While there were no significant grid events during the past week, you can see that ERCOT wind generation continues to rise. During this same time period in 2012, % wind generation *sometimes* hit 25%. Now, it often hits 30%. And, some days wind is peaking over 9000 MW.
The relative voltage phase angle of McDonald Observatory (in far West Texas) with respect to Baylor University in Waco continues to track overall ERCOT wind MW.
There was only one ringdown of significance. The graph shown below is the voltage phase angle of UT Pan American in far South Texas with respect to Baylor in Waco. The cause is unknown, except there was little change in frequency which indicates it was not caused by a unit trip.

Excel Solver makes the job of curve fitting the ringdown relatively easy, although a good starting guess for the equation coefficients is required. The objective of curve fitting is to determine the damped resonant frequency and the normalized damping ratio. The graph on the next page shows the actual ringdown in blue, and the curve-fitted ringdown in red.

The form of the second-order damped response used is

\[
\theta(t_{\text{start}} \leq t \leq t_{\text{stop}}) = A + (B - A) \left[ 1 - e^{-(t - T_1)/\tau_1} \right] u(t - T_1) +
\]

\[
+ C \cdot e^{-(t - T_2)/\tau_2} \sin(\omega_d (t - T_2)) \cdot u(t - T_2)
\]

where
Texas Synchrophasor Network, Summary of the Week Beginning Sunday, April 14, 2013
Prof. Mack Grady, Baylor University, and Prof. Jaime Ramos, U.T. Pan Am
April 22, 2013

- \( A + (B - A) \left(1 - e^{-\left(t-T_1\right)/\tau_1}\right) \cdot u(t - T_1) \) is the exponential term that transitions the steady-state angle from initial value \( A \) degrees to final asymptote value \( B \) degrees with time constant \( \tau_1 \).
- \( C \cdot e^{-\left(t-T_2\right)/\tau_2} \cdot \sin(\omega_d(t-T_2)) \cdot u(t - T_2) \) is the classic damped sinusoid.

<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
<th>A</th>
<th>B</th>
<th>T1</th>
<th>Tau1</th>
<th>C</th>
<th>T2</th>
<th>Tau2</th>
<th>Tdamp</th>
<th>Fdamp</th>
<th>Zeta</th>
<th>Avg. Sum Squared Error</th>
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<tbody>
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<td>27</td>
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<td>-7.05</td>
<td>1.22</td>
<td>29.73</td>
<td>25.76</td>
<td>-10.31</td>
<td>28.29</td>
<td>1.23</td>
<td>1.54</td>
<td>0.651</td>
<td>0.195</td>
<td>0.1682</td>
</tr>
</tbody>
</table>

Bottom Line? The damped resonant frequency \( F_{damp} \) is 0.651 Hz, and the normalized damping ratio \( Zeta \) is 0.195.
60 Seconds of RMS Voltage Measured by the Texas Synchrophasor Network at Baylor University during the West, Texas, Disaster, April 17, 2013
Prof. Mack Grady, Dept. of ECE, Baylor
(about 20 miles south of West)

USGS says the explosion occurred here (7:50:38 pm CDT)
As shown below, for the first time, percent wind generation exceeded 35%. That occurred for a 15 minute interval on Sunday, April 21.

![ERCOT Load and Wind MW](image)

![ERCOT Wind Gen (Percent of Load)](image)

On the next page, you can see the strong correlation between voltage phase angle in West Texas and wind generation. Most of ERCOT’s wind generation is in West Texas, although coastal wind in South Texas is growing and has favorable seasonal and daily profiles.
There were no dramatic events during the week. Even so, this is a good opportunity to demonstrate how the characteristics of a voltage angle ringdown due to a unit trip are computed.

Example of Damped Resonant Frequency and Normalized Damping Coefficient Calculations.
600 MW Generator Trip, April 23, 2013, 16:19 GMT (see www.ercot.com, then “Grid Information,” then “Operations Messages”)

The voltage phase angle ringdown graph data are saved as text file 2013_0423_1619_wave14.txt. In that way, the file name is tagged with day and time. File type”txt” is replaced by “csv”, then read into Excel, and then copied into the Second-Order Analyzer spreadsheet. Steps 1,2,3 on the following pages illustrate the process. The curve-fitting equation is shown in the Appendix.

1-Minute Frequency Window Showing Superimposed Frequencies for Baylor (Waco), McDonald Observatory (far West Texas), UT Pan Am (Rio Grande Valley)

Corresponding Voltage Phase Angle Ringdown of UT Pan Am with respect to Baylor. The rise in phase angle indicates that the tripped generating unit is not in the Rio Grande Valley. The red box indicates FFT activity in the 0.5 Hz range.
Step 1 (above). With the oscillation off (i.e., variable C = 0), enter values for the first six
coefficients (yellow cells) to get an approximate visual match between the actual curve (blue)
and the curve fit (red).

Step 2 (above). Let the Excel Solver adjust coefficients A, B, T1, Tau1 to minimize the sum of
squared error between the actual curve (blue) and the curve fit (red). Oscillation remains off
(i.e., variable C = 0).
Step 3 (above). Add starting values for variables C, T2, Tau2, and Tdamp to obtain a rough visual starting point. Then let Excel Solver adjust A, B, T1, Tau1, C, T2, Tau2, and Tdamp to obtain a good curve fit of the ringdown portion as shown above.

The key results are

Damped Resonant Frequency $F_{damp} = 0.657$ Hz, and Normalize Damping Coefficient $Zeta = 0.151$.

Appendix

The problem is to curve fit the ringdown with

$$\theta(t_{start} \leq t \leq t_{stop}) = A + (B - A) \left(1 - e^{-(t-T_1)/\tau_1}\right) u(t-T_1) +$$

$$+ C \cdot e^{-(t-T_2)/\tau_2} \cdot \sin(\omega_d(t-T_2)) \cdot u(t-T_2).$$

where

- $A + (B - A) \left(1 - e^{-(t-T_1)/\tau_1}\right) u(t-T_1)$ is the exponential term that transitions the steady-state angle from initial value $A$ degrees to final asymptote value $B$ degrees with time constant $\tau_1$.

- $C \cdot e^{-(t-T_2)/\tau_2} \cdot \sin(\omega_d(t-T_2)) \cdot u(t-T_2)$ is the classic damped sinusoid.
A Rough 10-Minute Ride This Morning. Frequency at Baylor, McDonald Observatory, and UT Pan Am (all superimposed), April 25, 2013, 11:35-11:45am
Mid-week was like summer, but winter returned at the end of week. Thursday was the biggest MWh wind day observed thus far, and also reached a new peak of 9686 MW. There was only one unit trip of interest, circled in red below. Analysis of the unit trip is shown on following pages.
The new wind peak of 9686 MW is circled below.

---

**ERCOT Load and Wind MW**  
**Week Starting 00.00 GMT, Sunday, April 28, 2013**

- **Load**
- **Wind**

**ERCOT Wind Gen (Percent of Load)**  
**Week Starting 00.00 GMT, Sunday, April 28, 2013**
As always, West Texas voltage phase angle with respect to central ERCOT continues to be highly correlated with wind generation.
The week’s significant frequency drop was due to the sudden loss of 520 MW of generation. Load at the time was 41,384 MW. A zoom-in of the moderate voltage phase angle ringdowns at McDonald Observatory and U.T. Pan Am are shown for a seven-second window.

ERCOT Unit Trip, April 29, 2013, 18:59 GMT. Freq. at Three PMUs

ERCOT Unit Trip, April 29, 2013, 18:59 GMT. McD Voltage Angle Ringdown wrt Baylor.

ERCOT Unit Trip, April 29, 2013, 18:59 GMT. UT Pan Am Voltage Angle Ringdown wrt Baylor.
A precursor to the unit trip is indicated below by the heavy red arrow.

Continuing at the top of the following page, a 5-second zoom-in of the precursor is shown, where you can see that the precursor is first noticed in the frequency at Baylor, then U.T. Pan Am, but is hardly noticeable at McDonald.

From the perspective of rms voltage, the bottom graph on the following page shows a 1% voltage drop at Baylor, followed 0.4 seconds later by a 0.5% voltage drop at U.T. Pan Am. A second dip at Pan Am occurs about 1.8 seconds after the first.

We have no information concerning the precursor.
ERCOT Unit Trip, April 29, 2013, 18:59 GMT. Precursor Freq. at Three PMUs.

ERCOT Unit Trip, April 29, 2013, 18:59 GMT. Precursor Vrms at Three PMUs.
Texas Synchrophasor Network. ERCOT Hits New Wind Peak of 9686 MW on May 2, 2013
Events for the week were already discussed in the “Fun Final Exam.” Here are the frequency, generation, and West Texas phase angle plots for the week.

Plots of Min and Max Frequencies for Each Minute of the Week

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, May 05, 2013

Baylor Maximum Frequency
1-Minute Intervals, Beginning Sunday, May 05, 2013
Plots of Load MW, Wind MW, and Wind MW as % of Load

ERCOT Load and Wind MW
Week Starting 00.00 GMT, Sunday, May 05, 2013

ERCOT Wind Gen (Percent of Load)
Week Starting 00.00 GMT, Sunday, May 05, 2013
Relationship Between Wind MW and West Texas Voltage Phase Angle w.r.t. Baylor

ERCOT Wind MW
Week Starting 00.00 GMT, Sunday, May 05, 2013

McDonald Observatory Average Voltage Phase Angle
1-Minute Intervals, Beginning Sunday, May 05, 2013
1. Plots of Load MW, Wind MW, and Wind MW as % of Load

Summer is fast approaching as ERCOT daily peaks exceed 50 GW, headed toward an expected summer peak over 70 GW. Wind generation exceeded 8 GW briefly. Wednesday night the terrible tornado hit Granbury. Wednesday was a also rough day for wind turbines, as noted on page 2 where very erratic total wind generation is believed to be due to winds gusting 50 miles per hour (higher at hub height) in West Texas, thus causing turbines to trip and reset repetitively.

There were two significant generating unit trips that caused the frequency to drop below 59.9. And, for the first time we are noticing unusual but small 2.7 Hz ringdowns in West Texas.
2. Relationship Between Wind MW and West Texas Voltage Phase Angle (with respect to Baylor)

ERCOL Wind MW
Week Starting 00.00 GMT, Sunday, May 12, 2013

McDonald Observatory Average Voltage Phase Angle
1-Minute Intervals, Beginning Sunday, May 12, 2013

Tornado hits Granbury (8pm CDT, 1am GMT) 50 miles southwest of Fort Worth
3. Plots of Min and Max Frequency for Each Minute of the Week

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, May 12, 2013

Trips below 450 MW are not reported

Baylor Maximum Frequency
1-Minute Intervals, Beginning Sunday, May 12, 2013

523 MW Trip
4. Significant Unit Trips (note red circles on page 3)

4. Significant Unit Trips, continued

5. Severe Thunderstorms Hit Central and North Texas on the Night of May 15, 2013 CDT

Thunderstorm Load Shedding: Frequencies at Baylor and West Texas
May 16, 2013, 03:27 GMT

Thunderstorm Load Shedding: Vrms at Baylor and West Texas
(West Texas is lowered on the graph by 0.005pu to better observe the two curves)
5. Severe Thunderstorms, continued

Zoom-In of Load Shedding Events
Thunderstorm Load Shedding. Frequencies at Baylor and West Texas
May 16, 2013, 03:27 GMT

Slope of first load shedding event is

\[(60.04 - 59.96) \text{ Hz} / (79.2 - 67.9) \text{ sec} = 0.0800 / 11.3 = 0.00708 \text{ Hz/ sec}.\]

Slope of second load shedding event is

\[(60.04 - 59.96) \text{ Hz} / (95.9 - 81.5) \text{ sec} = 0.0800 / 14.4 = 0.00556 \text{ Hz/ sec}.\]

ERCOT generation capability for this time, according to Dr. Grady’s ERCOT Wind Scraper program, is 39,150 MW.

Using

\[\Delta P_{LOAD} = \frac{-2H(P_{gen, rated}) df_S}{f_S dt},\]

with \(H = 7\) seconds, the estimated amounts of load shed are 65 MW and 51 MW, respectively.
6. Small But Unusual High-Frequency Ringdown at McDonald Observatory (West Texas)

This small ringdown observed at McDonald Observatory is unusual in two ways. First, the ringdown frequency of 2.7 Hz is about 3-to-4 times normal. Second, the normalized damping ratio is only 0.03, which means this waveform has less than normal damping.

Small But Unusual 2.7 Hz Voltage Angle Ringdown, West Texas w.r.t. Baylor, May 16, 2013, 04:03 GMT

Corresponding Frequencies at West Texas and Baylor
6. Small But Unusual High-Frequency Ringdown, continued

Curve fitting the response using the Second Order Illustrator produces a reasonably-good fit which captures the ringdown frequency and normalized damping ratio quite well.

<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
<th>A</th>
<th>B</th>
<th>T1</th>
<th>Tau1</th>
<th>C</th>
<th>T2</th>
<th>Tau2</th>
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<td>0.031</td>
<td></td>
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</tbody>
</table>

McDonald Observatory wrt Baylor, May 16, 2013, 04:03 GMT

- Measured
- Total Curve Fit
7. More Unusual McDonald Observatory 2.7 Hz Ringdowns

Between the time of the previous unusual ringdown and the end of the week, three more similar events were discovered. One is shown below. Note – nothing unusual was noticed in the U.T. Pan Am or Baylor waveforms.

![McDonald Observatory Voltage Phase Angle wrt. Baylor](May 18, 2013, 21:09 GMT)

![McDonald Observatory Frequency](May 18, 2013, 21:09 GMT)

![McDonald Observatory RMS Voltage](May 18, 2013, 21:09 GMT)
Texas Synchrophasor Network Fun Final Exam

Based on Events for the Week Beginning
Sunday, May 5, 2013, GMT

Prof. Mack Grady, Baylor, and Prof. Jaime Ramos, U.T. Pan American
Mack_Grady@baylor.edu, jramos8@utpa.edu

- Every day has synchrophasor surprises (but you have to find them)
- There is no substitute for real data

Also, soon to be operational
- Four more units in the Southwest Power Pool
- Austin (Austin Energy, plus 3M)
- Waco #2 (Brazos Electric Power Coop)
- Houston (Clean Line Energy)
- U.T. Arlington
- Texas Panhandle SPP (West Texas A&M University, Canyon)
Frequency graphs for all stations are shown simultaneously. The top graph shows 120 seconds, and the bottom graph shows a 10-second zoom in. The frequency ramp-up looks very much like a unit trip in reverse.

Assuming this is a load trip, and that ERCOT inertia constant $H = 7$ seconds, and using $f_s = 60$ Hz, use the dashed-line inertial slope portion of the ramp-up to estimate the MW of load shed using

\[
\Delta P_{LOAD} = -2H \left( P_{\text{gen, rated}} \right) \frac{df_s}{dt}.
\]

Dr. Grady’s ERCOT Wind Scraper shows that at the time of the event, $P_{\text{gen, rated}} = 38,757$ MW.
Frequency graphs for all three stations are shown in the top graph. The McDonald Observatory voltage phase angle (middle graph) shows only a small damped angle increase of about 1 degree. U.T. Pan American ringdown (lower graph) is large and falls about 4 degrees to a new steady-state value.
2a. Continuing from the previous page, given the choice of west or south, is the tripped unit more likely to be in West Texas, or in South Texas? Explain. The reference point (Waco) is in Central Texas.

2b. A zoom-in of the inertial slope is shown below. Estimate ERCOT inertia H (in seconds) for this event, using

\[ \Delta P_{GEN} = \frac{2H(P_{gen,rated})}{f_S} \frac{df_S}{dt} \]

ERCOT Wind Scraper shows that at the time of the event, \( P_{gen,rated} = 29,542 \text{ MW} \). Since 499 MW tripped off line, use 29,542 minus 499 as \( P_{gen,rated} \) after the trip.
Problem 3. Voltage Magnitudes are Useful, Too! Observed on Tuesday, May 7, 2013.
Phasor measurement units (PMUs) are well known for providing phase angles and frequency, but they also provide rms voltage magnitudes, which are often very useful in understanding events. The top graph on this page shows frequency at all three stations. The middle and bottom graphs show voltage phase angles at McDonald and U.T. Pan Am, respectively, with respect to Waco. The top graph shows frequency activity, but not a unit trip. The middle and lower graphs show small ringdowns, but no significant change in steady-state phase angle.
Problem 3, cont.
Now, consider the sometimes overlooked rms voltage in PMU data. Baylor and McDonald Observatory see voltage sags just prior to 52 seconds. 52 seconds corresponds to the onset of frequency and phase angle action on the previous page. McDonald also has a small precursor sag about 2 seconds before, but we cannot be sure if the precursor is a transmission event or a distribution event. Pan Am sees a tiny voltage sag – note the zoom-in scale.

Given the evidence, is it logical to conclude that this event
- Is not a unit trip
- Is a transmission fault
- Is closer to McDonald Observatory than to Waco
- Is far from U.T. Pan Am (even though Pan Am has a definite ringdown)

Explain.

Intense thunderstorms rolled through Waco last Thursday afternoon, showing up on the Texas Synchrophasor Network as a frequency event. A further examination of the voltage at all three stations shows that the storm triggered transmission faults that appeared as voltage sags throughout the state. The frequency up-ramp indicates load shedding, most likely confined to the Waco vicinity. Note – the bottom three graphs do not have the same time scale as the top graph.
ERCOT Wind Scraper shows that at the time of the event, $P_{\text{gen, rated}} = 44,434$ MW. Use the method in Problem 1, with $H = 7$ seconds, to estimate the MW load shed.

An event was observed last Saturday that had a very minor frequency event, and yet the event produced a textbook-quality voltage angle ringdown at U.T. Pan Am. The top graph on this page shows all three frequencies for 60 seconds. The bottom graph on this page shows the negligible angle response at McDonald Observatory for 10 seconds, and the following page shows the classic ringdown at U.T. Pan Am for 10 seconds.
Use Dr. Grady’s Second Order Illustrator spreadsheet to estimate the damped resonant frequency and normalized damping coefficient (zeta) for the Pan Am ringdown waveform. The curve-fitting equation has the form

\[ \theta(t_{\text{start}} \leq t \leq t_{\text{stop}}) = A + (B - A) \left(1 - e^{-(t-T_1)/\tau_1}\right) u(t-T_1) + 
\]

\[ + C \cdot e^{-(t-T_2)/\tau_2} \sin(\omega_d (t-T_2)) u(t-T_2). \]

where

- \( A + (B - A) \left(1 - e^{-(t-T_1)/\tau_1}\right) u(t-T_1) \) is the exponential term that transitions the steady-state angle from initial value \( A \) degrees to final asymptote value \( B \) degrees with time constant \( \tau_1 \).

- \( C \cdot e^{-(t-T_2)/\tau_2} \sin(\omega_d (t-T_2)) u(t-T_2) \) is the classic damped sinusoid.

Contact him if you want the spreadsheet with preloaded waveform. In the meantime, the output is shown on the next page.
Open book and notes. There is no solution key yet. You may work in teams.

<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
<th>A</th>
<th>B</th>
<th>T1</th>
<th>Tau1</th>
<th>C</th>
<th>T2</th>
<th>Tau2</th>
<th>Tdamp</th>
<th>Fdamp</th>
<th>Zeta</th>
<th>Squared Error</th>
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<tbody>
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<td>11</td>
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<td>6.58</td>
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<td>4.04</td>
<td>1.53</td>
<td>0.653</td>
<td>0.060</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

Event 5. UT Pan Am wrt Baylor, May 11, 2013, t = 0 is 21:44 GMT
There was only one event of significance this week – the trip of 834 MW of generation that caused ERCOT frequency to drop to 59.74 Hz. Until now, there have very few large frequency drops like this in 2013, as compared to 2012.

Wind generation averaged 13.2%, and there were four periods in which West Texas generation (i.e., Wind Country) was constrained due to stability limits.

1. Plots of Load MW, Wind MW, and Wind MW as % of Load
2. Relationship Between Wind MW and West Texas Voltage Phase Angle (with respect to Baylor)

ERCOT Wind MW
Week Starting 00.00 GMT, Sunday, May 19, 2013

McDonald Observatory Average Voltage Phase Angle
1-Minute Intervals, Beginning Sunday, May 19, 2013
3. Plots of Min and Max Frequency for Each Minute of the Week

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, May 19, 2013

Baylor Maximum Frequency
1-Minute Intervals, Beginning Sunday, May 19, 2013

Described in report
4. Stability Constraints Affect Wind Generation

Source: www.ercot.com/services/comm/mkt_notices/opsmessage)

Constraints were placed on West Texas generation for some hours because of stability limits. The following four time periods had constraints on West-to-North power flow (i.e., West Texas wind country toward the DFW area), and are listed in reverse chronological order.

- May 24 2013 03:27:32 CST. ERCOT has cancelled the following notice: ERCOT is constraining for the West-North stability limit.

- May 23 2013 12:17:17 CST. ERCOT has cancelled the following notice: ERCOT is constraining for the West-North stability limit.
  May 23 2013 01:09:08 CST. West-North Stability Limit: ERCOT is constraining for the West-North stability limit.

- May 23 2013 00:00:05 CST. ERCOT has cancelled the following notice: ERCOT is constraining for the West-North stability limit.

- May 21 2013 14:52:36 CST. ERCOT has cancelled the following notice: ERCOT is constraining for the West-North stability limit.

Their impact on capping wind generation is shown in the following figure, where four red rectangles indicate flow-limited periods.

![ERCOT Wind MW, and Periods Having Limits on West-North Flow](image-url)
5. Event 1, Major Generator Trip. May 22, 2013. 21:11 GMT

From www.ercot.com/services/comm/mkt_notices/opsmessages: “On 05/22/13, a sudden loss of generation occurred at 16:11 CDT totaling 834 MW. Frequency declined to 59.746 Hz, ERCOT load was 50,047 MW.”
5. Event 1, cont.

ERCOT Inertia Calculation

Event 1. May 22, 2013, t = 0 is 21:11 GMT

ERCOT Wind Scraper shows generation capacity at the time was 53,271 MW. The measured “green line” inertial slope for the event is

\[
\frac{(59.70 - 60.00)}{(30.1 - 24.6)} = \frac{-0.3 \text{ Hz}}{5.5 \text{ sec}} = -0.0545 \text{ Hz/sec}.
\]

Thus, the estimated H for ERCOT is

\[
H = \frac{\Delta P_{\text{GEN}} f_S}{2P_{\text{gen,rated}} \frac{df_S}{dt}} = \frac{-834 \cdot 60}{2 \cdot (53271 - 834) \cdot (-0.0545)} = 8.8 \text{ sec}.
\]
5. Event 1, cont.

Six-second Vrms sags (i.e., three vertical grid widths in the Vrms graphs) are visible at Baylor, McDonald Observatory, and U.T. Pan Am. Pan Am has the deepest sag, which suggests that the tripped generator was closer to Pan Am than to Baylor (Waco). Because McDonald has the least sag, it was most likely the most distant of the three PMUs.
5. Event 1, cont.

Voltage phase angles at McDonald Observatory and U.T. Pan Am both rise, w.r.t. Baylor, to provide support for lost generation in central ERCOT.
Because we were adding stations and maintaining the network this week, not enough contiguous data were recorded to produce meaningful phase angle summary plots. ERCOT reported two unit trips with frequency drops to 59.86 and 59.88 Hz, but these occurred in our unrecorded periods.

Wind generation was up, requiring wind graphs to be rescaled with springtime maxes of 10,000 MW and 35% of total.

There were three periods of stability limit constraints on flow from West Texas (i.e., “wind country”) to North Texas (i.e., DFW region).

1. Plots of Load MW, Wind MW, and Wind MW as % of Load

![Graphs showing ERCOT Load and Wind MW, and ERCOT Wind Gen (Percent of Load)]
2. Stability Constraints Affect Wind Generation

![ERCOT Wind MW, and Periods Having Limits on West-North Flow](image-url)

Week Starting 00.00 GMT, Sunday, May 26, 2013

- Stability Constraints Affect Wind Generation
As you can see below, peak load is gradually rising toward the expected summer peak of 70+ GW. There were no unusual events this past week, and only several generating unit trips, for which the frequency did not dip below 59.9 Hz. Two are illustrated in this document, and estimates of ERCOT inertia constant $H$ and tripped generation MW are made.

West Texas generation was limited only one hour this week, which corresponded to the time where the angular separation between west and central ERCOT reached 50 degrees. The impact of a windy cool front hitting West Texas is obvious on the wind graphs. Note – this time of the year, such events are not “cold” fronts!

The U.T. Pan Am data are not presently being logged due to software issues with the home concentrator at Baylor. We will fix that problem soon.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load

![Graph of ERCOT Load and Wind MW]

![Graph of ERCOT Wind Gen (Percent of Load)]

Cool front passing through West Texas with 50 mph gusts
2. West Texas Voltage Phase Angle Variation with Wind Gen MW

![Diagram showing ERCOT Wind MW and periods having limits on West-North Flow]

![Diagram showing McDonald Observatory average voltage phase angle]

*Cool front passing through West Texas with 50 mph gusts*
3. Sudden Loss of 607 MW of Generation

June 04, 2013, 23:04 GMT, Trip of 607 MW Generation
Frequency Measured at Baylor and McDonald Observatory

McDonald Observatory Voltage Phase Angle w.r.t. Baylor

Second
3. Continued, Zoom-In

Our ERCOT Wind Scraper program, which reads the ERCOT web site every minute, showed that the generation capability just prior to the unit trip was 59,589 MW. ERCOT inertia H constant is therefore estimated to be

$$H = \frac{\Delta P_{GEN} f_S}{2P_{gen,\text{rated}} \frac{df_S}{dt}} = \frac{-607 \cdot 60}{2 \cdot (59589 - 607) \cdot (-0.0381)} = 8.1 \text{ sec.}$$

Note that $P_{gen,\text{rated}}$ is the rated capability of generation on-line after the trip.

Regarding the phase angle of West Texas, the small rise in steady-state voltage phase angle at McDonald Observatory indicates that the unit trip was not in West Texas.
4. Generating Unit Trip, where the Generation Lost is Less than the 450 MW Threshold for Reporting on ERCOT’s “Operations Messages” Web Page

![Frequency Measured at Baylor and McDonald Observatory](image1.png)

![McDonald Observatory Voltage Phase Angle w.r.t. Baylor](image2.png)
4. Continued, Zoom-In

The generation capability just prior to the unit trip was 43,186 MW. Assuming an ERCOT inertia $H$ constant of 8 seconds, the MW tripped can estimated. Starting with

$$H = \frac{\Delta P_{GEN} f_S}{2 P_{gen,\text{rated}} \frac{df_S}{dt}}$$

then using $P_{gen,\text{rated}} = P_{gen,\text{rated}, \text{prior}} - \Delta P_{GEN}$.

$$H = \frac{\Delta P_{GEN} f_S}{2(P_{gen,\text{rated}, \text{prior}} - \Delta P_{GEN}) \frac{df_S}{dt}}$$

$$\Delta P_{GEN} f_S = 2H(P_{gen,\text{rated}, \text{prior}} - \Delta P_{GEN}) \frac{df_S}{dt}$$
4. Continued

\[ \Delta P_{\text{GEN}} \left( f_s + 2H \frac{df_s}{dt} \right) = 2HP_{\text{gen, rated, prior}} \frac{df_s}{dt} \]

yielding the estimated change in ERCOT generation

\[ \Delta P_{\text{GEN}} = \frac{2HP_{\text{gen, rated, prior}} \frac{df_s}{dt}}{f_s + 2H \frac{df_s}{dt}} = \frac{2 \cdot 8.0 \cdot 43186 \cdot (-0.0245)}{60 + 2 \cdot 8.0 \cdot (-0.0245)} = -284 \, MW. \]
Temperature continues to rise, and peak load is pushing 60 GW. Wind peaked over 7 GW on Sunday and averaged 8.5% for the week. There were two large MW generation trips, 911 MW and 825 MW. The larger one is highlighted in this report. The corresponding 5+ second voltage sags were clearly visible at Waco and McDonald Observatory, even though the two PMUs are separated by more than 400 miles.

There was one unusually-large wind ramp-up period of 2 GW rise in one hour. The response of West Texas voltage phase angle (i.e., the “loadflow” angle) was to rise 30 degrees.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load
2. West Texas Voltage Phase Angle Variation with Wind Gen MW

Cause of this wind jitter? Perhaps one of our wind generating companies can enlighten us?
2. Phase Angle and Wind, cont. Zoom-In of Rapid 1-Hour Wind Run-Up Period which Ends with a Small Generating Unit Trip.

![McDonald Observatory Phase Angle w.r.t Baylor](image)

**Note – this plot contains 126,000 points**

3. Large Generating Unit Trips

![Baylor Minimum Frequency](image)

- 911 MW
- 825 MW

Page 3 of 5
3. Generating Unit Trips, cont. 911 MW Trip.

**June 11, 2013, 15:56 GMT, Trip of 911 MW Generation**

*Frequency Measured at Baylor and McDonald Observatory*

**McDonald Observatory Voltage Phase Angle w.r.t. Baylor**

*June 11, 2013, 15:56 GMT*

**RMS Voltage at Baylor and McDonald Observatory**

*June 11, 2013, 15:56 GMT*
3. Generating Unit Trips, cont.  Zoom-In of 911 MW Trip.

The inertial slope is estimated by the dashed green line on the top graph. The estimate is

$$\frac{df_S}{dt} = \frac{(59.80 - 60.05)}{(36.0 - 31.3)} = \frac{-0.25}{4.7} = -0.0532 \text{Hz/sec}.$$  

Our ERCOT Wind Scraper program, which reads the ERCOT web site every minute, showed that the generation capability just prior to the unit trip was 53,201 MW. ERCOT inertia constant is therefore estimated to be

$$H = \frac{\Delta P_{\text{GEN}} f_S}{2 P_{\text{gen, rated}} \frac{df_S}{dt}} = \frac{-911 \times 60}{2 \times (53201 - 911) \times (-0.0532)} = 9.8 \text{sec.} \text{ (which is higher than usual).}$$
It was a fairly uneventful week, with only one generating unit trip reaching 59.9 Hz. Wind generation ranged from 493 MW to 8642 MW. Wind generation was up significantly the last half of the week, causing a return to the 9000 MW graph scale in this report. There were about 22 hours of West-North power flow constraints (i.e., limits on West Texas wind generation) due to grid stability limits. Even with the limits, wind generation for the week was 812 GWh. Voltage phase angle between West Texas and Central ERCOT varied more than 75 degrees.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load
2. West Texas Voltage Phase Angle Variation with Wind Gen MW

![Graph showing West Texas Voltage Phase Angle Variation with Wind Gen MW for the week starting 00.00 GMT, Sunday, June 16, 2013.](image)

The graph above illustrates the variation in voltage phase angle with wind generation in West Texas for the week starting 00.00 GMT, Sunday, June 16, 2013. The data is represented over 1-minute intervals, highlighting the impact of wind generation on voltage phase angles.
3. Stability-Constrained Periods for West-North Flow (i.e., Wind Generation)
Red rectangles represent the constrained periods, and their impact on limiting wind generation is obvious. Approximately 22 hours were constrained during the week.

4. Large Generating Unit Trips
4. Large Generating Unit Trips, cont. June 18, 2013, 04:59 GMT, 489 MW

Freq. at Baylor and McDonald Observatory

60 sec. windows

Voltage Phase Angle at McDonald w.r.t. Baylor. Angle drop hints that the tripped unit is in West Texas.

Voltage Sag at Baylor

Voltage Sag at McDonald Observatory
5. Typical Unusual Event #1, June 16, 2013, 22:28 GMT

Four disturbances at McD occur, separated by approx. 18 sec. The upward slopes in freq. hint at load shedding.

Baylor freq. also shows the disturbance, although highly attenuated. This indicates the disturbance is a grid event rather than a distribution event.

Bump-ups in McD phase angle also hint at load shedding, which then sends more of West Texas wind power toward central ERCOT.

Vrms gives few hints, except that the event is likely to be much closer to McD (red) than central ERCOT (black).
6. Typical Unusual Event #2, June 19, 2013, 22:52 GMT.
A mysterious 3.5 Hz oscillation starts suddenly at McDonald Observatory, 15 seconds after a voltage sag, and continues for 70 seconds. Then, it suddenly stops. Baylor shows no evidence of a 3.5 Hz oscillation. 3.5 Hz is possibly a local (i.e., West Texas) grid resonance. Or, perhaps the control system of one of the large telescopes at the observatory is creating this small oscillation on the mountaintop?

![RMS Voltage at Baylor and McDonald Observatory](image1.png)

![Frequency Measured at McDonald Observatory](image2.png)

![McDonald Observatory Voltage Phase Angle w.r.t. Baylor](image3.png)
7. **Routine 3-Second Time Correction**

Once synchronous clock-time error reaches 3 seconds, which occurs about once a week or so, a grid-wide time correction is made by speeding up (or slowing down) the generators long enough to bring clocks back to perfect time. A time correction was performed by ERCOT on Tuesday. The red box on the top graph clearly shows a small rise in 1-minute averaged frequency. Integrating the frequency rise yields the time correction in seconds.
Summer load climbed above 60 GW. Wind was strong, topping 9 GW the first half of the week, but then gradually declined as above-normal temperatures set in. On Saturday morning, ERCOT announced a three-hour long advisory for a possible geomagnetic disturbance (GMD) of K-7.

The PMU at McDonald Observatory is reliably sending data but started having difficulties staying synchronized. Thus, no McDonald phase angle plots are shown this week. However, McDonald Observatory frequency and Vrms measurements are synchronized well enough to be useful. A field trip to that beautiful scientific site in the Davis Mountains may be in order.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load

![Weekly Load and Wind MW Plot](image)

![Weekly Wind Gen Percent of Load Plot](image)
2. Stability-Constrained Periods for West-North Flow (i.e., Wind Generation)
Red rectangles represent the constrained periods, and their impact on limiting wind generation is obvious. Approximately 17 hours were constrained during the week. The blue rectangle on Saturday is the GMD advisory.

3. Large Generating Unit Trips
There were two trips of interest, one of which was a double trip.
4. June 27, 2013, 04:09 GMT, 808 MW

**Frequency Measured at Baylor and U.T. Pan Am**

*June 27, 2013, 04:09 GMT Event*

![Frequency Graph](image)

**U.T. Pan Am Voltage Phase Angle w.r.t. Baylor**

*June 27, 2013, 04:09 GMT Event*

![Phase Angle Graph](image)

*Rise in voltage phase angle at U.T. Pan Am indicates that the unit trip is not in far South Texas.*

**RMS Voltage at Baylor and U.T. Pan Am**

*June 27, 2013, 04:09 GMT Event*

![RMS Voltage Graph](image)
5. June 27, 2013, 22:45 GMT, 230 MW followed by 412 MW

Frequency Measured at Baylor and U.T. Pan Am
June 27, 2013, 22:45 GMT Event

U.T. Pan Am Voltage Phase Angle w.r.t. Baylor
June 27, 2013, 22:45 GMT Event

RMS Voltage at Baylor and U.T. Pan Am
June 27, 2013, 22:45 GMT Event

The deeper sag at PanAm and angle drop hint that the second trip was local to Pan Am
6. Five Minute Window of All Three U.S. Grid Frequencies
The frequency window below corresponds to the event shown on the previous page, except that this window starts one minute earlier.

**Frequency of ERCOT, Western, and Eastern Grids**
June 27, 2013, 5-Minutes Starting at 22:44 GMT
7. Western Grid Event.
The Cloudcroft, NM, PMU (20 miles east of Alamogordo) observed a major event in the Western Grid. Frequency and Vrms are shown below. As soon as the Los Alamos and Colorado Springs PMUs are running, we will also be able to show phase angle changes.

The damped resonant frequency has approximately two cycles in 5 seconds, corresponding to 0.4 Hz. The 0.4 Hz oscillation is also visible in Vrms.

![Frequency Measured at Cloudcroft, NM (Western Grid)
June 29, 2013, 17:28 GMT](image)

![RMS Voltage Measured at Cloudcroft, NM (Western Grid)
June 29, 2013, 17:28 GMT](image)
There were no significant events this week. Summer load fell below 60 GW, probably due to July 4th vacations. Three days had moderately strong wind, topping 6 GW.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load
2. Stability-Constrained Periods for West-North Flow (i.e., Wind Generation)
ERCOT placed no limits on West-North power flow this week, and there were no geomagnetic advisories.

3. Voltage Phase Angle Variations
One-minute averages of voltage phase angles with respect to Baylor are shown below. McDonald Observatory was having synchronization issues the first half of the week. That problem has been resolved. The correlation between wind MW (above) and West Texas phase angle at McDonald Observatory (below) is clear.
4. Large Generating Unit Trips
As seen below, there were no large unit trips this week.

5. Unusual Event #1, July 5, 2013, 13:47 GMT
Frequencies at Baylor and U.T. Pan Am showed a sharp but small increase, followed by significant frequency and angle ringdowns. Frequency was relatively high. The fact that the frequency event was seen at both locations confirms it is a grid event rather than a local distribution event. The angle ringdown in the lower graph was very lightly damped. The cause of the frequency rise might have been load shedding. If so, the load shedding was not in the Rio Grande valley because the voltage angle at Pan Am dropped slightly.
6. Unusual Event #2. July 06, 2013, 15:00 GMT
The 10-minute graphs below show three interesting unit trips that produced significant voltage angle and magnitude ringdowns at U.T. Pan Am. The fact that the voltage angle at Pan Am dropped 10 degrees, and that the voltage magnitude was also affected, indicates that the trips were probably in the vicinity of Pan Am.
Event #3 was most likely a small unit trip. The reason it is interesting is that the voltage ringdown at U.T. Pan Am (lower graph) was fairly pronounced.

![Frequency Measured at Baylor and U.T. Pan Am](image)

![U.T. Pan Am Voltage Phase Angle w.r.t. Baylor](image)

![RMS Voltage at Baylor and U.T. Pan Am](image)
8. Components of a 120V Single-Phase Phasor Measurement Unit (PMU)

Three 50 ft. (or two 75 ft.) pieces of RG-6 coax with TNC male connectors. A mail-to-mail TNC-TNC adapter is on one end of two of the cables.

15 ft. RG-6. One end connects to GPS antenna, the other end to a lightning arrestor. Ground the arrestor.

GPS antenna screws onto ¾” threaded male-to-1” smooth PVC adapter, which in turn slides into a 1” coupling. A 1” PVC pipe slides into the other end of the coupling. You may want to use a longer pipe to get a good sky view.

120V hot and neutral are jumpered over to phase A inputs.

Terminated T-BNC fits on left BNC jack

Power supply for satellite clock.

SEL2401 satellite clock receives RG-6 from GPS antenna, and connects to SEL421 through a small coax.

SEL2890 Internet transceiver screwed to Port 3

Texas Synchrophasor Network, Report for the Week Beginning Sunday, June 30, 2013, GMT
Prof. Mack Grady, Baylor University, and Prof. Jaime Ramos, U.T. Pan American
Texas Synchrophasor Network, Report for the Week Beginning Sunday, July 07, 2013, GMT
Prof. Mack Grady, Baylor University, and Prof. Jaime Ramos, U.T. Pan American

Texas Synchrophasor Network Summary Report
Week Beginning Sunday, July 07, 2013

Prof. Mack Grady, Baylor University, Mack_Grady@baylor.edu
Prof. Jaime Ramos, U.T. Pan American, jramos8@utpa.edu
It was a very hot, calm, typical July week, with only one large generating unit trip. For the most part, wind generation stayed below 5 GW. No stability limits were placed on the amount of wind generation.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load
2. Voltage Phase Angle Variation with Wind Generation

Most wind generators are in West Texas, but the number of wind generators in South Texas is increasing. South Texas has good daytime coastal wind. West Texas phase angle (at McDonald Observatory), shown in black in the lower graph, tracks total wind MW (top graph, green) due to power flow principle

\[ P \approx \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2) \]

Curiously, from a daily cycle perspective, South Texas 1-minute average phase angle variation (at U.T. Pan Am), shown in red, is nearly 180° out of phase with West Texas (black curve). When West Texas power export peaks in early a.m. CDT, South Texas power import peaks, and vice-versa.
3. Large Generating Unit Trips

There was one significant unit trip, 610 MW, which caused the frequency to drop to 59.879 Hz. The corresponding frequency and phase angle plots for the trip minute are shown below.
4. July 10, 2013, 17:34 GMT Event. Small Unit Trip and Switching Event?

**Frequency Measured at Baylor, McDonald, and U.T. Pan Am**

*July 10, 2013, 17:34 GMT Event*

Small drop in steady-state frequency. PanAm (red) is most impacted.

**RMS Voltage at Baylor, McD, and U.T. Pan Am**

*July 10, 2013, 17:34 GMT Event*

Voltage drop evident at Baylor and PanAm. McD (blue) voltage drop happens earlier, and perhaps is not relevant to this event.

**U.T. Pan Am Voltage Phase Angle w.r.t. Baylor**

*July 10, 2013, 17:34 GMT Event*

Strong phase angle ringdown at PanAm, settling at a slightly smaller value.

**McD Voltage Phase Angle w.r.t. Baylor**

*July 10, 2013, 17:34 GMT Event*

Small but distinct angle ringdown at McDonald Observatory.
5. **July 13, 2013, 15:59 GMT. Transmission Switching Event**

There was no significant change in steady-state frequency or phase angle after this grid-wide event, thus we conclude it was most likely a fault-induced transmission switching event. Baylor voltage was the most impacted.

![Frequency Measured at Baylor, McDonald, and U.T. Pan Am](image1)

![McDonald and U.T. Pan Am Voltage Phase Angles w.r.t. Baylor](image2)

![RMS Voltage at Baylor, McD, and U.T. Pan Am](image3)
Wind generation died down considerably. (Note - wind and load data for the first half of the week are not shown because MG is in Cloudcroft and does not have ready access to those data. However, the missing portions will be filled-in next week.)

No stability limits were placed on the amount of wind generation.

1. Weekly Plots of Load MW, Wind MW, and Wind MW as % of Load
2. Voltage Phase Angle Variation with Wind Generation
Unlike last week, there is no clear correlation between phase angles and wind generation. West Texas phase angle lags 10° to 20° the second half of the week.
3. Large Generating Unit Trips
There was one reported generating unit trip, 438 MW, which caused the frequency to drop to 59.89 Hz. The corresponding 1-minute plots are shown below and on the next page.

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, July 14, 2013

Hour of the Week, GMT

Frequency Measured at Baylor, McDonald, and U.T. Pan Am
July 18, 2013, 08:55 GMT Event

RMS Voltage at Baylor, McD, and U.T. Pan Am
July 18, 2013, 08:55 GMT Event

Voltage sags at Baylor and PanAm
3. Large Trip, cont.

U.T. Pan Am Voltage Phase Angle w.r.t. Baylor
July 18, 2013, 08:55 GMT Event

McDonald Voltage Phase Angle w.r.t. Baylor
July 18, 2013, 08:55 GMT Event
4. What????
There is no abrupt frequency drop, but the drop seems too deep to be a routine time correction.

![Baylor Average Frequency Chart](chart.png)

- Baylor Average Frequency
- One-Minute Averages Over a 24-Minute Period, Sunday, July 14, 2013
- Hz
- Hour of the Week, GMT
- Frequency, 30 Points Per Second
- 21,600 Points Plotted per Station
- Baylor
- McD
- PanAm

Minute
5. Question Dealing with “Real World” Data: Are These Very Large Phase Angle Jumps in the Top Graph Real or Not? (Event July 20, 2013, 02:28 GMT)

Unusual, abrupt changes in phase angle trigger the event screener.

Flat-line frequency periods at Baylor indicate loss of synchronism at home station.

Vrms at Baylor indicates voltage sags at home station.
1. Catching Up on Wind Generation Since Our Last Report

Dear Friends of the Texas Synchrophasor Network – the main reason for the long time since our last report (week of Sept. 8) is because I have been busy going to Baylor football games. Since football season started we have transitioned from the heat of summer to the cool of autumn. No freezes yet. You can see on this page that wind generation gained strength in September, reaching about 8500 MW on Sept. 27. Note on page 2 that wind generation rose above 9000 MW on Oct. 11. Also, on page 3 you can observe a 6000 MW run-up in wind generation during a 2.5 hour period.

![Graph of ERCOT Load and Wind MW for Week Starting 00.00 GMT, Sunday, Sept. 15, 2013]

![Graph of ERCOT Load and Wind MW for Week Starting 00.00 GMT, Sunday, Sept. 22, 2013]
1. Catching Up, cont.

ERCOT Load and Wind MW
Week Starting 00.00 GMT, Sunday, Sept. 29, 2013

ERCOT Load and Wind MW
Week Starting 00.00 GMT, Sunday, Oct. 06, 2013

Scale change

![Graph showing ERCOT Load and Wind MW from October 13, 2013 to October 19, 2013.](image-url)

- ERCOT Load and Wind MW
  - Week Starting 00.00 GMT, Sunday, Oct. 13, 2013
  - Two Days Starting 00.00 GMT, Thursday, Oct. 17, 2013
  - ERCOT Wind MW

- Wind MW, Thursday and Friday, Oct. 18-19, 2013
  - 6000 MW increase in about 2.5 hours

![Graph showing ERCOT Load and Wind MW for Week Starting 00.00 GMT, Sunday, Oct. 20, 2013.](image1)

![Graph showing ERCOT Load and Wind MW for Week Starting 00.00 GMT, Sunday, Oct. 27, 2013.](image2)
2. Weekly Load MW, Wind MW, and Wind MW as % of Load

Now, results for the week beginning Sunday, November 03, 2013. Wind rose strongly on Sunday, surpassing 30%. Perhaps one of the ERCOT engineers can comment on what appears to be a stuck wind reading?
3. Wind MW and ERCOT Voltage Phase Angles

ERCOT Wind MW
Week Starting 00.00 GMT, Sunday, Nov. 03, 2013

McDonald Observatory Average Voltage Phase Angle
1-Minute Intervals, Beginning Sunday, November 03, 2013
4. Capacity-to-Load Ratio

ERCOT Capacity-to-Load Ratio
Week Starting 00.00 GMT, Sunday, Nov. 03, 2013

Advisories given for low physical response capability

5. Minimum Frequency for Each 1-Minute Interval

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, November 03, 2013
6. Significant Disturbances

While the week of November 3 had no unit trips causing the frequency to drop below 59.9 Hz, a very large frequency drop occurred on Saturday morning, November 2, at 02:47 GMT. The sudden loss of 1212 MW caused ERCOT frequency to drop to 59.71 Hz.
Overview: There were three significant generating unit trips this week, plus an unusual run-up in voltage phase angle (i.e., “loadflow” angle) at U.T. Pan American in the Rio Grande Valley with respect to Baylor University in Waco. Wednesday and Thursday were cold days, indicated by the twin daily peaks. Morning peaks at 2am GMT correspond to 8am CST. Wind generation was above 30% for about two hours during the week.

1. Weekly Load MW, Wind MW, and Wind MW as % of Load
2. Wind MW and Time Windows with Significant Ramps

As usual, daily wind variation was strong, as seen in the top graph. The weekly peak remains short of the 9000+ all-time peak.

Zoom-ins for two significant ramp regions are shown in the bottom graph.
3. Wind MW and Voltage Phase Angle Variation

The strong correlation between wind generation, most of which is in West Texas, and voltage phase angle in West Texas is clear in the top two graphs. A “zoom-in” of the phase angle spike in South Texas is given on the following page. Note – each graph contains 10,080 points.
3. **Wind MW and Voltage Phase Angle Variation, cont.**

Three successive “zoom-ins” of the blue rectangle on the previous page illustrate the dynamic range of synchrophasors. In the top graph, the huge rise in South Texas phase angle indicates that power export from South Texas to Central and North Texas increases significantly a few minutes after a unit trip. The middle and lower graphs clearly show the classic (and healthy) 2nd order underdamped ringdown response. The temporary fall in South Texas phase angle at the end of the ringdown shows that, temporarily, South Texas export decreased for a few minutes before starting the huge increase.
Event 1. On Nov. 12, at 22:33 GMT, a sudden loss of 450 MW of generation caused ERCOT frequency to drop to **59.89 Hz**. ERCOT load was 34,391 MW.

Event 2. On Nov. 14, 08:38 GMT, a sudden loss of 820 MW of generation caused ERCOT frequency to drop to **59.79 Hz**. ERCOT load was 32,702 MW.
Event 2, 59.79 Hz, continued

Rising voltage phase angles at both stations with respect to Central ERCOT (Waco) indicate that the tripped unit was not in West Texas nor South Texas. All three stations experienced approximately the same voltage sag, which means that the tripped unit was not significantly closer to one that the others. Pan Am was slower to recover.
Event 3. Later on Nov. 14, at 17:01 GMT, a sudden loss of 539 MW of generation caused ERCOT frequency to drop to 59.86 Hz. ERCOT load was 36,431 MW.
1. Comments for the Week. A “norther” (i.e., cold front) moved through Texas on Thursday and Friday, producing a steep ramp-up in wind MW. Wind generation rose by 6000 MW in two hours. This report shows that it can be said with considerable confidence that Sweetwater, in addition to being rattlesnake capital of the world, is also “center of mass” of ERCOT wind generation. This claim is backed-up on pages 2 and 3 where ERCOT wind generation is plotted along with cold front wind speed and temperature drop at Sweetwater (www.weatherunderground.com). The correlation between ERCOT wind generation and cold front timing is clear and convincing.
2. Sweetwater Proves to be Center of Mass of ERCOT Wind Generation

![ERCOT Wind MW](chart1)

![Sweetwater, TX, Wind Speed and Gusts (MPH)](chart2)
2. Sweetwater, continued

Sweetwater, TX, Temperature (Deg F)
Thursday, Nov. 21

- Every day has synchrophasor surprises (but you have to find them)
- There is no substitute for real data
3. Phase Angle Variation
The correlation between ERCOT wind MW and West Texas voltage phase angle is clear.

![Graph showing phase angle variation](image-url)
4. Frequency Excursions
Only one generating trip was reported (see circle in top figure). It was unusual in three ways. First, the time at minimum frequency, shown in the bottom figure, was considerably longer than normal. Secondly, the frequency deviation at U.T. Pan Am (same figure) was quite erratic compared to the other two stations. Thirdly, U.T. Pan Am experienced an unusual voltage swell and voltage oscillation (top and bottom figures on page 6).

ERCOT Web: On 11/22/13, a sudden loss of generation occurred at 16:23 totaling 506 MW. Frequency declined to 59.885 Hz, ERCOT load 41,103 MW. The time is 22:23 GMT.
Unusual voltage swell indicates that South Texas suddenly had more reactive power generation than before.

Steady-state voltage phase angle and angle drop indicate that South Texas was exporting power before the unit trip, but export dropped considerably after the event.
Comments: Two events of interest occurred this week. First, a trip of 856 MW produced a classic phase angle ringdown at McDonald Observatory, the type that has become less common compared to two years ago. The McD ringdown also had a significantly higher damped resonant frequency than before. Transmission lines have been added west-to-central to better accommodate wind generation, which could explain the rise in damped resonant frequency. Second, a trip of unknown MW produced an interesting “non response” in voltage phase angle.

1. Total Load, Wind Generation, Non-Wind Generation (i.e., difference between Total and Wind), and Percent Wind Generation
2. One-Week Windows of Wind Generation, Voltage Phase Angle Variation, and Sweetwater Wind

**ERCOT Wind MW**

*Week Starting 00.00 GMT, Sunday, Nov. 24, 2013*

![Graph showing ERCOT Wind MW with no new peaks.]

**McDonald Observatory Average Voltage Phase Angle**

*1-Minute Intervals, Beginning Sunday, November 24, 2013*

![Graph showing McDonald Observatory Voltage Phase Angle with McD not communicating the first part of the week. For rest of week, phase angle is strongly correlated with ERCOT wind MW.]

**Sweetwater Wind Speed, MPH**

*Week Starting 00.00 GMT, Sunday, Nov. 24, 2013*

![Graph showing Sweetwater Wind Speed with correlation between Sweetwater wind speed and ERCOT wind MW is not as strong as in last week’s cold front example.]

No new peaks

McD not communicating the first part of the week. For rest of week, phase angle is strongly correlated with ERCOT wind MW.

Correlation between Sweetwater wind speed and ERCOT wind MW is not as strong as in last week’s cold front example.
3. Frequency Excursions

![Baylor Minimum Frequency graph]


![Frequency graph for November 27, 2013, 12:16 GMT Event]

![Voltage Magnitude graph for November 27, 2013, 12:16 GMT Event]

“Steady-state” voltage sags at all three stations. Baylor initially drops to 0.89pu (see next page).

**1-Second Zoom-In of Voltage Magnitude**

November 27, 2013, 12:16 GMT Event

- Baylor initially drops to 0.89 pu

**Voltage Phase Angle Ringdown at U.T. Pan Am**

November 27, 2013, 12:16 GMT Event

- Classic voltage phase angle ringdowns at Pan Am and McD.
- McD has a noticeably higher damped resonant frequency than Pan Am, as denoted by time between peaks.
- Phase angles indicate that after the trip, South Texas is exporting more, and West Texas is importing less.

**Voltage Phase Angle Ringdown at McDonald Observatory**

November 27, 2013, 12:16 GMT Event

- McD has a noticeably higher damped resonant frequency than Pan Am, as denoted by time between peaks.
5. Event 2. Nov. 29, 17:21 GMT, Generating Unit Trip, Details Unknown.

The interesting feature of this event is not what happened, but rather what did not happen.

This is the first time I recall seeing a unit trip with significant frequency drop (i.e. 0.1 Hz drop), but essentially no voltage phase angle ringing (see red boxes), and rather uniform voltage sags (see blue box).

It is as if many small 1 MW units, spread across ERCOT, tripped in unison.
Comments: The week finished with very cold weather, heavy load, and light wind. There was only one significant generating unit trip, and one unusual unexplained event (last page).

1. Weekly Load MW, Wind MW, Sweetwater Temperature, and Wind % of Load,

- **ERCOT Load and Wind MW**
  - Week Starting 00.00 GMT, Sunday, Dec. 01, 2013

- **Sweetwater Temperature**
  - Week Starting 00:00 GMT, Sunday, Dec. 01, 2013

- **ERCOT Wind Gen (Percent of Load)**
  - Week Starting 00.00 GMT, Sunday, Dec. 01, 2013
2. Weekly Correlation Between Wind MW, McDonald Voltage Phase Angle and Sweetwater Wind Speed

![Graph of ERCOT Wind MW]

![Graph of Average Voltage Phase Angle at McDonald Observatory and U.T. Pan Am]

![Graph of Sweetwater Wind Speed]
3. Weekly Frequency Excursions
Frequency readings are taken 30 times per second, and the minimum readings for each minute are shown here. Each station sends 18 million frequency readings per week. Only one significant unit trip was observed.

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, December 01, 2013

4. Sudden Loss of 804 MW. cont.

Frequency
December 02, 2013, 22:03 GMT Event

Voltage Magnitude
December 02, 2013, 22:03 GMT Event
4. Sudden Loss of 804 MW, cont.

Frequency
December 02, 2013, 22:03 GMT Event

10-Seconds of Frequency

Zoom-In of Voltage Phase Angle Ringdowns
December 02, 2013, 22:03 GMT Event

10-Seconds of Voltage Phase Angle
4. Sudden Loss of 804 MW, cont.

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**2nd Order Curve Fit for This Week**

U.T. Pan Am Voltage Phase Angle wrt Baylor, December 02, 2013, 22:03 GMT

Ringdown Characteristics. Dec. 02 Event

Damped. Res. Freq. = 0.66 Hz
Normalized Damp. Coef. = 0.093

Even though this week’s and last week’s events were quite different in angle magnitude, their damped resonant frequencies and normalized damping were approximately equal.

<table>
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<tr>
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<th>A</th>
<th>B</th>
<th>T1</th>
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**2nd Order Curve Fit for Last Week**

U.T. Pan Am Voltage Phase Angle wrt Baylor, November 27, 2013, 12:16 GMT

Ringdown Characteristics. Nov. 27 Event

Damped. Res. Freq. = 0.62 Hz
Normalized Damp. Coef. = 0.104
5. Frequency Event Recorded at Baylor Stadium

The cause of this event is unknown. No other PMUs in the Texas Synchrophasor Network observed it. There are unconfirmed reports that unusual disturbances continued throughout the night.

![Frequency at Baylor Stadium During Baylor-UT Big 12 Playoff](image-url)
Comments: Total wind generation was relatively low this week, and temperatures moderated. Three events were reported by ERCOT. The 3rd one was very unusual, two quick trips totaling 1365 MW, with frequency dropping to 59.74 Hz.

1. Weekly Load MW, Wind MW, Sweetwater Temperature, and Wind % of Load,
2. Weekly Correlation between Wind MW, McDonald Voltage Phase Angle and Sweetwater Wind Speed

ERCOT Wind MW
Week Starting 00:00 GMT, Sunday, Dec. 08, 2013

Average Voltage Phase Angle at McDonald Observatory and U.T. Pan Am
1-Minute Intervals, Beginning Sunday, December 08, 2013

Sweetwater Wind Speed
Week Beginning Sunday, December 08, 2013, 00:00 GMT
3. Weekly Frequency Excursions
Our frequency recording button was inadvertently turned off. However, we can report voltage magnitudes and phase angle ringdowns for the three events reported by ERCOT.

![Event 1. Sudden Loss of 576 MW, Frequency Fell to 59.89 Hz, ERCOT Load = 42,285 MW.](image)

**Voltage Phase Angle Ringdowns**
December 08, 2013, 19:07 GMT Event

**Voltage Magnitude**
December 08, 2013, 19:07 GMT Event
3. Weekly Frequency Excursions, continued

Event 2. Sudden Loss of 933 MW, Frequency Fell to 59.81 Hz, ERCOT Load = 45,537 MW.

Voltage Phase Angle Ringdowns
December 09, 2013, 14:43 GMT Event

Voltage angles in South and West Texas rise to support a unit trip that appears to be in Central ERCOT.

McDonald phase angle was raised 22 degrees in this graph to maintain an 8 degree vertical scale height as in Event 3.

Voltage Magnitude
December 09, 2013, 14:43 GMT Event
3. Weekly Frequency Excursions, continued

Event 3. Sudden Loss of 816 MW, Followed 36 Seconds Later by a Sudden Loss of 549 MW. ERCOT Load = 41,336 MW. Frequency Fell to 59.74 Hz.

Voltage angles, especially in South Texas, rise to support a unit trip that appears to be in Central ERCOT.
4. Excel Solver Curve Fit Determines Damped Resonant Frequency and Normalized Damping Coefficient of the First Ringdown of Event 3

\[ \Theta(t_{start} \leq t \leq t_{stop}) = A + (B - A) \left[ 1 - e^{-\left(\frac{t - T_1}{\tau_1}\right)} \right] u(t - T_1) + \\
+ C \cdot e^{-\left(\frac{t - T_2}{\tau_2}\right)} \cdot \sin\left(\omega_d \left(\frac{t - T_2}{\tau_2}\right)\right) \cdot u(t - T_2) \]

<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
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<th>B</th>
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<th>Tau2</th>
<th>Tdamp</th>
<th>Fdamp</th>
<th>Zeta</th>
<th>Avg. Sum Squared Error</th>
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<td>1.53</td>
<td>0.654</td>
<td>0.069</td>
<td>0.0139</td>
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</tbody>
</table>

Analysis starts

Analysis stops

Damped Resonant Frequency
Fdamp = 0.654 Hz

Normalized Damping Coefficient Zeta = 0.069
Comments: Wind generation approached the previous peak (week of April 28 shown below) but a West-North stability limit capped it. There was only one significant event reported.

![ERCO Wind MW graph](image)

1. Weekly Load MW, Wind MW, Sweetwater Temperature, and Wind % of Load,

![ERCO Load, Wind Gen, Conventional Gen graph](image)

Red rectangles are the time period where ERCOT constrained wind generation due to a West-North stability limit. Note rising wind but falling load.

![ERCO Wind Gen (Percent of Load) graph](image)

Two years ago, 20% wind was considered too risky. What happened to “20% in 2020”? 

Page 139 of 155
2. Weekly Correlation between Wind MW, McDonald Voltage Phase Angle and Sweetwater Wind Speed

![Graph of ERCOT Wind Gen MW](image1)

ERCOT constraining wind due to West-North stability limit.
Was wind gen. heading for a new peak?

![Graph of Average Voltage Phase Angle at McDonald Observatory and U.T. Pan Am](image2)

![Graph of Sweetwater Wind Speed](image3)
3. Weekly Frequency Excursions

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 15, 2013

Hour of the Week, GMT

A sudden loss of generation at 17:45 GMT totaling 786 MW. Frequency declined to 59.828 Hz, ERCOT load was 35,044.

4. Comparison to Eastern and Western US Grids for Same One-Week Period

Washington D.C. Area, Eastern Grid, Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 15, 2013

Cloudcroft, New Mexico, WECC, Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 15, 2013
5. ERCOT Event of Dec. 17, Sudden Loss of 786 MW Generation

- Voltage Phase Angle Ringdowns

- Voltage Magnitude
5. ERCOT Event of Dec. 17, Sudden Loss of 786 MW, Zoom-In

Frequency, 10-Second Zoom-In
December 17, 2013, 17:45 GMT Event

Voltage Phase Angle Ringdowns, 10-Second Zoom-In
December 17, 2013, 17:45 GMT Event

Voltage Magnitude, 10-Second Zoom-In
December 17, 2013, 17:45 GMT Event
Comments: It was a dull week in terms of grid events, with no significant unit trips. Nevertheless, when analyzing synchrophasor data, every day has surprises. A few of them are pointed out for your review.

1. Weekly Load MW, Wind MW, Wind % of Load, and Sweetwater Temperature

![Graph 1: ERCOT Load, Wind Gen, Conventional Gen](image1)

![Graph 2: ERCOT Wind Gen (Percent of Load)](image2)

![Graph 3: Sweetwater Temperature](image3)
2. Weekly Correlation between Wind MW, McDonald Voltage Phase Angle and Sweetwater Wind Speed

- ERCOT Wind Gen MW
  - Week Starting 00.00 GMT, Sunday, Dec. 22, 2013

- Average Voltage Phase Angle at McDonald Observatory and U.T. Pan Am
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013

- Sweetwater Wind Speed
  - Week Beginning Sunday, Dec. 22, 2013, 00:00 GMT

Strong correlations between wind generation, West Texas voltage phase angle (blue), and Sweetwater wind speed.
3. A Week Without Frequency Excursions

**One-Week Window, Beginning Sunday, Dec. 22, 2013, GMT**

- **Baylor Minimum Frequency**
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013
  - Minimum Frequency: 59.9, 60.0, 60.1

- **McDonald Observatory Minimum Frequency**
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013
  - Minimum Frequency: 59.9, 60.0, 60.1

- **U.T. Pan Am Minimum Frequency**
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013
  - Minimum Frequency: 59.9, 60.0, 60.1

- **Washington D.C. Area, Eastern Grid, Minimum Frequency**
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013
  - Minimum Frequency: 59.9, 60.0, 60.1

- **Omaha, Nebraska Area, Eastern Grid, Minimum Frequency**
  - 1-Minute Intervals, Beginning Sunday, Dec. 22, 2013
  - Minimum Frequency: 59.9, 60.0, 60.1

- **Two days in ERCOT with unusually tight frequency. Why?**
- **Time correction in the Eastern Grid?**
3. A Week Without Frequency Excursions, continued

The minimum frequency reading for each minute, with readings taken 30 times per second, at a cabin near Cloudcroft, NM, has many internet dropouts because of the mountain location 10 miles from town. Snow on the GPS antenna can also be a factor. WECC frequency has a half-day period of oscillation.
4. Small Unit Trip on Dec. 22, 17:59 GMT
This small event, with about 0.04 Hz drop, 1 degree voltage angle change, and 0.002 per unit voltage magnitude sag, illustrates the ability of common 120Vac wall outlets to provide useful information about grid events, including some level of direction finding.
5. Two Small Events Illustrate Normalized Damping Coefficient Zeta

The Excel Solver is used to curve fit the actual ringdowns and calculate damped resonant frequency ($F_{damp}$) and normalized damping coefficient (Zeta). In the middle curve, $zeta = 0.117$ is lightly damped and normal. In the bottom curve, $zeta = 0.236$ is more damping than we usually see.

An unrelated event occurs 4 hours later, whose only noticeable effect was a slight ringdown in South Texas. Notice that the damping is more heavily damped than in the middle graph.
5. Normalized Damping Coefficient Zeta, continued
Excel Solver results are shown below.

<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
<th>A</th>
<th>B</th>
<th>T1</th>
<th>Tau1</th>
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U.T. Pan Am Voltage Phase Angle wrt Baylor, December 26, 2013, 16:11 GMT

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<td>0.89</td>
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</table>

U.T. Pan Am Voltage Phase Angle wrt Baylor, December 26, 2013, 20:25 GMT
Comments: Wind MW was headed for a new peak (existing peak = 9896 MW), but a West-North stability limit capped it. This week, only one significant unit trip was observed.

1. Weekly Load MW, Wind MW, Wind % of Load, and Sweetwater Temperature

![Graphs showing ERCOT Load, Wind Gen, Conventional Gen and Sweetwater Temperature for the week starting 00.00 GMT, Sunday, Dec. 29, 2013.](http://web.ecs.baylor.edu/faculty/grady)
### 2. Weekly Correlations between Wind MW, McDonald Voltage Phase Angle and Sweetwater Wind Speed

- Strong correlations continue between wind generation, West Texas voltage phase angle (blue), and Sweetwater wind speed. The “anti phase” relationship between West Texas and South Texas phase angles (middle graph) shows that South Texas imports when West Texas has abundant wind, and exports when West Texas wind is low.

- South Texas, represented by U.T. Pan Am, swept through an unusually large voltage phase angle range of about 90 degrees.

- Wind curtailment (hours inside the brown dashed box) due to a West-North stability limit suggests that a new wind MW peak would have been set had there been no curtailment.
3. Frequency Excursions

Baylor Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 29, 2013, 00:00 GMT

Omaha, Nebraska Area, Eastern Grid, Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 29, 2013

Cloudcroft, NM, Minimum Frequency
1-Minute Intervals, Beginning Sunday, Dec. 29, 2013, 00:00 GMT

Sudden loss of 785 MW generation.
59.84 Hz. Load was 45,302 MW.

Internet dropouts at the Cloudcroft mountain cabin cause the sparse appearance of this graph

http://web.ecs.baylor.edu/faculty/grady
4. ERCOT Unit Trip, Dec. 30, 2013, 15:44 GMT, Sudden Loss of 785 MW

**Frequency**

**December 30, 2013, 15:44 GMT Event**

![Frequency Graph](image)

**Voltage Phase Angle**

**December 30, 2013, 15:44 GMT Event**

![Voltage Phase Angle Graph](image)

**Voltage Magnitude**

**December 30, 2013, 15:44 GMT Event**

![Voltage Magnitude Graph](image)
4. ERCOT Unit Trip, cont.

**Ringdown Analysis of Pan Am Phase Angle**

- Damped Resonant Frequency = 0.683 Hz
- Normalized Damping Coefficient Zeta = 0.162

### 5-Minute Window Shows Frequency Recovery

### Exponential Steady State Transition Curve

<table>
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<tr>
<th>Start Sec</th>
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<th>A</th>
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**U.T. Pan Am Voltage Phase Angle wrt Baylor, December 30, 2013, 15:44 GMT**