Implementation and Application of an Independent Texas Synchrophasor Network
Monitoring 120V Wall Outlet Voltages and Communicating Through the Public Internet


Wind generation is mostly in West Texas. 7001 MW peak so far this year. Many hours in the spring have 15-20% wind MW, and some have > 20%. Most windy days have wind curtailments.
Why are Synchrophasors Important?

Here’s All You Need to Remember

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

$$ jX $$

$$ V_1 \angle \delta_1 + \text{ground} - V_2 \angle \delta_2 $$

These are about 1pu

For small $x$, $\sin(x) = x$

$$ P = \frac{V_1V_2}{X} \sin(\delta_1 - \delta_2) $$

Charles Steinmetz, developed phasor theory to analyze AC circuits
Positive-sequence line constants for each 345kV circuit:
• $R = 0.06$ Ω/km per conductor
• $L = 1$ µH/m
• $C = 12$ pF/m
• Rating = 800 A per conductor
• From the $L$, $XL$ (500 km) = 188.5 Ω
• For 345 kV, 100 MVA base, $Z_{base} = 1190$ Ω
• For each 500 km circuit, $XL = 0.158$ pu
• Thus, four parallel circuits have $XL = 0.040$ pu, and six parallel circuits have $XL = 0.026$ pu

Relatively small phase angle variation in central ERCOT

Oscilloscope Example. If UT Austin = 0º ref, then McD leads by 60º, and Pan Am lags by 30º

Small oscillations in the relative phase angles give an indication of grid stability. These oscillations provide an “EKG” for large power grids.
Our First Remote Phasor Measurement Unit, UT Austin’s McDonald Observatory, in the Fire Station Attic

Living is good at the Astronomers’ Lodge

LOCATION

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 32.52.54</td>
<td>W 105.39.10</td>
<td>7583 feet</td>
</tr>
</tbody>
</table>

Satellite Signal Strengths (Min for Lock, 3 Sats > 3.0)

12.0 ; 7.0 ; 5.2 ; 6.0 ; 3.6 ; 5.2 ; 1.8 ; 15.2 ; -.- ; -.- ; -.- ; -.-
The Cloudcroft, NM, Station, Piggy-Backed onto Standard DSL Internet Service

DSL Modem and Wireless Router

“The Grid Monitor”
(a power strip)

SEL 421 Relay/PMU

GPS Receiver

Spare Antenna

Cloudcroft

Lincoln National Forest

New Mexico
The Motivation for this Project

1. To study the impact of large-scale wind generation on power grids, specifically ERCOT, with independent data obtained from 120V wall outlets

2. Synchrophasors are “health monitors” and give advance notice of system stability issues in time to take corrective action

3. To permit higher levels of wind generation by careful monitoring of grid stability indicators

4. To determine the best locations in a grid for phasor measurement units (PMUs)

5. To develop automated methods for mining the data to find the nuggets of information
The Good News and the Bad News

The good news – each remote PMU streams back via internet

• 30 readings per second,
• times 60 seconds per minute,
• times 60 minutes per hour,
• times 24 hours per day,

which equals 2.5 million lines of Excel data per PMU per day.

Each line has angle, freq, Vrms. Modal information every 10 seconds.
The Good News and the Bad News

The bad news – how do you deal with all the data, mine it, process it, and find the nuggets?

So we become Synchrophasor Detectives – EVERY day has surprises and clues.

We look for events, and when we find something interesting, we post it on the Texas Synchrophasor Network web page.

Let’s now take a look at some findings.
Here’s Something You Don’t See Every Day

Tuesday, March 31, 2009, 20 Minute Window Beginning 12:53 AM CDT
Superimposed Frequency Measurements Taken at
UT Austin (in black) and McDonald Observatory (in red)

From email traffic forwarded to me by ERCOT engineers: This was caused by one of the lignite units undergoing valve freedom testing. During the test the throttle valve got struck.
The Discovery of a New Wind Phenomenon – the “Pelosi Effect”

Wind Generation in West Texas Plummets During Health Care Vote

New High 6298 MW
Sat, March 20

The Discovery of a New Wind Phenomenon – the “Pelosi Effect”

Voting
Sun, March 21

New Low 77 MW
Mon, March 22

72 Hours Beginning 12am, March 20, 2010

Prof. Mack Grady
Texas Synchrophasor Network
U.T. Austin
April 1, 2010
Curtailment Jitter – Wind generation being held below 20% of total gen. via 15-min. price signal

One week through Monday, Oct. 18, 2010

-20.11, 2250.00

2.1 cents per kWh

Min, Max Price
Houston, North, South, West

Min, Recent, Max Freq - Hz
59.90, 60.02, 60.07

Min, Recent, Max Time Error - Seconds
-1.97, 1.01, 2.44

Min Scale, Recent, Max Spinning Reserve - %
0.00, 18.52, 43.06
$2.24/kWh

15 minute spike for non-West Texas gen., West Texas gen. price remains negative.
<table>
<thead>
<tr>
<th>Day of Year</th>
<th>Total ERCOT Gen</th>
<th>Wind Gen. %</th>
<th>Wind Gen</th>
<th>Window Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>291</td>
<td>28712</td>
<td>11.9 %</td>
<td>3416</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>42563</td>
<td>19.6 %</td>
<td>5024</td>
<td>3</td>
</tr>
</tbody>
</table>

Vertical axis on the above graph has zero reference.

-2.01 cents / kWh

Min, Max Price: Houston, North, South, West: -20.11, 51.67

Min, Recent, Max Freq - Hz: 59.93, 60.02, 60.05

Min, Recent, Max Time Error - Seconds: 0.00, 1.01, 2.04

Min Scale, Recent, Max Spinning Reserve - %: 0.00, 18.5, 32.19
Wind Generation Appears to Create New Ambient Frequency Modes of Oscillation Not Predicted in Stability Studies

1-Hour Modal Scatter Plots, With and Without Strong Wind

**Big Wind (5000 MW, 16%) has Concentrated 2 Hz Cluster**

**Small Wind (900 MW, 2%) has Dispersed 2 Hz Cluster**
5000 MW wind gen down and back in 24 hours

90° down and back West Texas phase angle response (with respect to central ERCOT)

Note - The four frequency plots are practically identical. Three are at 120V wall outlets, the other is at a 69kV grid monitor.

ERCOT Log. June 23, 2010, 15:20 15:49. Frequency dropped to 59.716 Hz due to XXXX and XXXX and XXXX tripped with 1213 MW. ERCOT load 58446 MW.
Event 1. Large Unit Trip, June 23, 2010, cont.

2-Minute Windows of All Four Vrms Readings, 1800 Samples per Minute

120V wall outlet voltages are clearly more noisy than 69kV grid, but nevertheless 120V wall outlets together with Schweitzer relays provide reliable phase angle measurements.
Event 1. Large Unit Trip, June 23, 2010, cont.

1-Minute Windows of Phase Angle Ringdowns, 1800 Samples per Minute

- The data stream in from 300 and 400 miles away and are then time synchronized.

- Compare red-to-red waveforms, and blue-to-blue waveforms. Do the ringdowns observed at the 120V wall outlet on campus and the 69kV grid monitor near campus look the same? (The correct answer is YES!)

- Essentially the only difference is the fixed 90° transformer-related offset plus a 0.3° power flow shift through the substation transformer.

- This example, plus many others, convince us that 120V wall outlets are OK for synchrophasor applications.
• The fixed net multiple of 30 degree phase shift between U.T. Austin 120V and Harris 69kV has been removed. The variable but steady 0.1 degree power flow phase shift through the substation transformer has also been removed.

• Compare the superimposed red-to-black waveforms. Do the ringdowns observed at the 120V wall outlet (in black) and at the nearby 69kV, 3Φ grid monitor (in red) look the same? (The correct answer is YES!)

Not enough frequency change to be a generator trip.

Requests a 1-minute long plot of UT Pan Am voltage angle with respect to UT Austin.

Plot contains 60 seconds * 30 points per second = 1800 points.

6.5 degree steady-state angle drop indicates that a generator tripped is probably in the Rio Grande Valley, or a 345 kV circuit tripped, or a 345 series cap switched out.

FFT screening tool shows magnitude and frequency of oscillation. Grid frequencies are not produced by distribution events.
Event 3, Oct. 4, 2010, cont. Plotting McDonald voltage phase angle with respect to UT Austin.

Much smaller ring, and only about 1 degree rise in steady-state angle. Event epicenter is not in West Texas.
Event 3, Oct. 4, 2010, cont. Detailed curve fit analysis of McDonald voltage ringdown (with respect to UT Austin).
Event 4. Find Thevenin Impedance $jX_{th}$ Between West Texas and Central ERCOT. Use a Wind MW Backdown Event, July 15, 2010.

1. Measure $V_{angle}$ and Wind Generation in West Texas for 90 One-Minute Consecutive Intervals

2. Then, Use the Excel Solver to Estimate $P_{load,conv}$, $P_{gen,conv}$, $P_{export}$, and $jX_{th}$

ERCOT Log. Frequency dropped to 59.920 Hz due to wind generation dropped 1400 MW after off-set was calculated. Issued fleet up of 400 MW due to out of Up Regulation. ERCOT load 35153 MW.

The knowns (all are given in one-minute average):
- Wind generation MW
- Wind generation phase angle $\delta$ with respect to central ERCOT (i.e., U.T. Austin)
- ERCOT total generation

The unknowns
- $jX_{TH}$
- Local conventional load minus generation in West Texas wind country
- Pexport

The equations
- Ignoring losses, power balance requires that
  \[ P_{\text{wind}} - (P_{\text{load},\text{conv}} - P_{\text{gen},\text{conv}}) = \frac{V_{\text{wind}} \cdot V_{\text{ERCOT}}}{X_{TH}} \sin(\delta) \]

Other assumptions
- Having access to no other information, assume that local net conventional ($P_{\text{load}} - P_{\text{gen},\text{conv}}$) varies with ERCOT total generation according to
  \[ P_{\text{load},\text{conv}} - P_{\text{gen},\text{conv}} = A \cdot P_{\text{ERCOT \ Total \ Gen}} + B \]

Excel Solver Setup
- Define \[ C = \frac{V_{\text{wind}} \cdot V_{\text{ERCOT}}}{X_{TH} (pu)} = \frac{1 \cdot 1}{X_{TH}(pu)} \]
- Instruct Excel Solver to vary coefficients A, B, and C to minimize the sum of squared error
  \[ \sum_{n=1}^{N} \left[ P_{\text{wind}} - (P_{\text{load},\text{conv}} - P_{\text{gen},\text{conv}}) - C \sin(\delta) \right]^2, \]
  \[ n = \text{minutes, for either the entire interval} \]

The balance equation: want left-hand side $\approx$ right-hand side for all 90 readings

Three unknowns, 90 minutes (i.e., sets) of readings. Least sum of squares minimization.

Squared area between the two curves is minimized when

A = -0.0471

B = 356

Xth = 0.0211 pu on 345kV, 100MVA base
Event 5. WECC Disturbance, Sept. 04, 2010, 23:24 GMT

Viewed at Pullman, WA, and Cloudcroft, NM (near White Sands)

Only 0.07 Hz peak-to-peak

Cloudcroft, NM, voltage phase angle with respect to Pullman, WA

(net 30 degree shift not known)
<table>
<thead>
<tr>
<th>Start Sec</th>
<th>Stop Sec</th>
<th>A</th>
<th>t1</th>
<th>B</th>
<th>Tau1</th>
<th>t2</th>
<th>C</th>
<th>Tau2</th>
<th>Wdamp</th>
<th>PMUs</th>
<th>Angle reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>45</td>
<td>31.48</td>
<td>23.94</td>
<td>29.85</td>
<td>2.60</td>
<td>25.56</td>
<td>8.91</td>
<td>5.72</td>
<td>2.07</td>
<td>CLOUD</td>
<td>SEL</td>
</tr>
</tbody>
</table>

Fdamp: 0.330  
Zeta: 0.084

Cloudcroft, NM, Voltage Angle with respect to Pulman, 2010/09/04 23:34:00.000

Event 5, WECC, Sept. 04, 2010, cont. Detailed curve fit analysis of Cloudcroft voltage ringdown (with respect to Pullman).

Freq. at Pullman and Cloudcroft

Above graph saved as 2010_1017_1339_wave45.txt

Voltage Ringdown at Cloudcroft with respect to Pullman appears to have a beat frequency.

A complex ringdown.
Does Wind Generation Impact Grid Stability?

More Observations

From Last Spring: Modal analysis of ambient oscillations show that high wind causes tighter clustering of damped resonant frequency points.
Ringdown Analysis of More Than 100 Unit Trips Yields No Clear Relationship Between Wind MW and **Damped Resonant Frequency**

Does Wind Generation Impact Grid Stability?
More Observations, cont.

Ringdown Analysis of More Than 100 Unit Trips Yields No Clear Relationship Between Wind MW and Normalized Damping Ratio

Does Wind Generation Impact Grid Stability?
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
Time to recover one-half of the frequency drop = X minutes
Event 1, 8/2/2010, 07:58:00 PM GMT Minute

-0.046 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).

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

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

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

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

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 \( P_{\text{rated}} \).
### The Eight ERCOT-Logged Unit Trips in 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>Wind Gen % of Total</th>
</tr>
</thead>
<tbody>
<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>
<td>7.4</td>
<td>1.97</td>
</tr>
<tr>
<td>2</td>
<td>Aug. 11, 20:34</td>
<td>56323</td>
<td>700</td>
<td>422</td>
<td>6121</td>
<td>0.12</td>
<td>0.034</td>
<td>10.0</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>Aug. 16, 13:14</td>
<td>60743</td>
<td>690</td>
<td>204</td>
<td>5347</td>
<td>0.16</td>
<td>0.025</td>
<td>12.7</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>Aug. 20, 15:25</td>
<td>61497</td>
<td>1320</td>
<td>2823</td>
<td>5174</td>
<td>0.27</td>
<td>0.100</td>
<td>6.1</td>
<td>4.59</td>
</tr>
<tr>
<td>5</td>
<td>Aug. 21, 08:28</td>
<td>40200</td>
<td>724</td>
<td>3325</td>
<td>10570</td>
<td>0.16</td>
<td>0.063</td>
<td>6.9</td>
<td>8.27</td>
</tr>
<tr>
<td>6</td>
<td>Aug. 22, 14:38</td>
<td>58998</td>
<td>862</td>
<td>674</td>
<td>3917</td>
<td>0.18</td>
<td>0.047</td>
<td>8.9</td>
<td>1.14</td>
</tr>
<tr>
<td>7</td>
<td>Aug. 24, 14:31</td>
<td>59874</td>
<td>824</td>
<td>4257</td>
<td>6237</td>
<td>0.16</td>
<td>0.045</td>
<td>8.4</td>
<td>7.11</td>
</tr>
<tr>
<td>8</td>
<td>Aug. 25, 05:58</td>
<td>36299</td>
<td>773</td>
<td>3456</td>
<td>8441</td>
<td>0.16</td>
<td>0.059</td>
<td>8.9</td>
<td>9.52</td>
</tr>
</tbody>
</table>

- Event 3 was a compound event, separated by 8 seconds. The inertial droop rate may not be a valid indicator of system response.

- Thus far, no clear impact. But “Big Wind” season is just starting.
What Have We Learned Thus Far?

1. After knowing “are the lights on everywhere?” voltage phase angles across a grid (i.e., synchrophasors) are arguably the next most important grid diagnostic measurement.

2. While voltage synchrophasors are valuable in steady-state analysis, they are far more valuable in observing the dynamic performance of a grid, e.g. damped resonant frequencies and normalized damping coefficients that indicate grid stress and stability.

3. Because voltage synchrophasors are very sensitive to grid disturbances, they can be thought of as the “EKG” of power grids. They quickly point out abnormalities not easily seen in conventional voltage, frequency, and power measurements. Grid “stress tests” come frequently, each time a generator trips off line or a major transmission line trips.

4. If Steinmetz had known about GPS time stamping in the early 1900’s, synchrophasors would have been in common use for the past 50-60 years.
What Have We Learned Thus Far, continued?

5. Excluding redundancy requirements, ten or so strategically-placed synchophasor units in a grid the size of ERCOT are adequate.

6. We have not yet observed any detrimental effect of wind generation on system damping. The jury is still out on system inertia $H$.

7. 120V wall outlets on distribution feeders have proven themselves to provide essentially the same results as transmission voltage measurements.

8. The three reasons that 120V wall outlets are suitable for synchrophasor purposes are that

   - Grid oscillations are in the 0.5 to 2 Hz range and readily pass through transformers of all sizes,
   - Schweitzer relays effectively filter out distribution and local load noise,
   - With 30 points streaming in each second from remote monitoring points, occasional dropouts due to deep voltage sags or internet traffic cause no problems.
Texas Synchrophasor Network

Thanks to

• Schweitzer Engineering Laboratories – for all the equipment and technical support that we have and will need

• EPRI – for past, present, and future funding of graduate students and faculty summer support

• Startup money in 2008 from the Texas Governor’s Emerging Technology Fund through CCET

• Austin Energy – for installing the 69kV grid monitor, and providing advice on system operating and protection

• Moral support from other utilities and wind generator manufacturers and companies, including AEP, Entergy, ERCOT, GE, and Eon Renewable Gen.

Dr. Mack Grady, Mr. Moses Kai, 37th Annual Western Protective Relay Conf., Spokane, WA, Oct. 20, 2010
Biographies

William Mack Grady is a Professor of Electrical & Computer Engineering at U.T. Austin and a Fellow of IEEE for “Contributions to the Analysis and Control of Power System Harmonics and Power Quality.” BSEE from U.T. Arlington, and MSEE and PhD from Purdue University. Research topics are power quality, grid studies, grid security, synchrophasors, and integration of renewable energy into the grid. Research sponsors are EPRI, Schweitzer Engineering Labs, Austin Energy, DOE, and NREL. Born in Waco, TX.

Moses Kai is a Graduate Research Assistant at U.T. Austin, working in the area of synchrophasors and impact of large-scale wind generation on ERCOT. BSEE and MSEE from U.T. Austin in 2007 and 2009, respectively. Now working toward PhD in synchrophasors. Serves as a Teaching Assistant for the Power Electronics Lab course, which has an enrollment of more than 130 students per year. Student member of IEEE and a U.S. citizen.