UTC). One Minute Window
EASTERN Event 11. February 23, 2017, 11:59 (UTC). One Minute Window
EASTERN Event 13. February 24, 2017, 17:13 (UTC). One Minute Window
M. Grady (Baylor), A. Mattei (BEPC), D. Jonsson (Baylor), Jaime Ramos (U.T. Rio Grande Valley)
Equipment Provided by Schweitzer Engineering Laboratory
McDonald Observatory experienced repeated bursts of sustained oscillation in the 3.4 Hz range for four minutes. The peak-to-peak voltage swings were approximately 6%. A one-minute zoom-in for minute 16:38 is shown on the following page.
Event 1, cont. One-Minute Zoom-In.
Each of the repeating bursts starts with a growing 3.4 Hz oscillation, which suddenly stops. The width of the repeating burst cycle becomes smaller toward the end of the event.
Here is an example of a lone 3.4 Hz burst, approximately three-seconds wide.
Here is a single 3.4 Hz burst, with the same shape as those in Figure 1. It appears to be related to a unit trip. However, the unit trip is far away in South Texas!
A single burst of 2.8 Hz oscillation occurs shortly after a two-unit trip event. The two-unit trip is not in West Texas.
The interesting feature of this event is the odd stair-step increase in voltage from 1.0 pu to 1.07 pu over a twenty second period.
The frequency drop caused by a unit trip is first and most severely seen in Kansas City. Note – there are two units at different locations in KC.

The frequency drop curve is delayed about 0.5 seconds at Garden City, and about 1.5 seconds at DC Area.
The unit trip is seen first at Joplin. Frequency drop curves at Garden City and DC Area are delayed by approx. 0.5 sec. and 2.0 sec, respectively.
DC Area sees the unit trip first. All others lag by about 2 seconds.

Zoom Secs 20 to 35
Garden City and Kansas City see the unit trip first. The time shift at Joplin and OKC is about 0.5 sec. The time shift in Eastern OK is about 0.75 sec. The time shift at DC Area is about 1.5 sec.
Supply Meets Demand – Lessons from Millisecond Measurements

Mack Grady
Prof. of Electrical & Computer Engineering, Baylor University, Waco, TX
There is No Substitute for Real Data

You see many surprising events, and after careful investigation, they usually make sense.

30 (or 60) time-synchronized measurements per second of:
- frequency
- voltage magnitude
- voltage phase angle

Synchrophasor data fill in the gap between state estimator steady-state data and high-speed event recorder data.

Current magnitude and angle, and thus P and Q, flowing through transmission lines and transformers can also be added.

The focus for today is Pecos County and far West Texas (recall the movies “No Country for Old Men” and “Lonesome Dove”?)
Event Identification Process Illustrated Using Two Common Types

For the first unit trip, angles fall at McD and Waco, but Rio Grande Valley angle quickly resumes its pre-trip value.

For the second unit trip, all three angles rise relative to Austin.

All stations have essentially the same frequency response.

Typically there are only one or two events per year with frequency this low.

Voltage sags are seen everywhere, but is most significant at Austin.

The above observations suggest that first trip is north and west of Waco, and the second trip is likely in the Austin to Houston regions.

Angles drop at McD and Waco, but rise at Rio Grande Valley. This suggests that less wind power is being sent from West Texas to Central ERCOT.

This is not a unit trip because frequency has no inertial drop.

Voltage ringing is seen at all stations. McD appears to see a voltage fault.

The above observations suggest this was a transmission fault in West Texas, with no reclose within the window shown.
Not many years ago, 20% was considered the allowable ceiling for wind generation in a grid. As you see in this wind % graph for March, remarkably, ERCOT is able to handle wind levels up to 50%.

The blue curve is ERCOT total generation for March.
The red curve is conventional generation (i.e., ERCOT total generation minus wind generation).

Compare the peak-to-peak variations in the red curve to those of the blue curve.

For March, conventional generation is experiencing roughly twice the daily MW swing it would have without wind.

Not many years ago, 20% was considered the allowable ceiling for wind generation in a grid.

As you see in this wind % graph for March, remarkably, ERCOT is able to handle wind levels up to 50%.
Not All Events are Caused by Nature, Accidents, or Equipment Failures

With the start of the new power market in ERCOT in 2011, market-induced oscillations like this one were common for a few months.

The top graph is West-to-North power flow rising and falling due to wind generation.

The bottom graph is voltage angle difference between McDonald Observatory (West Texas) relative to Austin.

Power flow is proportional to the sine of voltage angle difference.

The period of oscillation is 30 mins, corresponding to $1/30/60 = 0.000556$ Hz!

How did it happen? Price signals were sent to raise (or lower) wind generation. By the time wind farms could adjust their output, they were sent the opposite price to lower (or raise) wind generation. Continue, continue, continue.
A reduced wind forecast for West Texas most likely led to a red-spike price “call for help.” Indeed, wind generation dropped to almost zero.

The “word” is that Houston was had serious congestion constraints.

The question is “Why did the West and North zone prices simultaneously go negative?”

The price movements were over about the time any phase angle movement was noted.

During the next two days, West Texas to Rio Grande Valley phase angle cycled through a dramatic 135 degree swing. See next slide.
Continued from previous slide:

Dramatic changes in wind generation and voltage phase angles across ERCOT are becoming more common.

The voltage angle shown is West Texas relative to Rio Grande Valley.
ERCOT Has No Monopoly on Grid Events!
Consider the Eastern Grid. June 17, 2016, 07:12 UTC. Reference Angle is OKC.
Large 0.4 Hz. Oscillation, Ending 45 Minutes Later with a Unit Trip

The entire Eastern Grid oscillated at 0.4 Hz. for 45 minutes.
The “word” is that the cause was governor control failure at a large generator in Southwest Louisiana.
OG&E sends us three transmission PMU feeds, and we use the one near OKC as our Eastern reference.
One Event, Two Grids, June 02, 2017, 15:03 UTC
DC-Tie Trip, 580 MW. Appears as Unit Trip in ERCOT, and Load Shedding in EASTERN
Oct. 14, 2016, 17:50 UTC.
20-Seconds of 0.6 Hz Ringing Across ERCOT

Bursts of 0.6 Hz oscillation like this were very common in the last three months of 2016 while many wind farms were going through commissioning tests to tune their control systems. Sometimes the ringing lasted 10 minutes.

Considering the fact that Rio Grande Valley is most affected in the frequency graph, this appears to be a wind farm commissioning in South Texas near the Gulf of Mexico where wind is good most of the year.
Sept. 11, 2016, 18:05 UTC. Reference Angle is OKC. Sustained 1.2 Hz Oscillation at Joplin, MO

Our station at Union Electric Company occasionally experiences localized high-frequency sustained oscillations that are believed to be due to hydro generation controllers 100 miles distant.

Ringing in the 1 to 3 Hz range is not grid-wide, but typically between two points separated by 20 - 100 (or so) miles, rather than 1000 miles. This sometimes happens between wind farms, and their controllers can be tuned to minimize the problem.

This example points out the power of synchrophasor data to find abnormalities that usually go unnoticed in day-to-day operation. It may or may not be a problem, but it is best to know about it.

Sustained ringing like this is never welcome!
Southeast NM

Pecos County – Perfect for Wind Farms and Solar Farms

Our McDonald Observatory PMU is 106 miles west of the new solar farm that is discussed in following slides.
Close-Up of Installation Shows Two-Axis Trackers

Shadows of transmission towers show the sun azimuth angle to be 190° degrees (10° west of south)

For this day of year (53) and location (31° N, 102.2° W), 190° azimuth angle corresponds to 42.4° zenith angle. The time is 13:30 CST.
A line from array corner to corresponding shadow corner shows zenith angle = 193°, which agrees reasonably well with the 190° measurement at the substation transmission tower.

The shadow dimensions are 7 meters by 12 meters = 84 square meters. If the sun is directly overhead and the array is horizontal, then the array shadow area equals the array area. Any time the array is perpendicular to the sun, then the surface area of the shadow is larger than the array by a factor of 1 / (cosine of the zenith angle). For zenith angle = 42.4°, the result is 114 square meters for the perpendicular case (i.e., perfect tracking). If not perpendicular, then the array must be larger than 114 square meters.
Let’s Estimate the Power Rating of the Two-Axis Plant on the Right-Hand Side of the Photo

- From the yellow line, 4.0 inches corresponds to 3728 meters.
- The combined area of the green boxes is 4.32 square inches, which corresponds to 3.75 square km.
- By zooming-in to a rectangle (not shown here) that encompasses 196 arrays, it appears that each array occupies 330 square meters.
- On the previous slide, each array is estimated to have a surface area of 114 square meters.
- Thus, the fraction of area covered by arrays is 114 / 330 = 0.35.
- Then, the total surface area of panels is 3.75 * 0.35 = 1.31 square km.
- Assuming approx. 150 W per square meter times 0.80 DC-AC operational conversion factor, the plant rating would be 157 MW.
## ERCOT Solar Update

### Solar Operational Resources

<table>
<thead>
<tr>
<th>Solar Operational Resources</th>
<th>County</th>
<th>Zone</th>
<th>Start Year</th>
<th>Capacity (MW)</th>
</tr>
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<tbody>
<tr>
<td>ACACIA SOLAR</td>
<td>ACACIA_UNIT_1</td>
<td>SOLAR</td>
<td>WEST</td>
<td>2012</td>
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<td>HOVEY_UNIT1</td>
<td>PECOS</td>
<td>SOLAR</td>
<td>WEST</td>
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<td>PECOS</td>
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<td>SIRIUS_UNIT1</td>
<td>PECOS</td>
<td>SOLAR</td>
<td>WEST</td>
</tr>
</tbody>
</table>

**Operational Capacity Total (Solar) - Zone West**: 419

### Planned Solar Resources with Executed SGIA

<table>
<thead>
<tr>
<th>Planned Solar Resources with Executed SGIA</th>
<th>County</th>
<th>Zone</th>
<th>Start Year</th>
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<td>SOLAR</td>
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<td>DAWSON</td>
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<td>WEST</td>
<td>2017</td>
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<tr>
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<td>SOLAR</td>
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<td>OCI ALAMO 6</td>
<td>PECOS</td>
<td>SOLAR</td>
<td>WEST</td>
<td>2017</td>
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</tbody>
</table>

**First noticed the oscillations at McDonald Observatory in Fall 2016**

**Same general area as Pecos**

**Same general area**

**More coming**
We First Noticed Oscillations Like This at McDonald Observatory in Fall 2016 (100+ miles away)

10 second zoom-in

5.8 Hz
Sunrise is sooner, sunset is later. Intense sunsets in combination with two-axis tracking panels, enhanced by decreasing load levels. Intense sunrises in combination with two-axis tracking panels, damped somewhat by increasing daily load levels.

Increasing system load level as we move toward summer damps the ringing.

All Information Shown Here Comes From Two Synchrophasor PMUs – The Remote PMU is at McDonald Observatory, and the Reference PMU is at Austin.

- The scanning frequency range was 2.0 – 8.0 Hz.
- The average and median trigger frequencies were both 6.0 Hz. The maximum frequency was 7.8 Hz.
- Only 34 of the 10,000+ triggers were below 5.0 Hz.
- While the ringing is clearly due to PV installations, the role that nearby wind generation plays is not yet known.
Solar Can Help!

ERCOT Total Generation for March 2017

Wind Generation for March 2017

Conventional Generation (Total Minus Wind) for March 2017

Solar Generation at Fort Davis State Park for March 2017

Load-Friendly Shape
With 10 GW Peak Solar, blue load shape becomes red load shape.

With 15 GW Peak Solar ...

With 20 GW Peak Solar ...

Solar Can Help!
Acknowledgements

- SEL for donating the equipment.
- EPRI/SPP for a three-year project to help integrate synchrophasor data analysis techniques into their control center. Ended in May.
- Austin Energy, U.T. Rio Grande Valley, Mike Bollen (DoD-DTRA consultant) for hosting PMUs.
- KCP&L, Union Electric, Sunflower Electric, Oregon State University, Sandia National Lab, and soon Los Alamos National Lab for hosting PMUs.
- Austin White, OG&E, for feeding us data from three of their transmission system PMUs.
- Baylor PhD student David Jonsson.
- Andrew Mattei, System Protection Engineer for Brazos Electric and Baylor PhD student.
- Mike Rooney, DoD-DTRA, for support and enhancement of our equipment security.
- Bill Blevins, ERCOT, for an upcoming project to develop a “Grid Strength Index” using real-time synchrophasor data.