Enhancement of State Estimation Results using Real Time Phasor Measurement Data

Policy Advisory Committee
Sacramento, CA

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Project Motivation: Why Use Phasors?

- Utilities in the west installed PMUs for over a decade.
- Used high rate data for after-the-fact studies.
- Helpful to understand the phenomena and physics of the system during the transient states.
- However, not used in Steady State studies.
- Power System SE computes the phase angle differences in steady state using real power measurements from RTUs.

**Why Not use the phasor data from the PMUs as additional measurements? (Not the 1st)**

**Question:** Can the estimates be improved?

**Reasonable to assume it will benefit all downstream applications that depend on SE output**
Project Objectives

- **Problem Statement**: To investigate methods to integrate Phasor measurement data into the Power System State Estimator (SE) on the EMS System of SDG&E with a view to improve the quality of the power system state estimates and thus establish a reliable real time database.

- **Project goals**: Project consists of two phases:
  1. Integrate real-time phasor data for use by State Estimator in order to improve its results
     
     *(Target completion date: June 30, 2008)*
  2. Investigate and evaluate methods to use Phasor data and SE results to better manage congestion problems.

     *(Target completion date: June 30, 2009)*
Project Background

This is a co-funded project between the California Energy Commission (CEC) PIER/TRP and San Diego Gas & Electric (SDGE).


Its project team comprises of SDG&E, EPG, SEL, GE & OSI soft Inc:
- Schweitzer Engineering (SEL): Synchro Phasor Processing (SPP / PDC) Unit and associated software.
- OSI soft Inc: Software to interface SPP data in IEEE 37.118 protocol with PI Server
- General Electric (GE): Bi-directional Software to Interface PI data with EMS RTDB.
- Electric Power Group (EPG): Project consultants

Addresses NERC recommendations 10 and 12 from the August 14, 2003 blackout investigation (July 13, 2004).
PMUs installed on the important tie line of the South West Power Link (SWPL) and other critical stations.
**Implementation Architecture - Overview**

**Task 1:** Acquire & Deploy PMUs

**Task 2:** Install PDC (SEL 3306) & Software

**Task 3:** Integrate PDC with the PI Server

**Task 4:** Integrate Phasor Data with EMS Data

**Task 5:** Use Phasor Data to Enhance State Estimator

**Task 6:** Measure Performance Improvement of WLS Estimator

**Task 7:** Data Sharing (FUTURE)

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**C37.118-PI Interface**

Per Standard 37.118 over Ethernet (UDP or TCP)

**Data Rate:** 12 – 60 Measurements per Second

**Concentrator SEL3306**

**Historian (PI)**
**Algorithm Modifications (within GE SE)**

- Choose to use *Phase Angle Differences* as SE inputs along with the traditional SCADA input measurements (i.e. real & reactive power flows, voltage magnitudes).

\[
\delta_i - \delta_j = \theta_{ij}
\]

where \(\delta_i\) and \(\delta_j\) are the original State Vector variables

\(\theta_{ij}\) are “New” Measurement Vector variables (i.e. Angle Differences)

- The ‘traditional’ SE formulation is modified as follows:

\[
x = \begin{bmatrix} \delta_i \\ \delta_j \\ V_i \\ V_j \\ P_{ij} \\ Q_{ij} \end{bmatrix}
\]

\[
z = \begin{bmatrix} \theta_{ij} \\ \varepsilon_i \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_{N-1} \end{bmatrix}
\]

OR

\[
z = h(x) + \varepsilon = \begin{bmatrix} \delta_i - \delta_j \\ \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_{N-1} \end{bmatrix}
\]

\[
= \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_{N-1} \end{bmatrix}
\]

- Total of 5 *Phase Angle Difference measurements* were integrated with the SCADA measurements.
Testing Performed

- The following tests were performed:
  - Ensure phasor measurement data availability in SE.  
    *(Tested Successfully)*
  
  - Verify the validity of phasor measurements within SE by comparing PMU angle differences & calculated angles in SE for a given timestamp.  
    *(Tested Successfully)*
  
  - Verify that these measurements can be disabled by the user.  
    *(Tested Successfully)*
  
  - Verify that weights are appropriately assigned for these measurements and these can be modified.  
    *(Tested successfully – SE tested with varying weights)*
  
  - Run SE under different conditions such as with & without PMU measurements.  
    *(Tested successfully – PMU+SCADA, PMU Only, SCADA Only, No PMU + No SCADA)*
### Angle Differences - Measurement Buffer

<table>
<thead>
<tr>
<th>TP</th>
<th>State/Value</th>
<th>QTL</th>
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<tbody>
<tr>
<td>1</td>
<td>2,20100</td>
<td>-5.276947</td>
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<td>2</td>
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<tr>
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<tr>
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<td>2,20104</td>
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Use page data entry to specify which TP to dynamically display. Selecting the TP or state/value field will result in that point being selected. All TPs entered are lost when the display is terminated.
## Sample Test Results

### SDG&E SE Test Results with and without Phasors

<table>
<thead>
<tr>
<th>Measurement name</th>
<th>SCADA Measuremen t</th>
<th>Estimate</th>
<th>PMU meas</th>
<th>PMU estimate</th>
<th>Angle estimate</th>
<th>SCADA Measuremen t</th>
<th>Estimate</th>
<th>%error with PMU-meas</th>
<th>%error w/o PMU-meas</th>
<th>%error Diff PMU-w/o PMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITH PMU MEASUREMENTS</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2-M2 line 23</td>
<td>227.76</td>
<td>223.93</td>
<td>-4.88</td>
<td>-4.99</td>
<td>227.76</td>
<td>223.27</td>
<td>1.68</td>
<td>1.97</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>S2-M2-line 21</td>
<td>238.61</td>
<td>233.11</td>
<td>-3.72</td>
<td>-4</td>
<td>238.61</td>
<td>233.06</td>
<td>2.31</td>
<td>2.33</td>
<td>-0.02</td>
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<tr>
<td>S2-M2-line 41</td>
<td>240.04</td>
<td>233.14</td>
<td></td>
<td></td>
<td>240.04</td>
<td>233.14</td>
<td>2.87</td>
<td>2.87</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>M5-M2 Trans</td>
<td>766.92</td>
<td>764.29</td>
<td>-5.5</td>
<td>-4.83</td>
<td>766.92</td>
<td>761.28</td>
<td>0.34</td>
<td>0.74</td>
<td>-0.39</td>
<td></td>
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<tr>
<td>WITHOUT PMU MEASUREMENTS</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2-M2 line 23</td>
<td>221.7</td>
<td>220.51</td>
<td>-4.78</td>
<td>-4.89</td>
<td>-4.84</td>
<td>221.7</td>
<td>218.32</td>
<td>0.54</td>
<td>1.52</td>
<td>-0.99</td>
</tr>
<tr>
<td>S2-M2-line 21</td>
<td>223.65</td>
<td>222.76</td>
<td>-3.51</td>
<td>-3.8</td>
<td>-3.77</td>
<td>223.65</td>
<td>220.95</td>
<td>0.40</td>
<td>1.21</td>
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<tr>
<td>S2-M2-line 41</td>
<td>224.69</td>
<td>222.79</td>
<td></td>
<td></td>
<td>-3.99</td>
<td>224.69</td>
<td>220.97</td>
<td>0.85</td>
<td>1.66</td>
<td>-0.81</td>
</tr>
<tr>
<td>M5-M2 Trans</td>
<td>772.8</td>
<td>782.93</td>
<td>-5.49</td>
<td>-4.92</td>
<td>-4.87</td>
<td>772.8</td>
<td>775.14</td>
<td>1.31</td>
<td>0.30</td>
<td>1.01</td>
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<tr>
<td>ERRORS</td>
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<td></td>
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</tr>
<tr>
<td>TEST 1: MW(line &amp; transformer Original sigmas values), Phasor Measurement sigma=0.1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2-M2 line 23</td>
<td>221.7</td>
<td>220.46</td>
<td>-4.78</td>
<td>-5.04</td>
<td>-5.13</td>
<td>221.7</td>
<td>230.72</td>
<td>3.05</td>
<td>4.07</td>
<td>-1.02</td>
</tr>
<tr>
<td>S2-M2-line 21</td>
<td>223.65</td>
<td>223.09</td>
<td>-3.51</td>
<td>-3.79</td>
<td>-3.99</td>
<td>223.65</td>
<td>232.97</td>
<td>0.25</td>
<td>4.17</td>
<td>-3.92</td>
</tr>
<tr>
<td>S2-M2-line 41</td>
<td>224.69</td>
<td>223.11</td>
<td></td>
<td></td>
<td>-4.49</td>
<td>224.69</td>
<td>233</td>
<td>0.70</td>
<td>3.70</td>
<td>-3.00</td>
</tr>
<tr>
<td>M5-M2 Trans</td>
<td>772.8</td>
<td>789.63</td>
<td>-5.49</td>
<td>-4.95</td>
<td>-4.85</td>
<td>772.8</td>
<td>769.46</td>
<td>2.18</td>
<td>0.43</td>
<td>1.75</td>
</tr>
<tr>
<td>TEST 2: sigmas defined from equation:3<em>sig=full scale value</em>error% and sigma phasor meas = 0.1</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2-M2 line 23</td>
<td>221.7</td>
<td>228.46</td>
<td>-4.78</td>
<td>-5.04</td>
<td>-5.13</td>
<td>221.7</td>
<td>230.72</td>
<td>3.05</td>
<td>4.07</td>
<td>-1.02</td>
</tr>
<tr>
<td>S2-M2-line 21</td>
<td>223.65</td>
<td>223.09</td>
<td>-3.51</td>
<td>-3.79</td>
<td>-3.99</td>
<td>223.65</td>
<td>232.97</td>
<td>0.25</td>
<td>4.17</td>
<td>-3.92</td>
</tr>
<tr>
<td>S2-M2-line 41</td>
<td>224.69</td>
<td>223.11</td>
<td></td>
<td></td>
<td>-4.49</td>
<td>224.69</td>
<td>233</td>
<td>0.70</td>
<td>3.70</td>
<td>-3.00</td>
</tr>
<tr>
<td>M5-M2 Trans</td>
<td>772.8</td>
<td>789.63</td>
<td>-5.49</td>
<td>-4.95</td>
<td>-4.85</td>
<td>772.8</td>
<td>769.46</td>
<td>2.18</td>
<td>0.43</td>
<td>1.75</td>
</tr>
<tr>
<td>TEST 3: Sigmas as in test 2 and RTU's at M5, M2, N2 and S2 blocked(not used in SE), phasor sigma=0.1</td>
<td></td>
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</tr>
<tr>
<td>N2-M2 line 23</td>
<td>221.7</td>
<td>227.76</td>
<td>-4.88</td>
<td>-5.05</td>
<td>-5.13</td>
<td>221.7</td>
<td>222.61</td>
<td>0.14</td>
<td>2.26</td>
<td>-2.12</td>
</tr>
<tr>
<td>S2-M2-line 21</td>
<td>238.61</td>
<td>234.87</td>
<td>-3.72</td>
<td>-4.08</td>
<td>-4.88</td>
<td>238.61</td>
<td>233.36</td>
<td>0.57</td>
<td>1.72</td>
<td>-0.65</td>
</tr>
<tr>
<td>S2-M2-line 41</td>
<td>240.04</td>
<td>234.84</td>
<td></td>
<td></td>
<td>-4.88</td>
<td>240.04</td>
<td>233.39</td>
<td>0.17</td>
<td>1.77</td>
<td>-0.60</td>
</tr>
<tr>
<td>M5-M2 Trans</td>
<td>766.92</td>
<td>794.65</td>
<td>-5.5</td>
<td>-4.99</td>
<td>-5.5</td>
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<td>763.53</td>
<td>3.62</td>
<td>0.44</td>
<td>3.17</td>
</tr>
<tr>
<td>TEST 4: MW(line &amp; trans sigma as in test 2) and Phasor sigma=0.03</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

The table above summarizes the test results for various measurements with and without Phasor measurements, comparing the errors with and without PMU measurements. The tests cover different scenarios, including MW measurements, transformer measurements, and phasor measurements, with varying sigmas and error percentages.
Test Summary

- By adding Phasor Measurements
  ⇒ % error on key line flows goes down by up to 0.39%
  (in some cases negligible improvements)

- Further relaxing weights on SCADA measurements
  ⇒ % error further improves by up to 0.99%.

- Placing higher confidence weights on Phasor measurements
  ⇒ % error improves still further up to 2.1%.

- By blocking SCADA measurements at substations with Phasor Measurements
  ⇒ maximum % error improvements up to 3.92%.
Conclusions

- The Phasor Measurements were successfully integrated with the SCADA measurements, in a WLS Power System State Estimator.
- No phasor measurements were made at the reference bus.
- The traditional SE ran without any convergence problems with Phasor Measurements.
- Only marginal accuracy improvements were observed due to:
  - SDG&E is a small system with ~70% metered & observable by SCADA
  - Small number of phasor measurements used (4 PMUs)
  - A very stable & well tuned WLS estimator used for testing
- SE accuracy and robustness gains from Phasor Measurements can be significant when SCADA measurements are unreliable or unavailable.
- Poorly calibrated and heavily weighted Phasor Measurements can degrade the overall SE accuracy.