This past week we found three interesting events in ERCOT, four in the Eastern Grid, and one in the Western Grid. We also identified that even though the percent of PV generation in ERCOT is small, it can cause large rises and falls in West Texas voltage phase angle.

A second document, 2010_Texas_Synchrophasor_Unit_Trip_and_Inertia_Analysis.pdf, is sent separately. It deals with wind power and measured inertia and is discussed in ERCOT Event 2.
Note the dashed line in the top two graphs. Upward bumps in McDonald Observatory voltage phase angle are highly correlated with PV generation. We have not noticed this before. The next three pages help to explain it.
Why are Synchrophasors Important?

Here’s All You Need to Remember

Average Power Flow P Through a Mostly Inductive Transmission Line (138kV and above)

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

The full derivation

\[ S_{12} = \bar{V}_1 \left[ V_1 \angle \delta_1 \left( V_1 \angle \delta_1 - V_2 \angle \delta_2 \right) \right] - jX \]

\[ S_{12} = \frac{V_1^2 \cos(\delta_1 - \delta_2) - jV_1 V_2 \sin(\delta_1 - \delta_2)}{X} - \bar{V}_1 \]

\[ S_{12} = P_{12} + jQ_{12} = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2) + \frac{V_1 - V_2 \cos(\delta_1 - \delta_2)}{X} \]

\[ S_{12} = P_{12} + jQ_{12} \]

Stability limit is when the angle difference reaches 90 degrees.
Positive-Sequence Line Parameters of a 345kV Line, Single Circuit

- $R = 0.0364\,\text{ohm/km}$, for 100 km, $R = 3.64\,\text{ohms}$
- $L = 0.947\,\text{mH/km}$, for 100 km, $L = 94.7\,\text{mH}$
- $C = 12.21\,\text{nF/km}$, for 100 km, $C = 1.221\,\mu\text{F}$

Most of the solar generation is relatively close to McDonald Observatory, and far from the reference PMU at Austin. Voltage angle difference between McDonald and Austin rises as solar generation rises. As a first approximation, MW flow is proportional to the **sine of the voltage angle difference**. You can see in the right-hand curve above that degrees per MW are smallest at zero degrees 1, and gradually rise toward infinity at 90 degrees 2.
Using the MW and voltage phase angle equations, we can better understand the large variations in McDonald Observatory voltage angle variation on page 2 (and shown again here).

By experimenting with the number of equivalent 345 kV lines between McDonald Observatory and Austin that matches what we see in real data, we find that 7 parallel lines place the sharply nonlinear range of degrees per MW in the typical PV 3000 to 4000 MW daily range in West Texas.

While not a significant event, this minute has a 2.2 Hz brief ringing event at McDonald Observatory. The fact that it appears in voltage phase angle, frequency 1, and slightly in voltage magnitude ensures that it is real and not simply noise. The event is at 16:11 UTC (10:11 CST) and is likely due to PV controllers. There are times when ringing lasts for long periods. The second dashbox shows a line trip and reclose near Waco, which is not linked to the ringing far away.
ERCOT Event 1, cont. 12-Second Zoom-In of the 2.2 Hz Oscillation.

This 12-second zoom-in of the previous graph shows the rise and fall of the ringing at McDonald. The frequency graph at the bottom of the graph has twelve 1-second windows for each test frequency, layered vertically from 1 to 4 Hz. Each window is the middle of a 5-second window used for Fourier calculations. The Fourier method has proven to be a powerful event detector, while at the same time filtering out noise. Our primary search range is 0.4 to 2 Hz. In addition to 2.0 to 4.0 Hz, we also use a 2.0 to 8.0 Hz range. 2.2 Hz is shown in the lower right window.
A classic unit trip with frequency dropping to 59.87 Hz is shown 1. Voltage angles drop at McDonald Observatory and Waco, and rise at UT Rio Grande 2. Waco and Austin have the largest voltage drops 3. Rio Grande is importing power, and the import drops 4. The tripped unit is most likely west or northwest of Waco, but not near McDonald.
The hypotenuse of the red triangle is parallel to the frequency drop curve for the first few seconds. It’s slope indicates the net inertia for the remaining generation. For that short period of time, the remaining generators have not yet slowed down the frequency drop. Courtesy of MS Windows, the triangle vertical height is 1.24”, which corresponds to \(dF = 0.15 \text{ Hz}\). The 6 second window length is 3.16”. The triangle width is 1.48”, which corresponds to \((6 \text{ sec.} \times 1.48 / 3.16) = 2.81 \text{ seconds}\). Thus, the rate of frequency drop is \(0.15 \text{ Hz} / 2.81 \text{ seconds} = 0.0534 \text{ Hz per second}\).
Inertia by itself will not stop the frequency drop – only additional power from the remaining generators, or load shedding, will do that. Thus, the time it takes to “stop the drop” depends on how many generators are operating below 100% capability and thus have reserve. Generators operating at max power will not help.

PV obviously has no rotating inertia and is always operating at max power point because its control system constantly “dithers” to stay at max power. Wind turbines have rotating inertia, but they also stay at max power by varying blade pitch.

If wind and PV generation operated at 5% below their max power point, then when there is a unit trip (which is always seen by all generators in the grid), they could quickly move to their max power point to help stop the frequency drop. Thus, it would have “an equivalent renewable inertia.”

According to ERCOT, the sudden loss of generation in this example was 718 MW, total load was 41,238 MW, generation capacity was 52,231 MW, wind generation was 7,996 MW, PV generation was 3,898 MW, and (Wind + PV) accounted for 41.2% of total generation.

The “H constant” is a value in seconds used to estimate the net kinetic energy of the entire grid by examining the rate of decline in frequency due to a unit trip. The definition is \( H = \frac{1}{2} J \omega^2 \) seconds. The correct interpretation of \( H \) is “the number of seconds of rated power stored in generator(s) as kinetic energy”. For this event, \( H = -\frac{(718 \times 60 / 2)}{(52,231 - 718)/(-0.0534)} = 7.83 \) seconds.

A TSN synchrophasor report from 2010, [2010_Texas_Synchrophasor_Unit_Trip_and_Inertia_Analysis.pdf](#), is emailed separately. It shows the theory and equations for \( H \), as well as \( H \) calculations for nine ERCOT events in 2010. Max wind generation was only about 10% at that time. The 2010 events showed no obvious correlation between \( H \) and percent wind generation. The 7.83 sec. value for this week’s Event 2, which has 41.2% wind, fits well into the results of 2010 which had only 10% or less wind power.

The green triangle in the Event 2 frequency graph shows recovery time to be approx. 3.68 seconds. Perhaps the ratio of (\( H \) sec. / Recovery Time sec.) would be better for evaluating the effect of renewables, rather than using only inertia.

Wind generation drops steadily for about 8 minutes 1. The concern is that frequency also drops 2! This called for an examination of the next 15 minutes. Continued.
ERCOT Event 3, cont. The NEXT 15-Minute Window.

Frequency recovers, with significant ringing 1, and then a unit trip occurs 2. Continued.
ERCOT Event 3, cont. Both 15 Minute Windows, Pasted Together to Create a 30-minute Window.

Pasting the two previous graphs together yields a 30-minute view. It appears there was an unexpected slow loss of wind power, and the same time, the grid was short on reserves.
Moving on to Eastern Grid events, let us first compare the range of voltage phase angles across ERCOT and Eastern. **Conroe** (near Houston) and **Virginia** phase angles relative to **OKC** are shown. The Eastern Grid covers a range of approx. 70 to -130 = 200 degrees. The maximum difference between the two curves is approx. 120 degrees.

ERCOT covers a range of approx. 70 to -30 = 100 degrees. The maximum difference between the two curves is approx. 100 degrees.
**EASTERN GRID Event 1. January 24, 2021, 00:39 UTC. 1-Minute Window.**

A fault causes a transmission line to trip 1, and it did not reclose during this window. The highest voltage dip is in Eastern OK. VA voltage magnitude was not impacted 2. VA voltage phase angle appears to have changed 1, but the change is actually in the reference PMU at OKC – see next page.
EASTERN GRID Event 2, cont. The View from Virginia (formerly at DC_Area)

The view from VA (meaning that VA is the angle reference) 1, shows that OKC and Western OK angles dropped 2. Conroe (near Houston) was not affected 3. It appears that the event was between OKC and Eastern OK.

Frequency drops to 59.93 Hz 1, meaning that this is a major unit trip in the Eastern Grid. VA phase angle drops 2, and VA has the largest frequency and voltage ringing 3. The tripped unit is likely close to the VA PMU.

This is a 12-second zoom-in of a simple ringing event. VA voltage is steady 1, while the others ring 2. Thus, the cause of this ringing is not near VA. The biggest voltage dip is at OKC 3. This is likely a transmission line fault and reclose near OKC.

As mentioned in the last report, since **Cloudcroft** (near White Sands) and **ABQ** are only 160 miles apart, and they are our only Western Grid PMUs, we are unable to find many events using voltage phase angle. But unit trips are easily detected via frequency drops, and they tend to look the same throughout the entire grid. This event is a moderate-sized unit trip somewhere in the Western grid, and it would have essentially the same appearance in Los Angeles, Seattle, Salt Lake City, etc.
Observations from the Texas Synchrophasor Network, Sept. 2, 2010

The equivalent system H values for all 11 significant unit trips in ERCOT (including an HVDC tie trip) for August 2010 are presented here and plotted versus wind generation. The results thus far show no obvious correlation.

Prof. Mack Grady, U.T. Austin

The Unit Trips Logged on ERCOT Daily Operations Reports for August 2010

<table>
<thead>
<tr>
<th>Event</th>
<th>Day/Time CDT</th>
<th>Total Gen MW</th>
<th>Gen Lost MW</th>
<th>Wind Gen MW</th>
<th>Spinning Reserve MW</th>
<th>Freq Drop Hz</th>
<th>Inertial Droop Rate Hz/sec</th>
<th>Estimated H Constant</th>
<th>Estimated H</th>
<th>Wind Gen % of Total</th>
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<tr>
<td>1</td>
<td>Aug. 2, 14:59</td>
<td>60992</td>
<td>730</td>
<td>1200</td>
<td>4413</td>
<td>0.16</td>
<td>0.046</td>
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<td>2</td>
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<td>700</td>
<td>422</td>
<td>6121</td>
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<td>61497</td>
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<td>0.059</td>
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<td>9</td>
<td>Aug. 30, 18:19</td>
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<td>5077</td>
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<td>10</td>
<td>Aug. 31, 10:29</td>
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<td>Aug. 31, 20:34</td>
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<td>794</td>
<td>2834</td>
<td>4636</td>
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<td>5.25</td>
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</tbody>
</table>

Event 3 was a compound event, i.e., two events separated by 8 seconds. The inertial droop rate may not be a valid indicator of system response.
08/02/2010, 14:59 15:19. Deployed 539 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 3710 MW with an obligation of 2300 MW when frequency dropped to 59.878 Hz due to XXXX tripped with 730 MW. ERCOT load 62224 MW.

Generation lost = 730 / 60992 = 1.2%
Wind generation = 1200 (2.0%)
Spinning reserve = 4413 MW
Frequency drop = 0.16 Hz
Inertial droop rate = −0.046 Hz/sec
Event 1, cont.

Event 1. 8/2/2010, 19:58 GMT

-0.046 Hz/sec
08/11/2010, 20:34 20:48. Deployed 555 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 4360 MW with an obligation of 2300 MW when frequency dropped to 59.863 Hz due to XXXX tripped with 700 MW. ERCOT load 56920 MW.

Generation lost = 700 / 56323 = 1.2%
Wind generation = 422 MW (0.8%)
Spinning reserve = 6121 MW
Frequency drop = 0.12 Hz
Inertial droop rate = −0.036 Hz/sec
Event 2, cont.

Event 2. 8/12/2010, 01:33 GMT

![Graph showing frequency vs. second of the minute]

-0.036 Hz/sec

- UT Austin
- Harris 69
- McD
- UT PanAm
Event 3

08/16/2010, 13:14 13:25. Deployed 416 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 4090 MW with an obligation of 2300 MW when frequency dropped to 59.877 Hz due to XXXX tripped with 690 MW. ERCOT load 61400 MW.

Generation lost = 690 / 60743 = 1.1%
Wind generation = 204 (0.3%)
Spinning reserve = 5347
Frequency drop = 0.16 Hz
Inertial droop rate = −0.030 Hz/sec
Event 3, cont.

Event 3. 8/16/2010, 18:13 GMT

-0.008 Hz/sec
-0.030 Hz/sec
08/20/2010, 15:25 15:51. Deployed 1150 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 3857 MW with an obligation of 2300 MW when frequency dropped to 59.750 Hz due to XXXX tripped with 1320 MW. ERCOT load 62179 MW.

Generation lost = 1320 / 61497 = 2.2%
Wind generation = 2823 MW (4.6%)
Spinning reserve = 5174 MW
Frequency drop = 0.27 Hz
Inertial droop rate = −0.10 Hz/sec
Event 4, cont.
08/21/2010, 08:28 08:41. Deployed 421 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 6299 MW with an obligation of 2300 MW when frequency dropped to 59.891 Hz due to XXXX unit tripped with 724 MW. ERCOT load 40198 MW.

Generation lost = 724 / 40200 = 1.8%
Wind generation = 3325 MW (8.3%)
Spinning Reserve = 10570 MW
Frequency drop = 0.16 Hz
Inertial droop rate = -0.063 Hz/sec
Event 5, 8/21/2010, 13:28 GMT

-0.063 Hz/sec

UT Austin
Harris 69
McD
UT PanAm

Event 5.  8/21/2010, 13:28 GMT
08/22/2010, 14:38 15:03. Deployed 859 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 3258 MW with an obligation of 2300 MW when frequency dropped to 59.805 Hz due to XXXX tripped with 778 MW and XXXX with 84 MW. ERCOT load 59876 MW.

Generation lost = (778 + 84) / 58998 = 1.5%
Wind generation = 674 MW (1.1%)
Spinning Reserve = 3917 MW
Frequency drop = 0.18 Hz
Inertial droop rate = −0.047 Hz/sec
Event 6. 8/22/2010, 19:38 GMT

-0.047 Hz/sec
08/24/2010, 14:31 14:51. Deployed 688 MW Responsive Reserve Service from actual adjusted Responsive Reserve of 4200 MW with an obligation of 2300 MW when frequency dropped to 59.84 Hz due to XXXX tripped with 824 MW. ERCOT load 60503 MW.

Generation lost = 824 / 59874 = 1.4%
Wind generation = 4257 MW (7.1%)
Spinning reserve = 6237 MW
Frequency drop = 0.16 Hz
Inertial droop rate = −0.045 Hz/sec
Event 7, 8/24/2010, 19:31 GMT

-0.045 Hz/sec

Texas Synchrophasor Network, Supported by EPRI and Schweitzer Engineering Labs
08/25/2010, 05:58 06:22. Deployed 533 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 5586 MW with an obligation of 2300 MW when frequency dropped to 59.87 Hz due to XXXX tripped with 733 MW. ERCOT load 37137 MW.

Generation lost = 773 / 36299 = 2.0%
Wind generation = 3456 MW (9.5%)
Spinning reserve = 8441 MW
Frequency drop = 0.16 Hz
Inertial droop rate = −0.059 Hz/sec
## Event 8, cont.

### Voltage Phase Angle

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<th>Event 8</th>
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<td>PMU 7</td>
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<td>60.02</td>
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<tr>
<td>UT PanAm</td>
<td>60.04</td>
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</tbody>
</table>

**Event 8. 8/25/2010, 10:56 GMT**

- **Frequency**: 59.04 Hz
- **Phase Angle**: Approximately 0.059 Hz/sec

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**UT Austin**

**Harris 69**

**McD**

**UT PanAm**

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**Texas Synchrophasor Network, Supported by EPRI and Schweitzer Engineering Labs**

Page 124 of 135
08/30/2010, 18:19 18:38. Deployed 389 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 4918 MW with an obligation of 2300 MW when frequency dropped to 59.892 Hz due to the East DC Tie tripped with an import of 593 MW. ERCOT load 56076 MW.

Generation lost = 593 / 55547 = 1.1%
Wind generation = 5077 MW (9.1%)
Spinning reserve = 8360 MW
Frequency drop = 0.13 Hz
Inertial droop rate = −0.044 Hz/sec
Event 9, 8/30/2010, 23:18 GMT

-0.044 Hz/sec
08/31/2010, 10:29:10. Deployed 341 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 4062 MW with an obligation of 2300 MW when frequency dropped to 59.909 Hz due to XXXX tripped with 411 MW. ERCOT load 48205 MW.

Generation lost = 411 / 47588 = 0.9 %
Wind generation = 3685 MW (7.7%)
Spinning reserve = 5867 MW
Frequency drop = 0.11 Hz
Inertial droop rate = −0.030 Hz/sec
Event 10

Event 10. 8/31/2010, 15:29 GMT

-0.030 Hz/sec
Event 11

08/31/2010, 20:34 20:47. Deployed 592 MW of Responsive Reserve Service from actual adjusted Responsive Reserve of 39392 MW with an obligation of 2300 MW when frequency dropped to 59.886 Hz due to XXXX tripped with 794 MW. ERCOT load 54873 MW.

Generation lost = 794 / 54012 = 1.5 %
Wind generation = 2834 MW (5.2%)
Spinning reserve = 4636 MW
Frequency drop = 0.18 Hz
Inertial droop rate = −0.057 Hz/sec
Event 11

Event 11. 9/01/2010, 01:34 GMT

![Graph showing frequency over time](chart)

-0.057 Hz/sec

UT Austin
Harris 69
McD
UT PanAm
\[ W_{ke} = \frac{1}{2} J \omega_s^2 \]  
Stored kinetic energy in the generators

\[ \frac{dW_{ke}}{dt} = J \omega_s \frac{d \omega_s}{dt} \]

Rate of change of stored kinetic energy equals net mechanical power into generators, minus net electrical power out of generators

\[ \frac{dW_{ke}}{dt} = P_m - P_e \]

Before the unit trip, \( \omega_s \) is constant, and there is power balance.

When one of the many generators trips (i.e., loss of \( \Delta P_m \)), \( P_e \) temporarily remains unchanged because voltage regulators maintain load voltage and load power. Thus generators begin to give up some of their stored kinetic energy (commonly called the inertial droop).

\[ \frac{dW_{ke}}{dt} = \left( P_{m}^{\text{pre}} - \Delta P_m \right) - P_e = -\Delta P_m \]
The “H constant”

\[
H = \frac{1}{2} \frac{J \omega_s^2}{P_{\text{rated}}} = \frac{1}{2} \left( \frac{J \omega_s}{P_{\text{rated}}} \right) \cdot \frac{\omega_s}{P_{\text{rated}}} = \frac{1}{2} \left[ \frac{-\Delta P_m}{d \omega_s / dt} \right] \frac{\omega_s}{P_{\text{rated}}}
\]

\[-\Delta P_m = J \omega_s \frac{d \omega_s}{dt}, \text{ so } \frac{d \omega_s}{dt} = \frac{-\Delta P_m}{J \omega_s}\]

\[
H = \frac{1}{2} \left[ \frac{-\Delta P_m}{P_{\text{rated}}} \right] \left( \frac{\omega_s}{d \omega_s / dt} \right) = \frac{-\Delta P_m}{2P_{\text{rated}}} \frac{2\pi f_s}{2P_{\text{rated}}} \frac{2\pi (df_s / dt)}{2} = \frac{-\Delta P_m f_s}{2P_{\text{rated}} (df_s / dt)}
\]

H has the units of seconds. The correct interpretation is that the kinetic energy in a machine corresponds to H seconds of rated power. Thus, the machine could provide rated power for H seconds, at which time it would have spun down to zero RPM.

The multiplier $f_s$ term in the numerator can be considered constant. $P_{\text{rated}}$ is post-event and should not contain the tripped generator. Spinning reserve should be included in $P_{\text{rated}}$. 

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