Enhancement of State Estimation Results using Real Time Phasor Measurement Data

Policy Advisory Committee

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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).

Initially proposed in 2005 & approved in 2006 – Project kick-off meeting held in San Diego on March 6th, 2007.

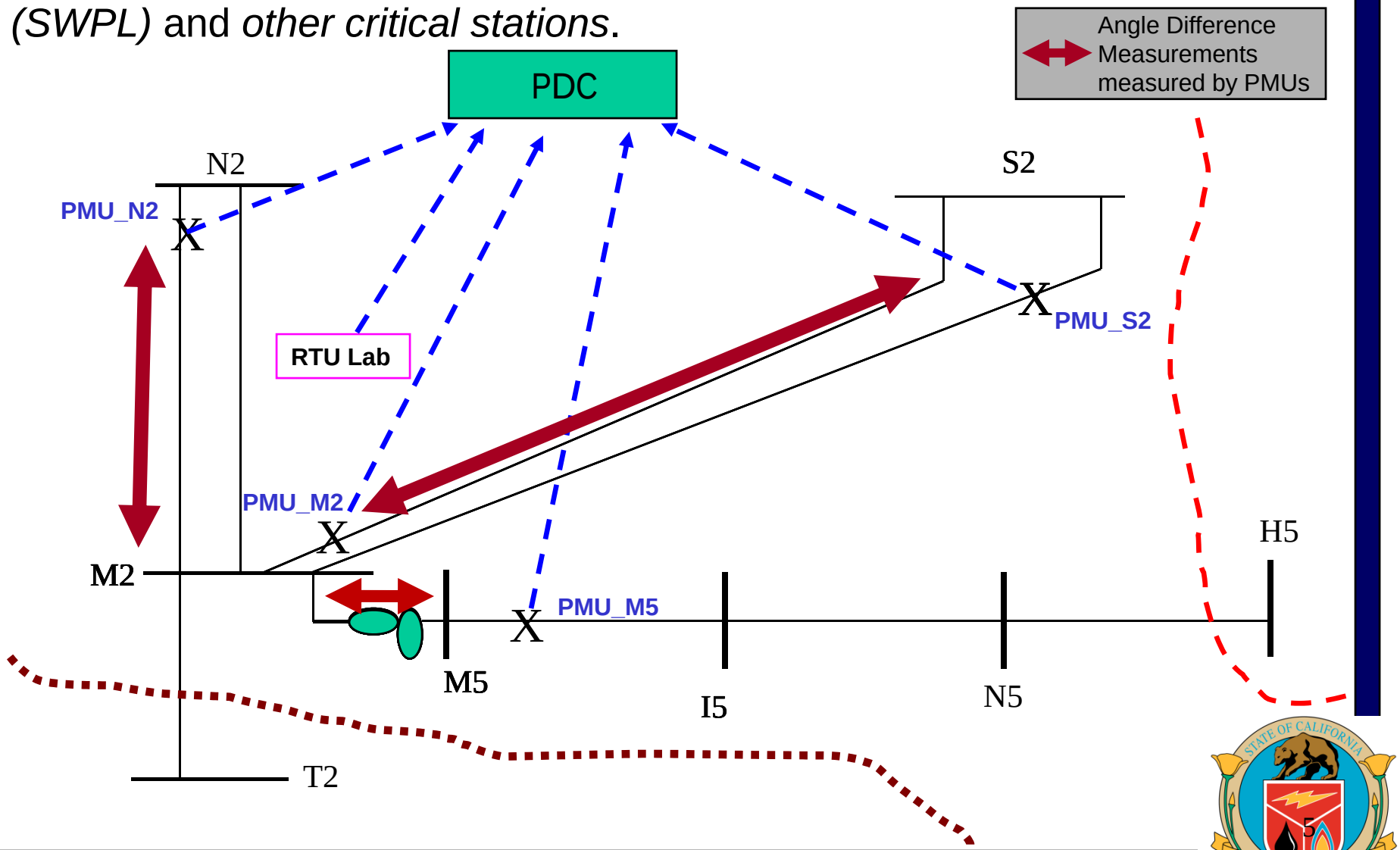
Its ***project team*** comprises of SDG&E, EPG, SEL, GE & OSI soft Inc:

- 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

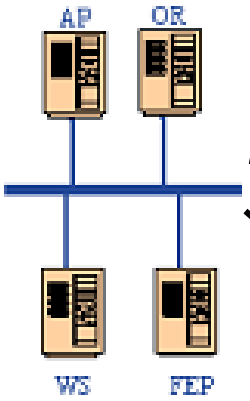
Addresses NERC recommendations 10 and 12 from the August 14, 2003 blackout investigation (July 13, 2004).

SDG&E Phasor Network (PMU Locations)

PMUs installed on the important tie line of the *South West Power Link (SWPL)* and *other critical stations*.



Implementation Architecture - Overview



EMS

Task 5:
Use Phasor Data to Enhance State Estimator

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

XA21-PI Interface

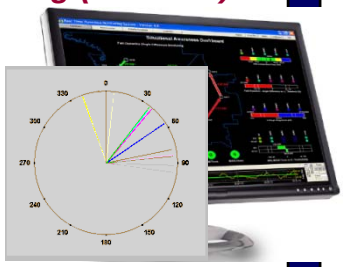
Task 4:
Integrate Phasor Data with EMS Data

Historian (PI)

C37.118-PI Interface
Per Standard 37.118 over Ethernet (UDP or TCP)

Task 3:
Integrate PDC with the PI Server

Task 7: Data Sharing (FUTURE)



Concentrator SEL3306

Task 2:
Install PDC (SEL 3306) & Software

Data Rate: 12 – 60
Measurements per Second

Task 1:
Acquire & Deploy PMUs

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).

$$\delta_i - \delta_j = \theta_{ij} \quad \text{where}$$

δ_i and δ_j are the original State Vector variables

θ_{ij} are "*New*" Measurement Vector variables (i.e. Angle Differences)

- The 'traditional' SE formulation is modified as follows:

$$x = \begin{bmatrix} \delta_i \\ \delta_j \\ \vdots \\ V_i \\ V_j \end{bmatrix}$$

State Vector

$$z = \begin{bmatrix} \theta_{ij} \\ V_i \\ V_j \\ \vdots \\ P_{ij} \\ Q_{ij} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_{N-1} \\ \varepsilon_N \end{bmatrix}$$

"*New*" Measurement Vector
('ε' is the noise / error)

New Terms

OR

$$z = h(x) + \varepsilon = \begin{bmatrix} \delta_i - \delta_j \\ V_i \\ V_j \\ \vdots \\ \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \\ \frac{V_i^2 - V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \vdots \\ \varepsilon_{N-1} \\ \varepsilon_N \end{bmatrix}$$

- 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

	TP	State/Value	QTL
1	2,20100	-5.276947	
2	2,20101	-8.972519	
3	2,20102	-12.014923	
4	2,20103	-3.695572	
5	2,20104	-6.737976	
6	2,20105	-3.042404	
7	0		
8	0		
9	0		
10	1,10600	0	
11	1,10603	0	
12	1,10606	0	
13	0		
14	0		
15	1,10650	0	M
16	0		
17	0		
18	0		
19	0		
20	0		

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

	WITH PMU MEASUREMENTS				WITHOUT PMU MEASUREMENTS			ERRORS		
Measurement name	SCADA Measurement	Estimate	PMU meas	PMU estimate	Angle estimate	SCADA Measurement	Estimate	%error with PMU-meas	%error w/o PMU-mes	%error Diff PMU-w/o PMU
TEST 1: MW(line & transformer Original sigmas values), Phasor Measurement sigma=0.1										
N2-M2 line 23	227.76	223.93	-4.88	-4.99		227.76	223.27	1.68	1.97	-0.29
S2-M2-line 21	238.61	233.11	-3.72	-4		238.61	233.06	2.31	2.33	-0.02
S2-M2-line 41	240.04	233.14				240.04	233.14	2.87	2.87	0.00
M5-M2 Trans	766.92	764.29	-5.5	-4.83		766.92	761.28	0.34	0.74	-0.39
TEST 2: sigmas defined from equation:3*sig=full scale value*error% and sigma phasor meas = 0.1										
N2-M2 line 23	221.7	220.51	-4.78	-4.89	-4.84	221.7	218.32	0.54	1.52	-0.99
S2-M2-line 21	223.65	222.76	-3.51	-3.8	-3.77	223.65	220.95	0.40	1.21	-0.81
S2-M2-line 41	224.69	222.79				224.69	220.97	0.85	1.66	-0.81
M5-M2 Trans	772.8	782.93	-5.49	-4.92	-4.87	772.8	775.14	1.31	0.30	1.01
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										
N2-M2 line 23	221.7	228.46	-4.78	-5.04	-5.13	221.7	230.72	3.05	4.07	-1.02
S2-M2-line 21	223.65	223.09	-3.51	-3.79	-3.99	223.65	232.97	0.25	4.17	-3.92
S2-M2-line 41	224.69	223.11				224.69	233	0.70	3.70	-3.00
M5-M2 Trans	772.8	789.63	-5.49	-4.95	-4.85	772.8	769.46	2.18	0.43	1.75
TEST 4: MW(line &trans sigma as in test 2) and Phasor sigma=0.03										
N2-M2 line 23	227.76	228.08	-4.88	-5.05		227.76	222.61	0.14	2.26	-2.12
S2-M2-line 21	238.61	234.87	-3.72	-4.08		238.61	233.36	1.57	2.20	-0.63
S2-M2-line 41	240.04	234.84				240.04	233.39	2.17	2.77	-0.60
M5-M2 Trans	766.92	794.65	-5.5	-4.99		766.92	763.53	3.62	0.44	3.17

Test Summary

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

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

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

- By blocking SCADA measurements at substations with Phasor Measurements
  $\Rightarrow$ 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.