welcome

Enhancement of State Estimation Results using Phasor Measurements

Presented to:
NASPI Work Group Meeting
March 6-7, 2008, New Orleans, LA

by
Lu Kondragunta
San Diego Gas & Electric®

❖Disclaimers & Appreciation.

  ❖This presentation reports the results of a synthesized work based on the dedicated works of various groups of researchers and technologists.

  ❖There is neither discovery nor innovation in the material to be presented.

  ❖I express great reverence and admiration to all the great discoverers and scientists, and to the great technologists for their leading the way

SDGE

A Sempra Energy utility®

❖ TOPICS:

➢ SDG&E® Real Time System Operations

➢ The Phasor Project

➢ Implementation

➢ Testing and Results

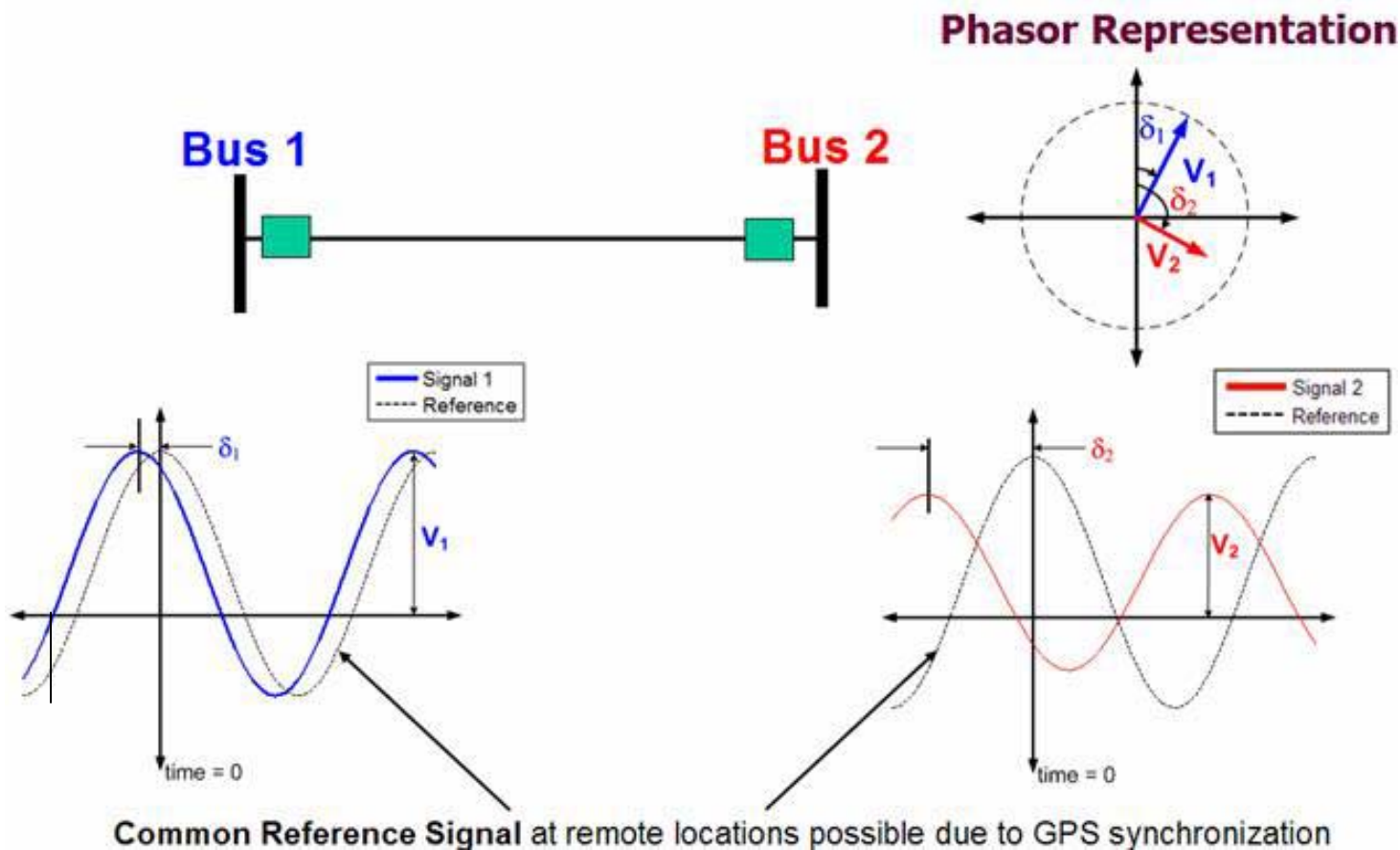➢ Conclusions

SDG&E - Real Time System Operations (RTSO)

- ## EMS System
  - ### SCADA – SOD s; Tabular Displays; PI (displays)
  - ### Transmission Security Management –
    - #### Sub-System in EMS – Real Time Network Applications (SE) ; Real Time Contingency Applications; Real Time Voltage Var Scheduling; Real Time Security Constrained Dispatch
    - #### SE & CA
      - Run every 5 and 10 minutes respectively (on time trigger); 99.9% uptime and convergence.
    - #### CA :325 contingencies (N-2, Bus, Generator and RAS);
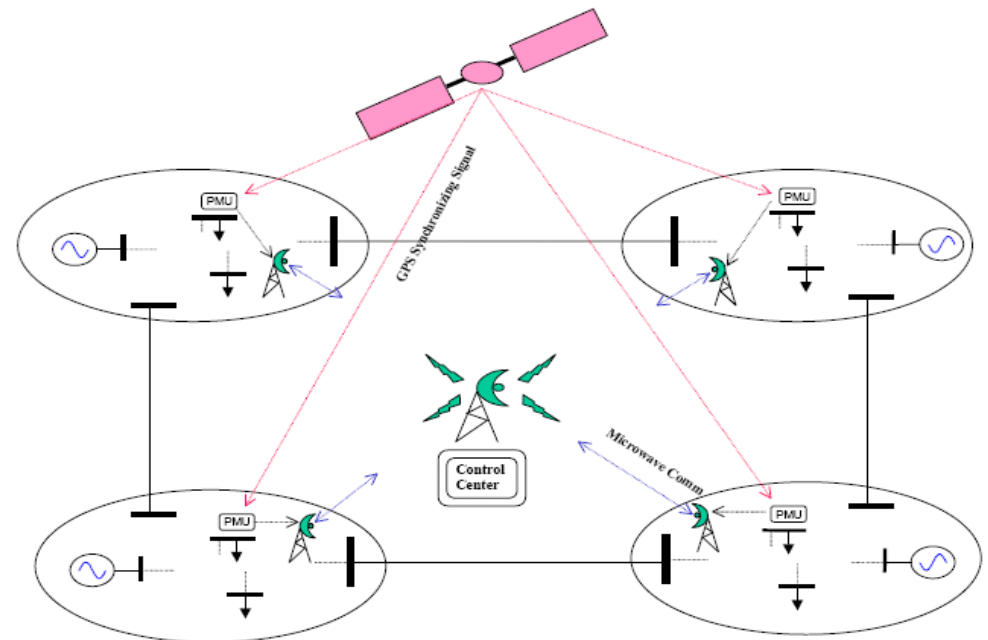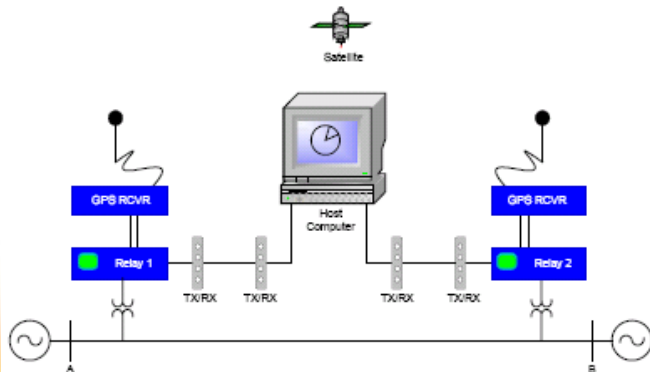
PHASORS – What and Why?
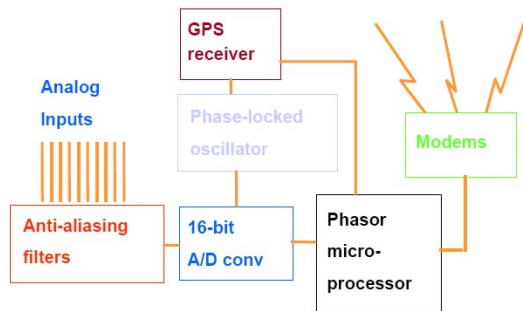
- ## PHASORS

  - Phasor - A Concept in Electrical Engineering. Represents a Sinusoid.

  - PMU: Advancements in Microelectronics and Digital Signal Processing – measures the magnitude and phase of voltages and currents at a bus. ($|V|$, δ_v, $|I|$, δ_i)

  - GPS Time Synchronized sampling at very high rates. High rate time synchronized data.

SDGE

A *Sempra Energy* utility®

PHASORS – What and Why? (contd.)

Phasor Representation

Common Reference Signal at remote locations possible due to GPS synchronization

PHASORS – What and Why?
(contd.)

PHASORS – Why?

PHASORS - Use

- 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.

- 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 ones- there exists prior work in academic institutions)***

- ***Can the estimates be improved?***

CIEE – PIER/TRP (CEC) PROJECT

- **The Project:**
  - "**Enhancement of State Estimation Results Using Real Time Phasor data**" **(June 2006; Sept. 2006)**
  - *Co-funded project* : California Energy Commission (CEC) CIEE (PIER/TRP) and (SDG&E).
  - **Kick off Meeting - March, 2007**
    - **SDG&E, CEC, CIEE, EPG, OSIsoft, GE, SEL**
  - **SEL: Synchro Phasor Processing (SPP / PDC) Unit and associated software.**
  - **OSIsoft: Software to interface SPP data in IEEE 37.118 protocol with PI Server**
  - **GE: Bi-directional Software to Interface PI data with EMS RTDB.**
  - **EPG: Consultants - RTDMS**
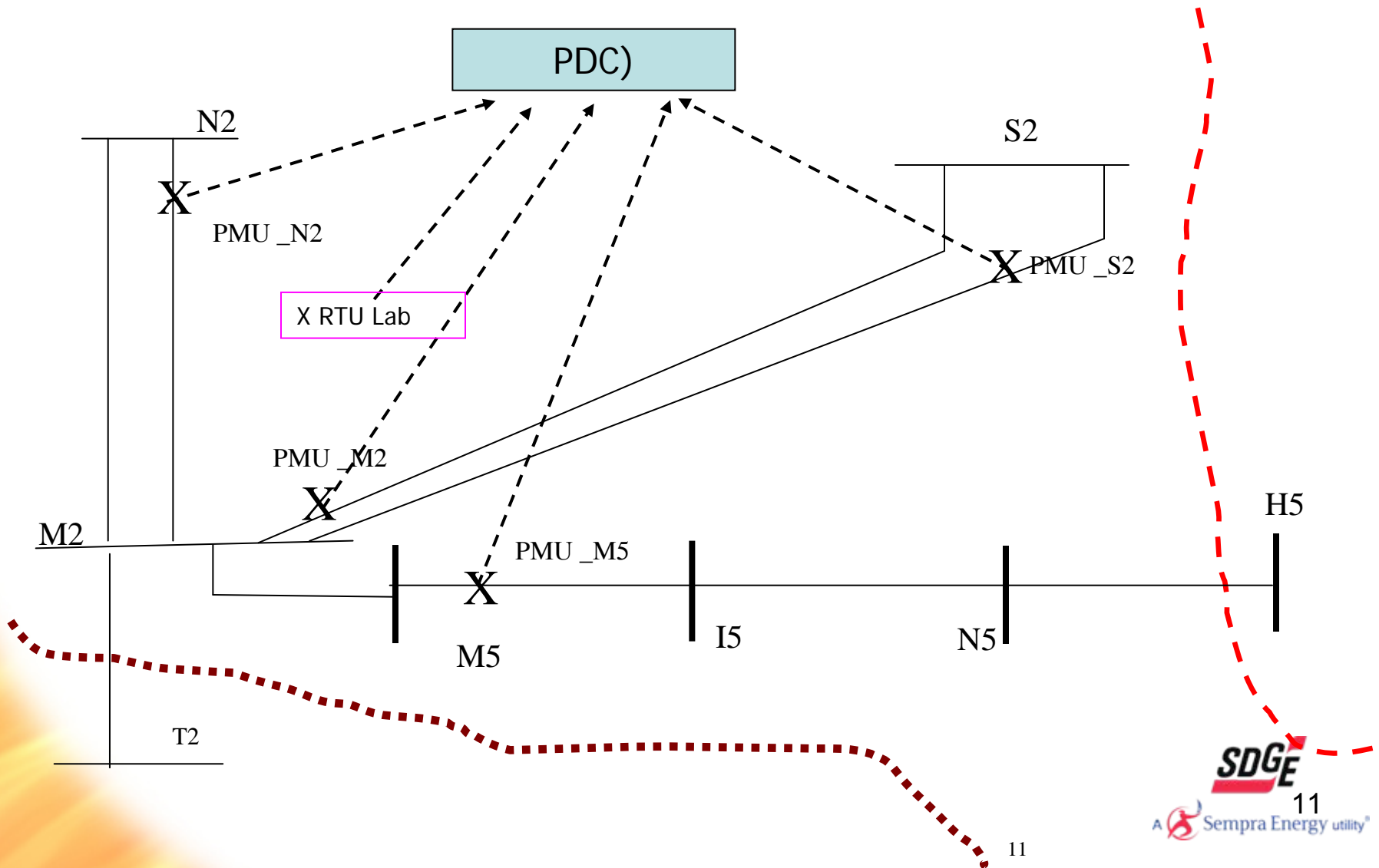
Objective & Goals

❖ **Objective:**

- **Statement of the Problem**: **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.**

❖ **The *project goals:* 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)*

SDG&E

A **Sempra Energy** utility®

PMU LOCATIONS

PDC)

N2

X

PMU _N2

X RTU Lab

S2

X PMU _S2

PMU _M2

X

M2

PMU _M5

X

M5

H5

I5

N5

T2

SDGE

A Sempra Energy utility®

Implementation Architecture - Overview

AP   **OR**

EMS

Task 5:
Use Phasor Data to
Enhance State Estimator

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

EMS PI Interface

WS   **FEP**

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

Task 2:
Install PDC & Software

Data Rate: 12 – 60
Measurements per Second

Task 1:
Acquire & Deploy PMUs

State Estimation

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

$$x^{k+1} = x^k + \left[H(x^k)^T \bullet R^{-1} \bullet H(x^k) \right]^{-1} H(x^k) \bullet R^{-1} \left[z - h(x^k) \right]$$

- The Reference Bus
  - LF : Accounts for the Slack
  - SE : Meaningful Difference in angle measurements
  - No need to have Phasor Measurements at the ref. bus
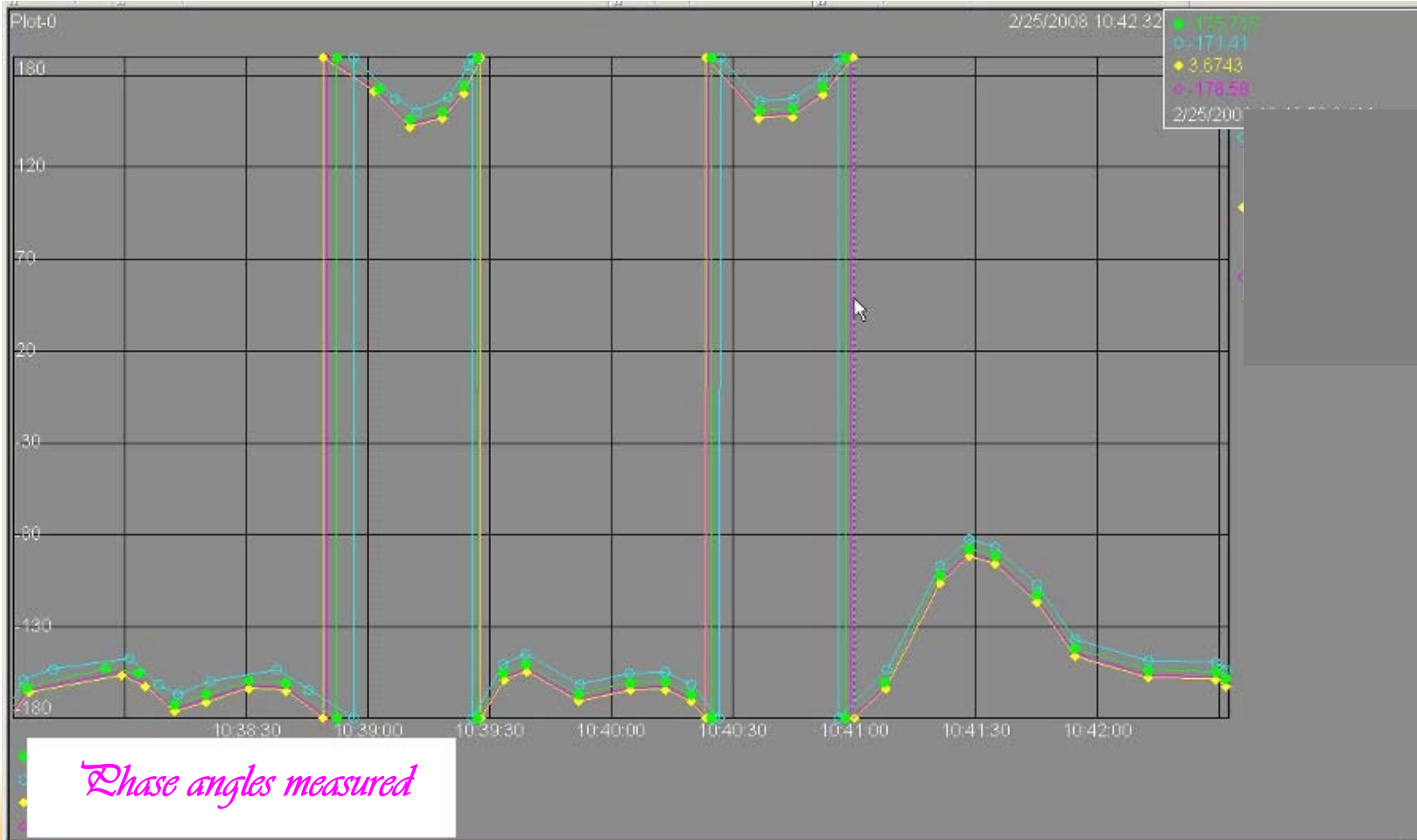 - N(N-1)/2 Phase angle difference measurements

$$P_{km} = (V_k V_m / X_{km}) [(\delta_k - \delta_m)]$$

$$\delta_{km} = (1.0) \quad [(\delta_k - \delta_m)]$$

Testing

- The following tests were performed
  - Ensure phasor measurement data availability in SE – (Tested Successfully).
  - Verify the validity of phasor measurements within state estimator – compare angle differences between measured angles by PMUs and caculated 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 was tested with varying measurement weights).

Measured Absolute Phase Angles

Phase angles measured

15

Angle Differences – EMS 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.

Test Results - 1 (12-06-2007)

	SDG&E SE TEST WITH PHASORS FROM 12/6/07 TO 12/7/07													
Test 1, date 12/6/07	with phasor Meas						without phasor Meas							
measuremen	Measurement	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual Angle	Meas w/o phasor	estimate	residual w/o ph	%error with ph-meas	%error w/o ph-mes	%error Diff ph-wph
	MW(line &transf sigmas at Original values), Phasor sigma=0.03													
N2-M2 line 23	227.76	223.93	-0.03	-4.88	-4.99	3.74			227.76	223.27	2.24	1.68	1.97	-0.29
S2-M2-line 21	238.61	233.11	0.38	-3.72	-4	9.19			238.61	233.06	2.77	2.31	2.33	-0.02
'S2-M2-line 4	240.04	233.14	0.52			3.94			240.04	233.14	3.45	2.87	2.87	0.00
M5-M2 Trans	766.92	764.29	-2.31	-5.5	-4.83	-18.96			766.92	761.28	2.82	0.34	0.74	-0.39
	%error= abs((meas-est)/meas), No appreciable difference in error% by adding Phasor measurements													
Test 2, date 12/6/07	with phasor Meas						without phasor Meas							
measuremen	Measurement	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual	w/o phasor	estimate		%error with ph-meas	%error w/o ph-mes	diff
	original sigmas for line trans, phasors sigma=0.1, Threshold set to 20													
N2-M2 line 23	242.91	228.52	21.21	-5.17	-5.26				242.91	229.67	18.91	5.92	5.45	0.47
S2-M2-line 21	219.71	215.51	2.58	-3.4	-3.2				220.5	216.5	1.79	1.91	1.81	0.10
'S2-M2-line 4	221.54	215.53	5.43						222.33	216.52	4.65	2.71	2.61	0.10
	%error= abs((meas-est)/meas), No appreciable difference in error% by adding Phasor measurements													

SDG&E

A Sempra Energy utility®

Test Results -2 (12-07-2007)

	with phasor Meas						without phasor Meas							
SDG&E SE TEST WITH PHASORS FROM 12/6/07 TO 12/7/07														
Test 3, date-12/07/07	measurement	Measurement	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual Angle	Meas w/o phasor	estimate	residual w/o ph	%error with ph-meas	%error w/o ph-mes	%error Diff ph-wph
measurement	Measurement	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual Angle	Meas w/o phasor	estimate	residual w/o ph	%error with ph-meas	%error w/o ph-mes	%error Diff ph-wph
Relax sigmas(3*sig=full scale value*error%) sig 500=12,sig 230=10,sig 138=5,sig69=4, sigma phasor meas 0.1														
N2-M2 line 23	221.7	220.51	0.12	-4.78	-4.89	1.09	-4.84		221.7	218.32	0.34	0.54	1.52	-0.99
S2-M2-line 21	223.65	222.76	0.09	-3.51	-3.8	2.89	-3.77		223.65	220.95	0.27	0.40	1.21	-0.81
'S2-M2-line 41	224.69	222.79	0.19						224.69	220.97	0.37	0.85	1.66	-0.81
M5-M2 Trans	772.8	782.93	-0.84	-5.49	-4.92	-5.65	-4.87		772.8	775.14	-0.19	1.31	0.30	1.01
error% improves by adding Phasor measurements														
	Jph	670.21	from ph	72			Jwoph	538.98						
Test 4, date-12/07/07		with phasor Meas						without phasor Meas						
measurement	Measurement	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual Angle	Meas w/o phasor	estimate	residual w/o ph	%error with ph-meas	%error w/o ph-mes	%error Diff ph-wph
Sigmas as above- RTU's at ML,MS and MX blocked, phasor sigma=0.1														
N2-M2 line 23	221.7	228.46		-4.78	-5.04	2.58	-5.13		221.7	230.72		3.05	4.07	-1.02
S2-M2-line 21	223.65	223.09		-3.51	-3.79	2.77	-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	-5.4	-4.85		772.8	769.46		2.18	0.43	1.75
error% improves by adding Phasor measurements														
Test 5, date-12/07/07		with phasor Meas						without phasor Meas						
measurement	with phasor Meas	estimate	residual	angle meas	angle est	Residual Angle	angle est w/o ph	Residual Angle	Meas w/o phasor	estimate	residual w/o ph	%error with ph-meas	%error w/o ph-mes	%error Diff ph-wph
MW(line &trans sigma as above Phasor sigma=0.03														
N2-M2 line 23	227.76	228.08	-0.03	-4.88	-5.05	3.74			227.76	222.61		0.14	2.26	-2.12
S2-M2-line 21	238.61	234.87	0.38	-3.72	-4.08	9.17			238.61	233.36		1.57	2.20	-0.63
'S2-M2-line 41	240.04	234.84	0.52						240.04	233.39		2.17	2.77	-0.60
M5-M2 Trans	766.92	794.65	-2.31	-5.5	-4.99	-13.61			766.92	763.53		3.62	0.44	3.17
error% improves by adding Phasor measurements														

Test Results – 3 (02-25-2008)

			PMU+ SCADA		SCADA		PMU		NO SCADA&NO PMUS	
		Meas	Est	%Error	Est	%Error	Est	%Error	Est	%Error
Angles										
	M2 - M5	-5.26	-4.64	-11.79	-4.65	-11.60	-4.64	-11.79	-4.64	-11.79
	S2-M2	-3.68	-3.92	6.52	-3.94	7.07	-3.88	5.43	-3.9	5.98
	S2-M5	-8.94	-8.56	-4.25	-8.59	-3.91	-8.51	-4.81		
	N2-M2	-6.7	-6.84	2.09	-6.86	2.39	-6.82	1.79	-6.84	2.09
	N2-M5	-11.96	-11.48	-4.01	-11.51	-3.76	-11.46	-4.18	-11.48	-4.01
	N2-S2	-3.02	-2.92	-3.31	-2.92	-3.31	-2.94	-2.65	-2.94	-2.65
BRANCH FLOWS										
M2	M2-M5 Bk 1	778.68	783.87	0.67	784.01	0.68	783.52	0.62	783.65	0.64
	M2-M5 Bk 2	748.44	744.19	-0.57	744.32	-0.55	743.83	-0.62	743.96	-0.60
	M2-S2 ln21	235.46	231.78	-1.56	232.79	-1.13	229.16	-2.68	230.32	-2.18
	M2-S2 ln41	237.67	231.82	-2.46	232.83	-2.04	229.19	-3.57	230.35	-3.08
	N2-M2 ln22	324.21	319.58	-1.43	312.89	-3.49	318.39	-1.80	318.75	-1.68
	N2-M2 ln23	311.59	311.71	0.04	312.01	0.13	310.64	-0.30	310.98	-0.20
	M2-T2 ln40	-92.8	-92.08	-0.78	-93.45	0.70	-91.22	-1.70	-92.63	-0.18
S2	M2-S2 ln21	-236.4	-230.38	-2.55	-231.38	-2.12	-227.79	-3.64	-228.94	-3.16
	M2-S2 ln41	-233.74	-230.44	-1.41	-231.43	-0.99	-227.84	-2.52	-228.99	-2.03
N2	N2-M2 ln22	-316.27	-315.97	-0.09	-316.27	0.00	-314.8	-0.46	-315.15	-0.35
	N2-M2 ln23	-311.08	-307.12	-1.27	-307.4	-1.18	-306.08	-1.61	-306.41	-1.50

No PMU Measurements				
Bus	M2	7.56	M5	12.21
	S2	3.62	N2	0.70
NO SCADA & NO PMUs				
Bus	M2	7.53	M5	12.17
	S2	3.63	N2	0.69

SE TESTING

SDGE — A Sempra Energy utility

Conclusions

1. The Phasor Measurements were successfully integrated with the SCADA measurements, in a WLS Power System State Estimator.

2. No phasor measurements were made at the reference bus.

3. The phase angle differences are treated as measurements.

4. Regarding accuracy no definite conclusions could be made due to:

   i. Small number of phasor measurements used;

   ii. A very stable and accurate WLS estimator used for testing;

   iii. A marginal improvement in the accuracy of the estimates is noted.

Acknowledgments &Thanks!

- California Energy Commission (CEC)
- Center for Energy and Environment (CIEE)
- Schweitzer Engineering Laboratories (SEL)
- OSIsoft
- General Electric (GE)
- Electric Power Group (EPG)
- And, All those whose wisdom contributed to the success of this project *(on whose broad shoulders we stand and innovate a little and peep into the future with a hope for a better tomorrow)*

SDGE
A **Sempra Energy** utility®

Questions?

QUESTIONS?

Thank you, all!