2009 NASPI Working Group Meeting

California ISO’s PMU initiatives Past and Future

Soumen Ghosh and Matthew Varghese
Network Applications - California ISO

SynchroPhasor Definitions

- PMU measurements that occur at the same time are "synchrophasors"
- Synchrophasors measure voltages and currents at diverse locations and the outputs are GPS time-stamped phasor quantities
- Since these phasors are truly synchronized, synchronized comparison of two quantities is possible, in real time at a rate of 30 samples/second
- A phasor is a complex number that represents both the magnitude and phase angle of voltage and current sinusoidal waveforms

SynchroPhasor Applications

- Fast Data Acquisition in milliseconds with time synchronization
- Typical SCADA spaced at 4 seconds - too slow to measure dynamic events
- SynchroPhasors have typical rates of 30 samples/second
- Need SynchroPhasors to measure and assess Dynamic Stability Events
- New SynchroPhasor standard in real time IEEE C37.118 – 2005
- SynchroPhasors essential for Wide Area Monitoring and Control Systems

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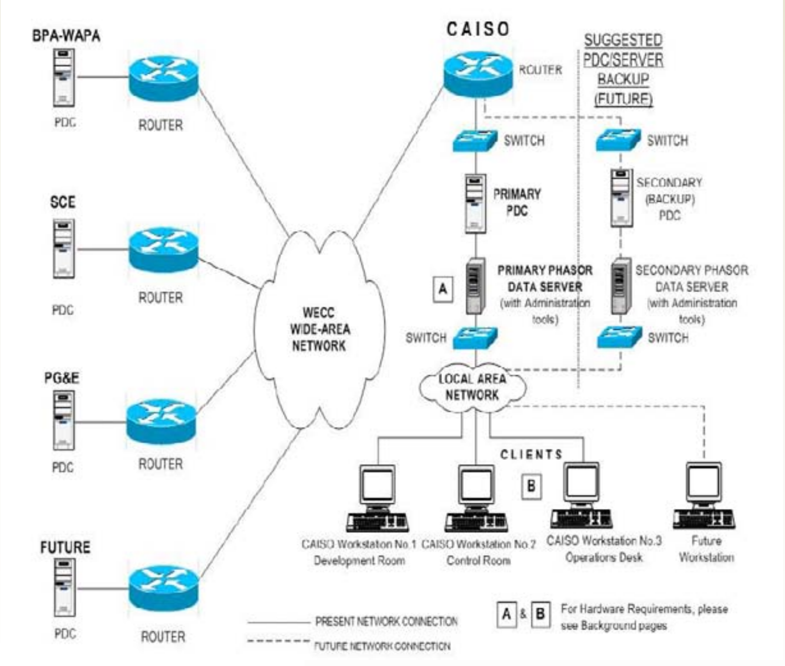
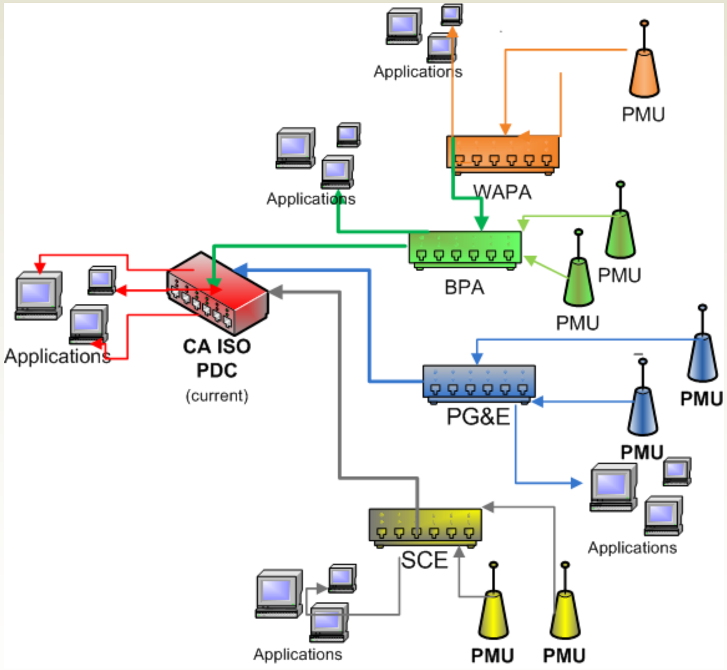
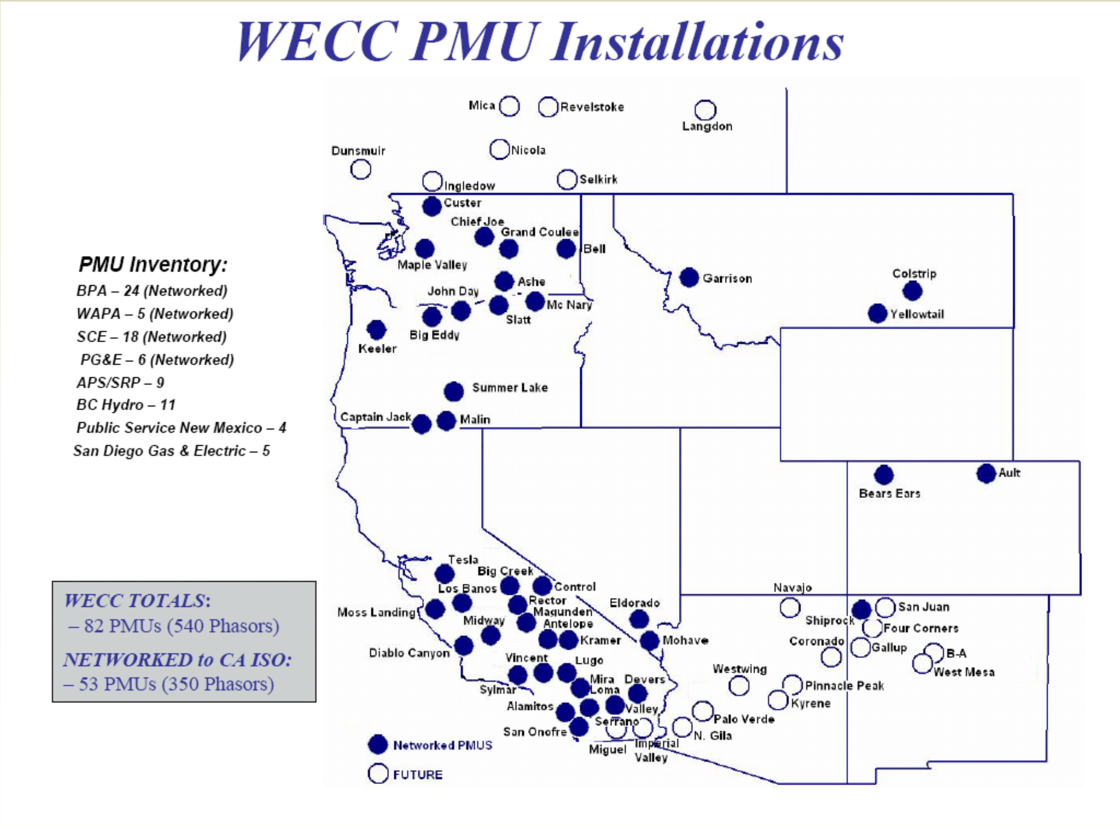
PMU History at California ISO

- In 2002 the CAISO PDC was installed with 14 PMUs gathering data at 30 samples/second
- In 2009 the CAISO PDC gets data from 59 PMUs
- BPA & SCE & PG&E connect with CAISO via WECC WAN
- Schematics – courtesy of http://electricpowergroup.com/





Current WECC PMU Installations



See WECC site at http://www.wecc.biz/documents/meetings/OC/CMOPS/WAMTF/2008/PMU%20and%20PhasorList%20WECC12-3-08.pdf

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List of Substations in Current CAISO PMU Network

Vincent	Ault
Mead	Bears Ears
Mohave G S	Shiprock
Devers	Yellow Tail
Big Creek 3	Grand Coulee
Alamitos G S	John Day
San Onofre Switchyard	Malign
Kramer	Colstrip
Antelope	Big Eddy
Valley 115	Maple Valley
Magunden	Keeler
Eldorado	Captain Jack
Lugo	Summer Lake
Control	Slatt
Mira Loma	McNary
Serrano	Ashe
Rector	Bell
Vesta	Chief Joseph
Springville	Custer
Sylmar - LADWP	Garrison
Moss Landing	Midway
Pittsburg	Diablo Canyon
Los Banos	Tesla

DATA STORAGE REQUIREMENTS

- Expected usage of **1.0 GB/day** for SQL at **06 samples/second**
- Expected usage of **2.5 GB/day** for PI at **30 samples/second**
- Data storage requirement for **90 days** would be about **120 GB**

19 PMU substations in SCE
01 PMU substation in LADWP
06 PMU substations in PGAE
16 PMU substations in BPA
04 PMU substations in WAPA

46 PMU substations in CAISO Network

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500 KV Transmission - 10 PMUs in SCE and 5 PMUs in PGAE

- 01 Mead
- 02 Mohave
- 03 Devers
- 04 San Onofre
- 05 Vincent
- 06 Valley
- 07 Eldorado
- 08 Lugo
- 09 Mira Loma
- 10 Serrano
- 01 Diablo Canyon
- 02 Midway
- 03 Moss Landing
- 04 Los Banos
- 05 Tesla

Note: *There are no PMUs from SDGE connected to the CAISO PMU Network*

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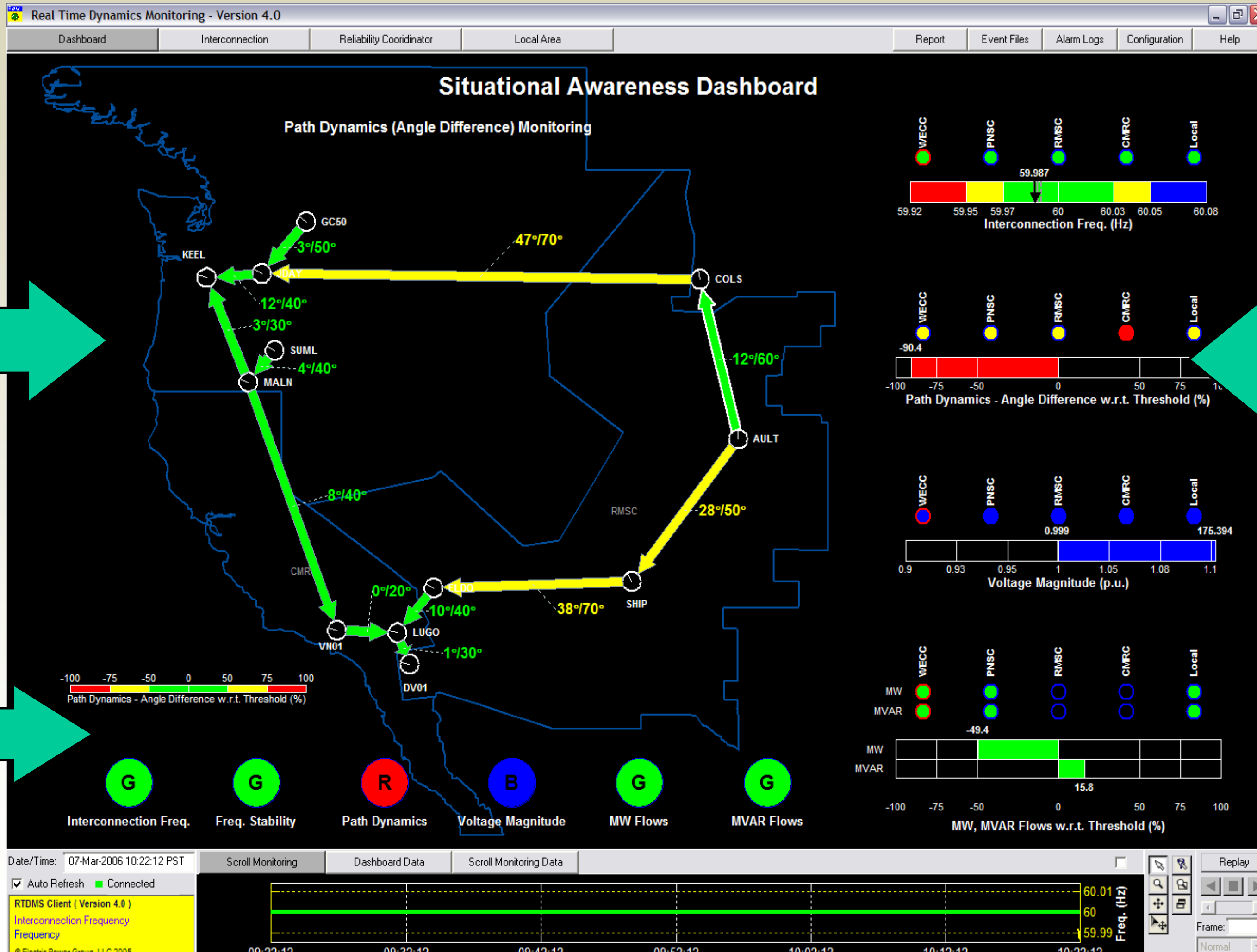
RTDMS Visualization for Reliability Co-ordinators

Angle Difference Shown in Geographic Display

Partitioned into Reliability Coordinator Regions

Monitor status of key metrics



Gauges quantify worst metric

Red indicator provides location information

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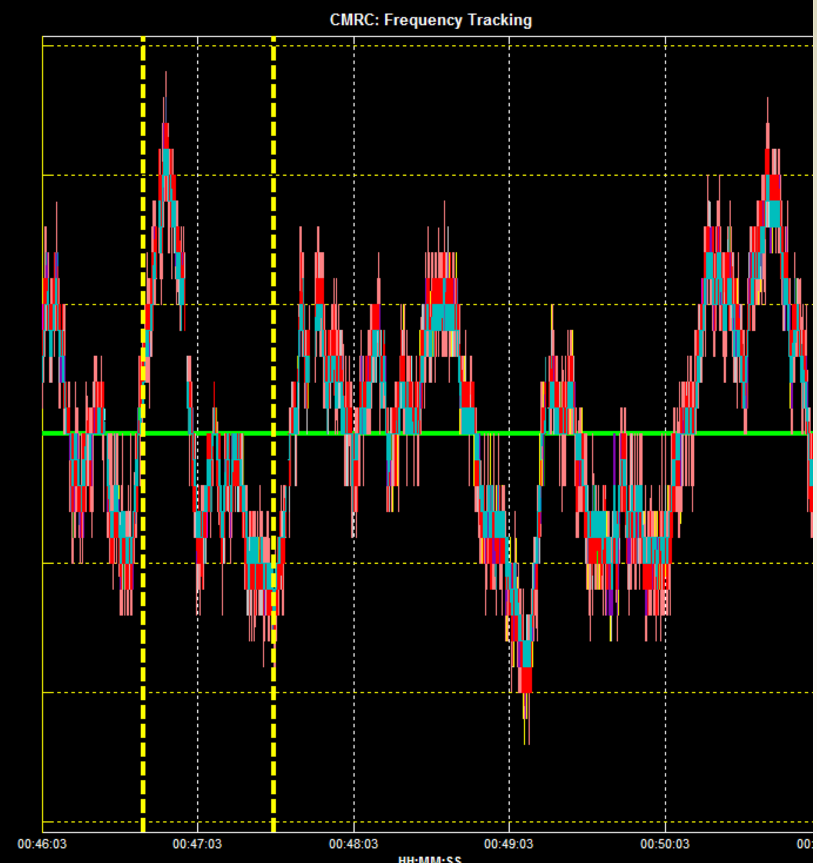
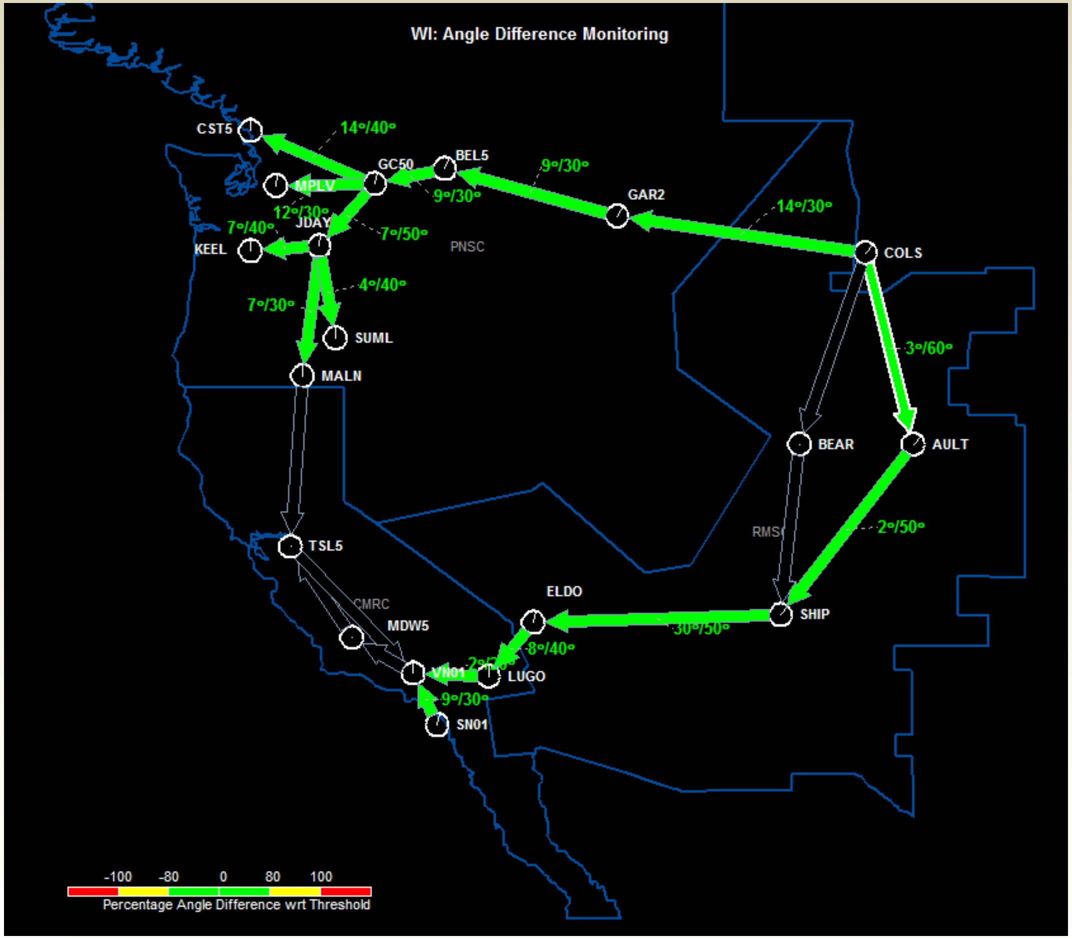
RTDMS Visualization – Frequency Tracking

Deselect All

Select All	Freq1(Hz)	Freq2(Hz)	Delta(Hz)
LOSB	60.002	59.994	-0.008
PTSB	60.002	59.994	-0.008
ML50	60.002	59.993	-0.009
TSL5	---	---	---
DCPP	---	---	---
MDW5	---	---	---
VEST	60.002	59.993	-0.009
SPVL	60.002	59.993	-0.009
RCT2	60.002	59.993	-0.009
RCT1	60.002	59.993	-0.009
SRNO	60.003	59.993	-0.01
MRLM	60.003	59.993	-0.01
LUGO	60.003	59.993	-0.01
ELDO	60.003	59.993	-0.01
MAGN	---	---	---
VALY	60.003	59.993	-0.01
ANTP	60.001	59.994	-0.007
DV02	60.003	59.993	-0.01
SN01	60.002	59.993	-0.009
ALGS	60.002	59.993	-0.009
BC01	60.002	59.993	-0.009
MOGS	---	---	---
VN01	60.002	59.993	-0.009
SYLM	---	---	---
Time (HH:MM:SS)	00:46:43.100	00:47:33.300	Delta(s) 50.2



RTDMS Visualization– Angle Differences Across Control Areas



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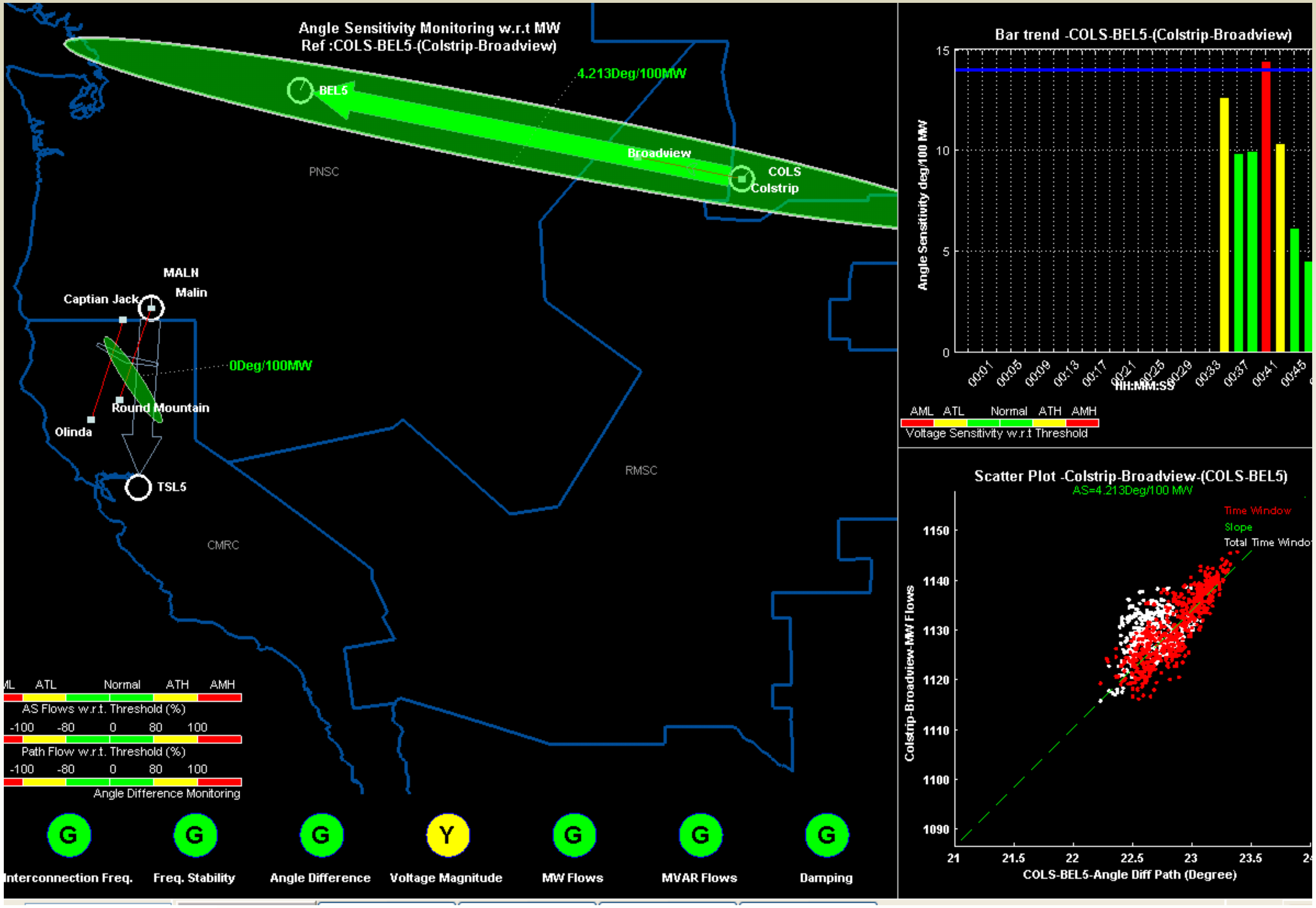
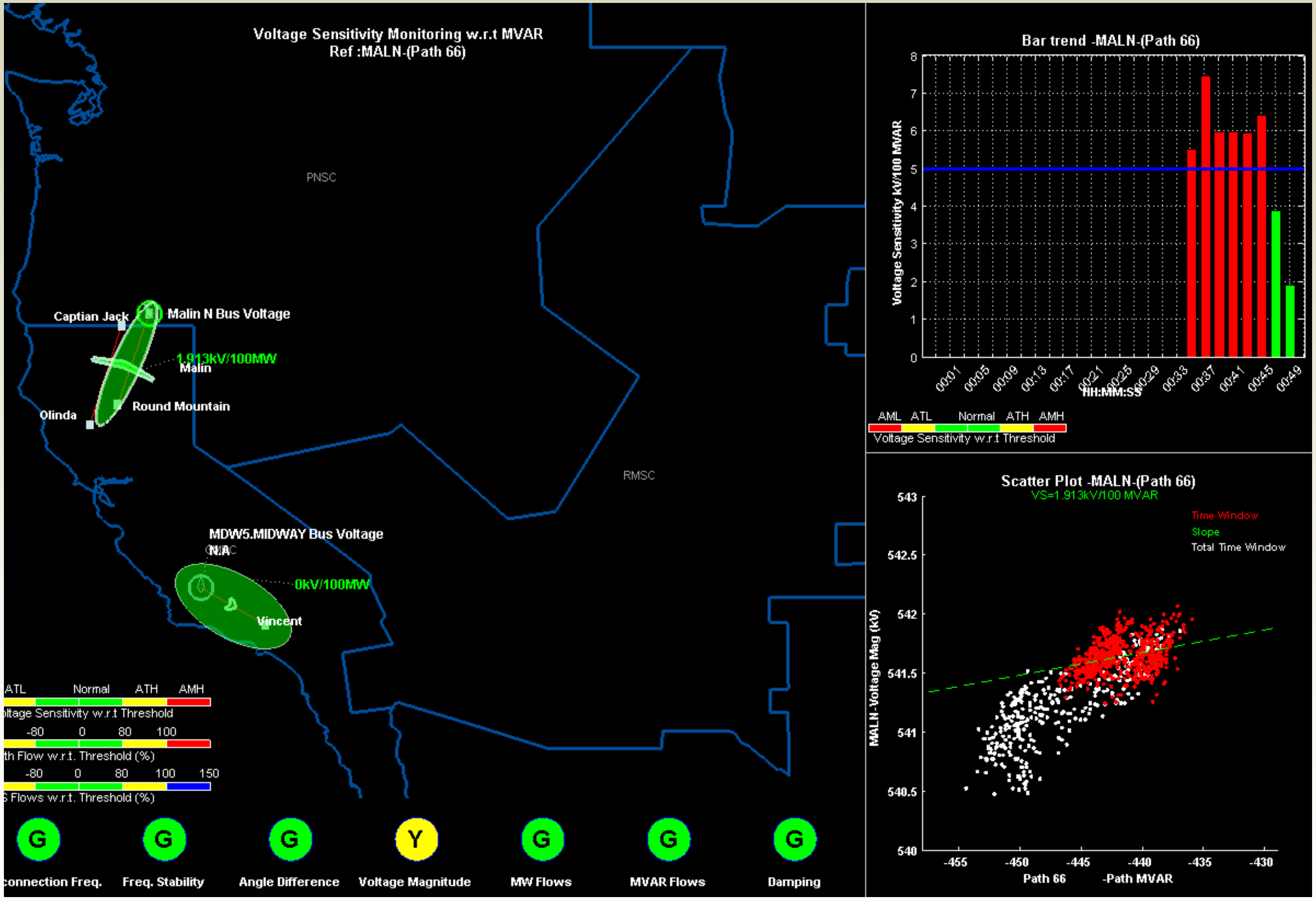
RTDMS Visualization– MW Angle Sensitivities for Colstrip to Bell



RTDMS Visualization– MW Voltage Sensitivities across Path 66



PMU Road Map

IMPLEMENTATION IN CONTROL CENTER

(1) Dispatcher Awareness Tools with PI displays
(2) Oscillation Detection
(3) RTDMS Dynamic Equivalents for Angle Differences
(4) SynchroPhasor Nomograms
(5) Optimal PMU Placement

2009 to 2010

IMPLEMENTATION IN CONTROL CENTER

(6) Migration to ePDC
(7) Synchro-Phasors in State Estimation
(8) PMU Small Signal Stability Analysis in DSA
(9) PMU based Parameter Estimation Methods

2009 to 2013

RESEARCH AND DEVELOPMENT

(1) NASPInet DOE project
(2) PNNL Pilot Project on Characteristic Ellipsoid (CELL)
(3) ePDC Beta testing
(4) PMU University Projects

2011 to 2013

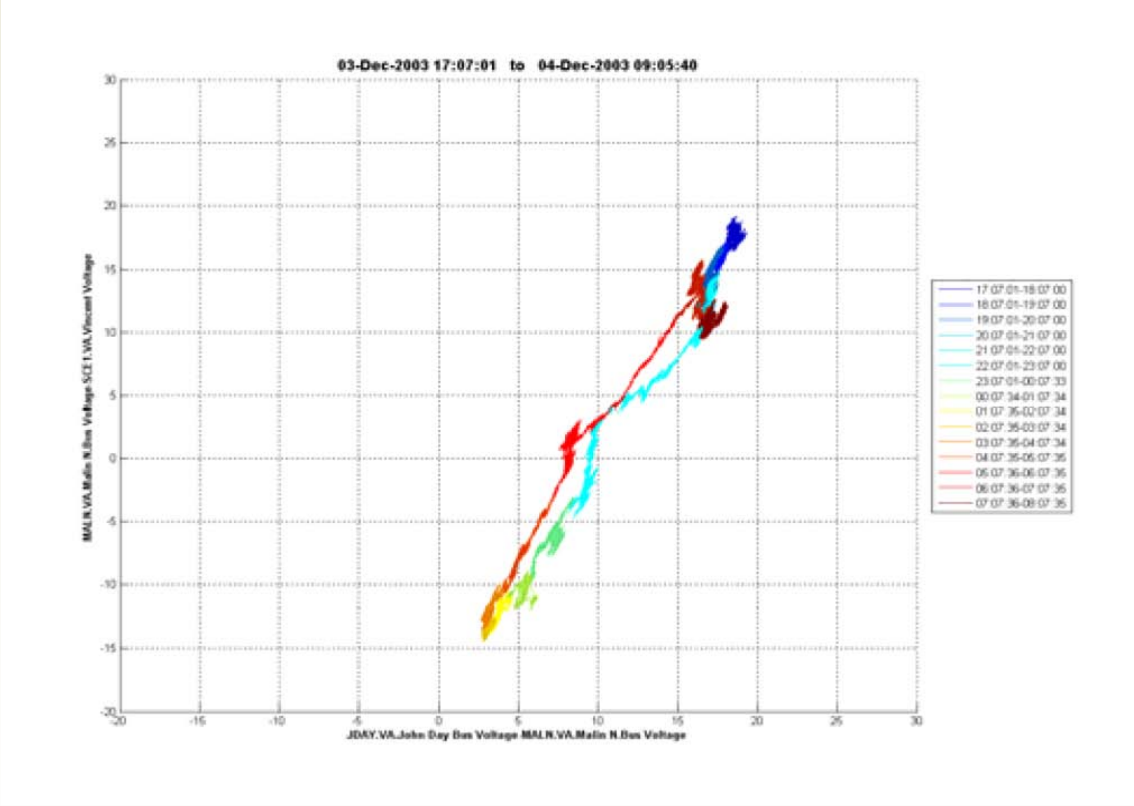
Projects for Control Room Implementation

- Dispatcher Awareness Tools with PI displays
- Oscillation Detection
- Reduced Dynamic Equivalents for Angle Differences
- SynchroPhasor Nomograms
- Optimal PMU Placement
- Improved State Estimation & Small Signal & Dynamic Stability
- PMU Measurement Based Parameter Estimation

Dispatcher Awareness Tools with PI displays

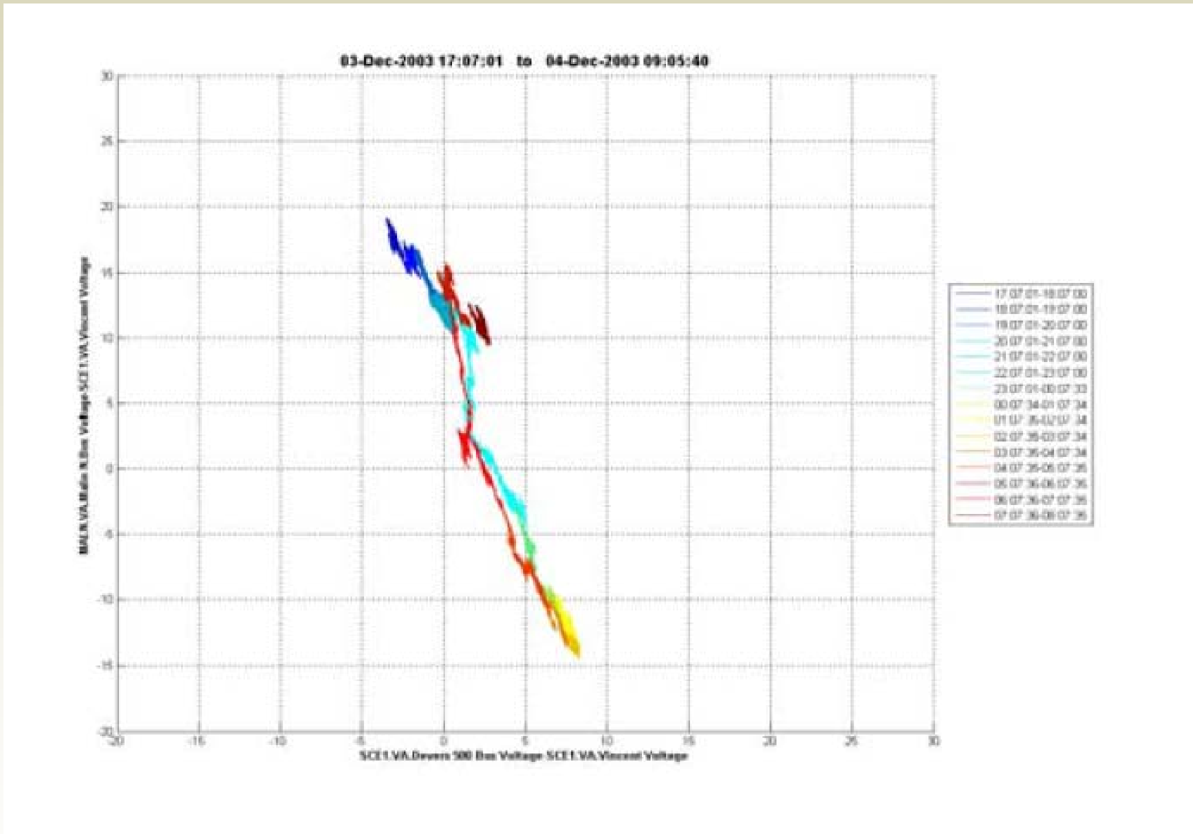
- Selection of important PMU locations to display with PI
    - One option – use Optimal PMU Placement algorithms
- Plots for PMU Pairs
    - Angle Difference versus Angle Difference
    - Frequency versus Frequency using Lissajous Curves
- Replay capabilities in PI of severe disturbances from the archived data

Angle Difference Plots of Vincent - Malin & John Day - Malin for 12 hours



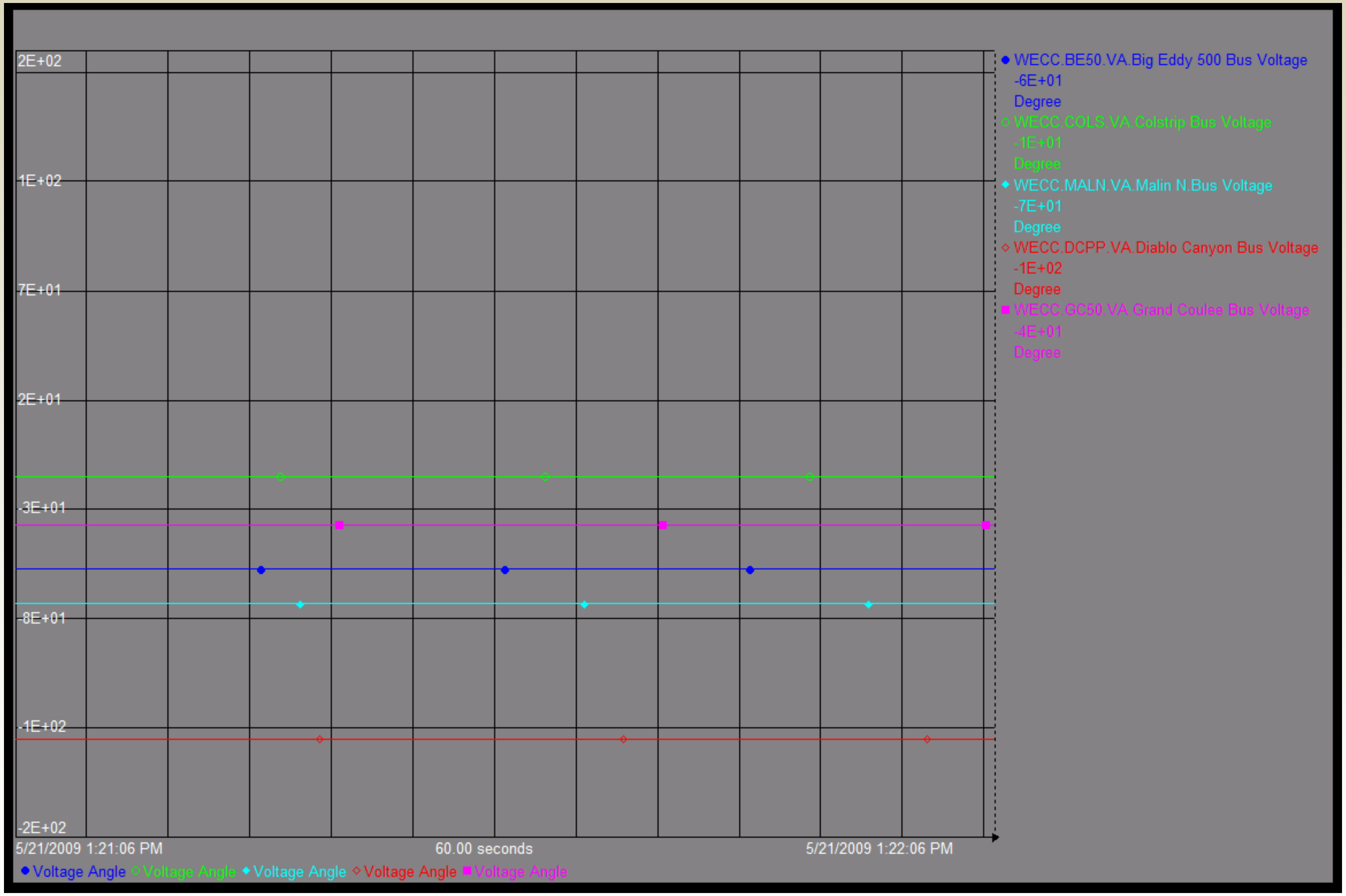
Plot is courtesy of http://certs.lbl.gov/pdf/phasor-feasibility-2008.pdf

Angle Difference Plots of Malin - Vincent & Devers - Vincent for 12 hours



Plot is courtesy of http://certs.lbl.gov/pdf/phasor-feasibility-2008.pdf

60 seconds of Angles in PI of Big Eddy & Diablo & Colstrip & Chief Joseph & Malin



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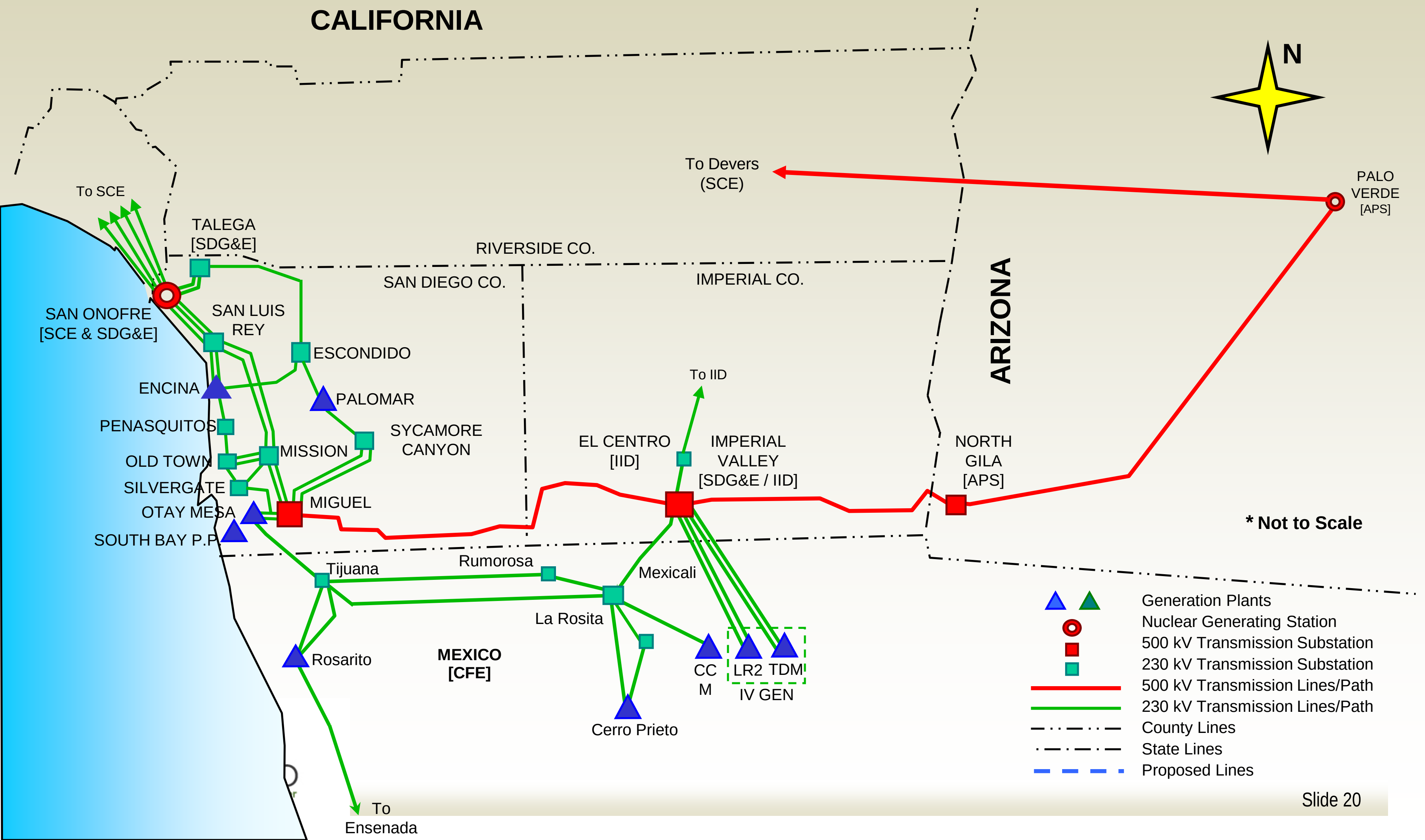
SDG&E Area - Using State Estimator to calculate Angle Differences

- <u>Not</u> much change in Angles in 60 seconds
- State Estimator cycles every 60 seconds
- State Estimator can “fill in” for <u>non PMU</u> Angles
- Example – CAISO has no connection to any PMU from SDG&E
- Planned SWPL outage of <u>May 16-17 2009</u>

SDG&E Area - Using State Estimator to calculate Angle Differences

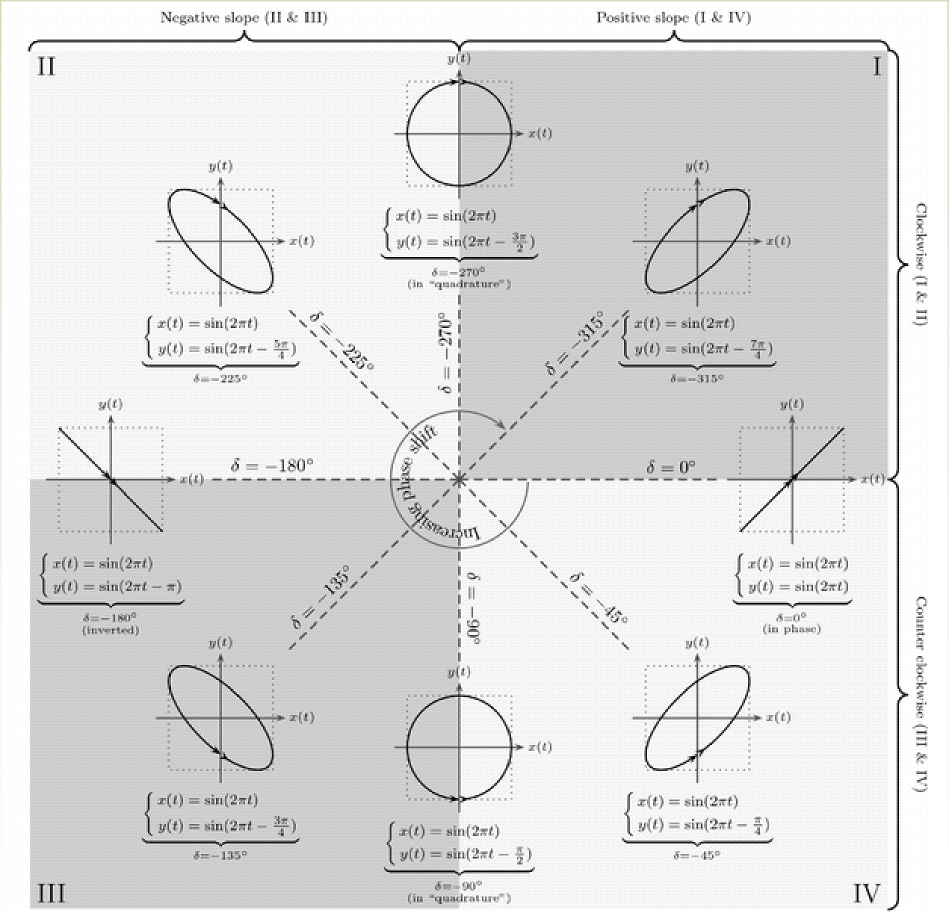


Angles for the May 16-17 2009 SWPL outage from State Estimator

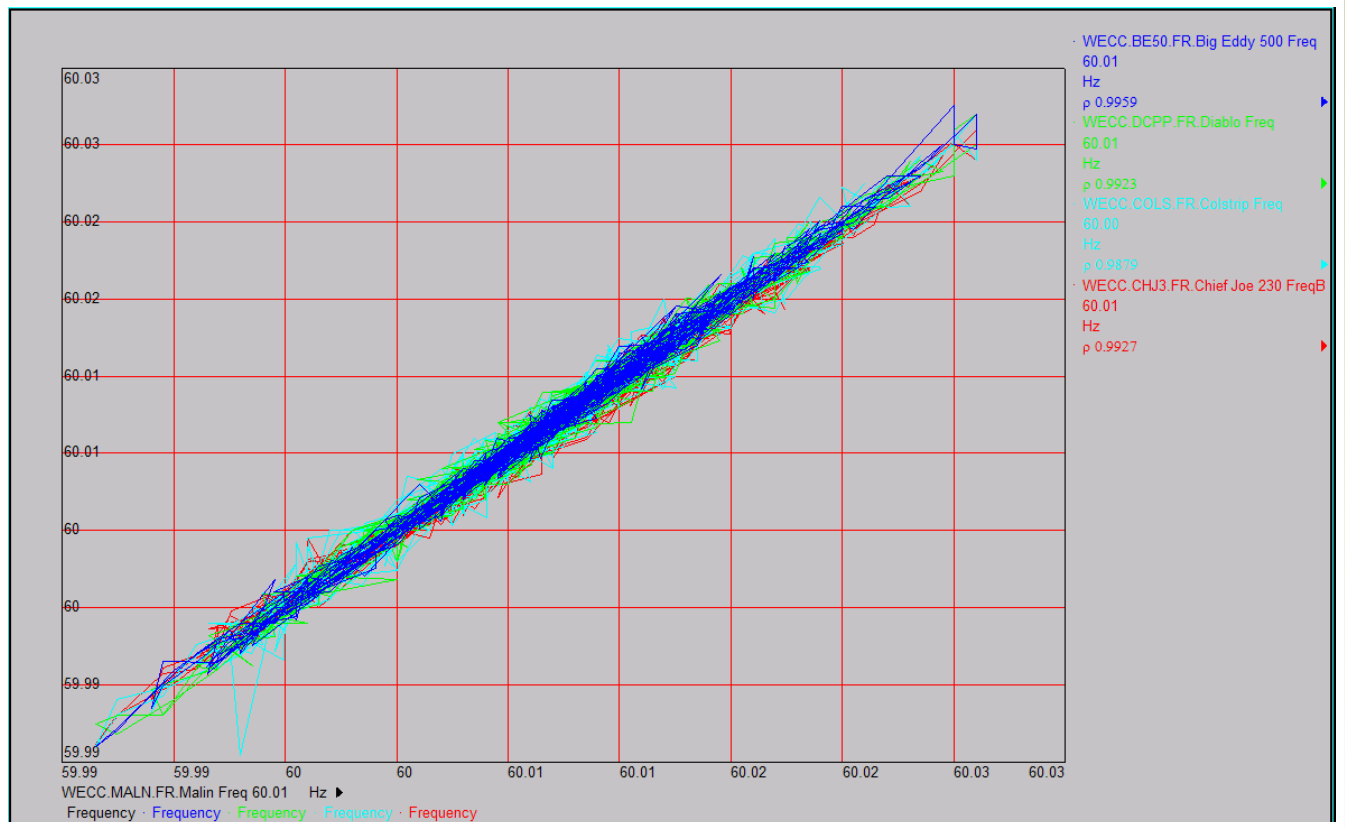
	Note: Angles Computed by State Estimator		TL50001 OUTAGE PHASE ANGLES	*Note : SDGE PMU at Miguel 500 & 230 Not connected to CAISO PMU Network*	
Voltage	**Station Name & Bus**	**Fri May 15 09 1800 hrs**	**Sat May 16 09 1700 hrs**	**Sun May 17 09 1730 hrs**	**Mon May 18 09 1030 hrs**
500 KV	SDIVALY5 North Bus	Plus 3.1 degrees	0 degrees Split Bus	0 degrees Split Bus	Plus 5.9 degrees
500 KV	SDIVALY5 South Bus	Plus 3.1 degrees	Plus 29 degrees Split Bus	Plus 32 degrees Split Bus	Plus 5.9 degrees
230 KV	SDIVALY2 North Bus	Plus 3.9 degrees	Plus 28 degrees	Plus 30 degrees	Plus 4.8 degrees
230 KV	SDIVALY2 South Bus	Plus 3.9 degrees	Plus 28 degrees	Plus 30 degrees	Plus 4.8 degrees
500 KV	SDMIGUL5 BusBar 1	Minus 6.5 degrees	0 degrees	0 degrees	Minus 3.5 degrees
500 KV	SDMIGUL5 BusBar 2	Minus 6.5 degrees	0 degrees	0 degrees	Minus 3.5 degrees
500 KV	SDMIGUL5 BusBar 3	Minus 6.5 degrees	0 degrees	0 degrees	Minus 3.5 degrees
230 KV	SDMIGUL2 North Bus	Minus 9.1 degrees	Plus 2 degrees	Plus 11 degrees	Minus 7 degrees
230 KV	SDMIGUL2 South Bus	Minus 9.1 degrees	Plus 2 degrees	Plus 11 degrees	Minus 7 degrees

Lissajous Curve Methodology

http://en.wikipedia.org/wiki/File:Lissajous_phase.png



10 min of Frequency versus Frequency in PI using Lissajous Curve Methodology



Big Eddy & Diablo & Colstrip & Chief Joseph on the Y axis and Malin on the X Axis

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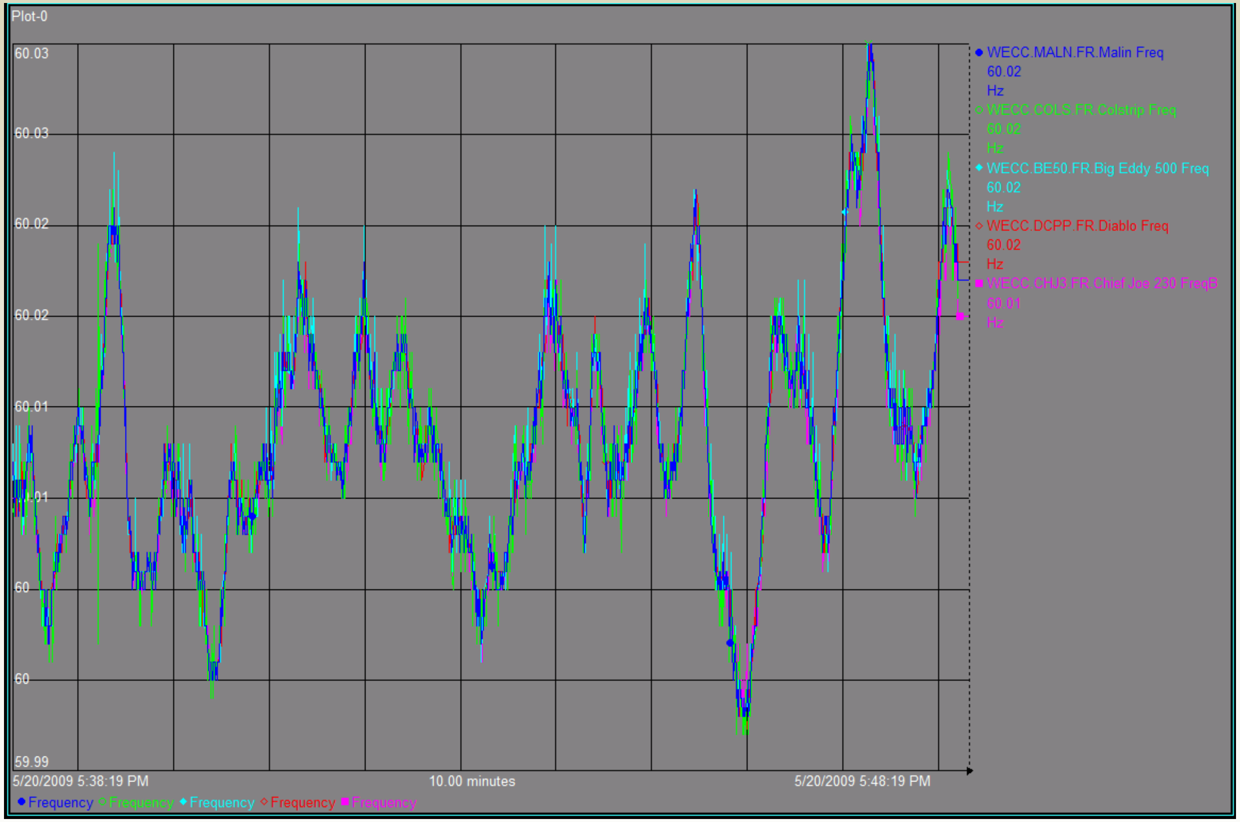
10 min Frequency Plots in PI of Big Eddy & Diablo & Colstrip & Chief Joseph & Malin



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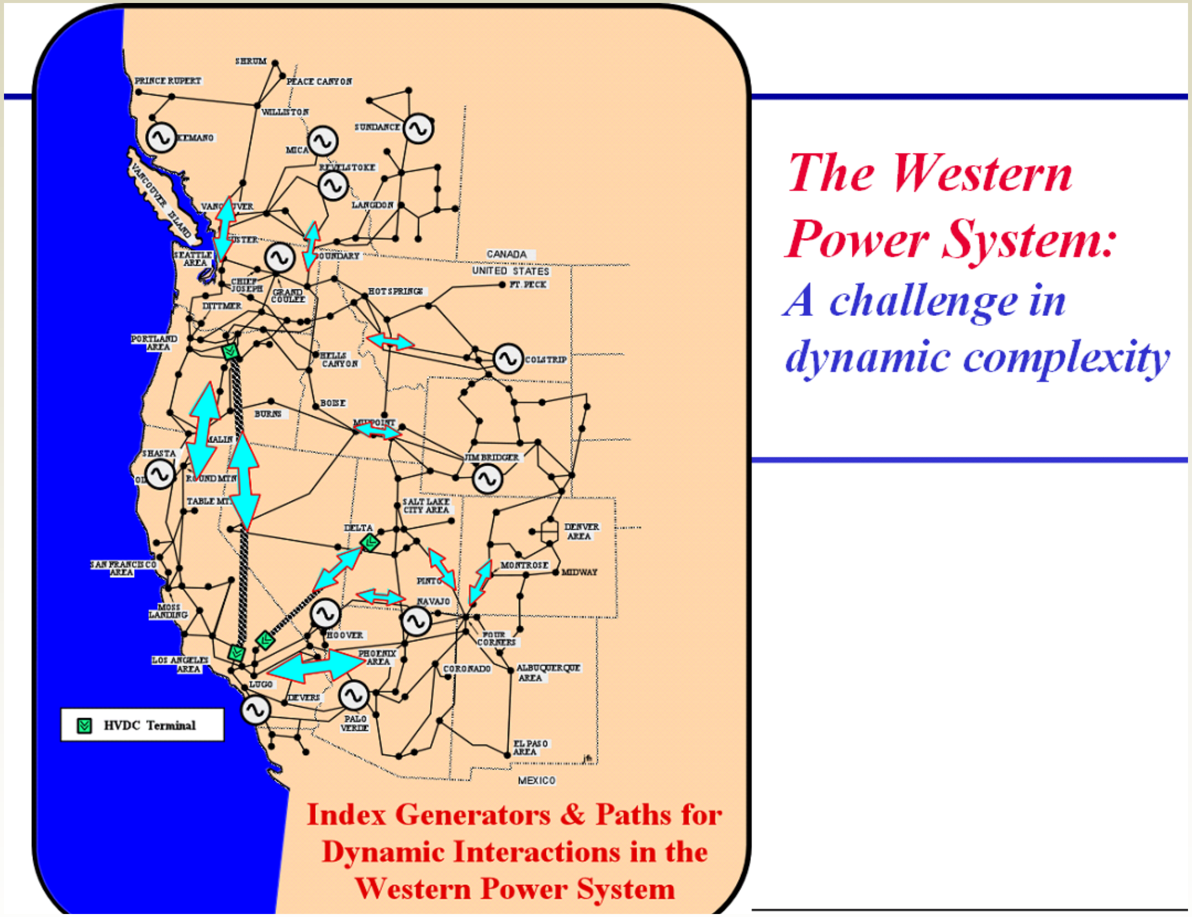
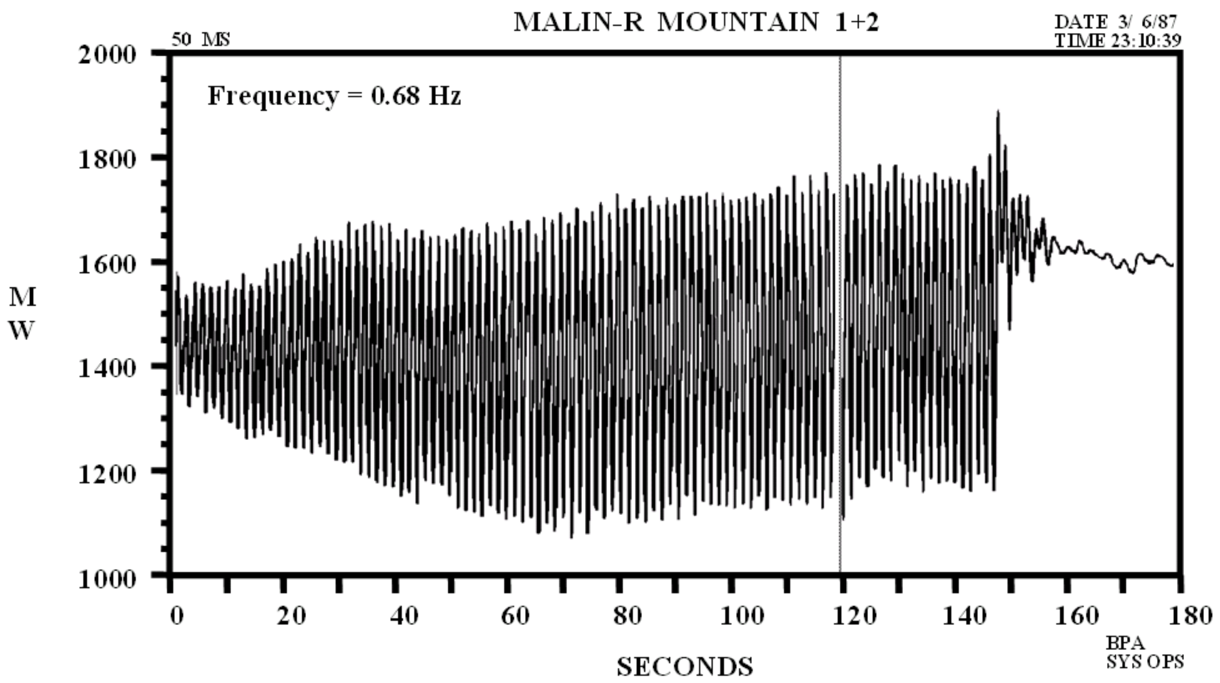
WECC map of modes – Source WECC



Mar 06 1987 MW Oscillation – Source DOE Report

Latest major oscillations with WECC transmission intact:
Produced by feedback controller on IPP HVDC line, March 6, 1987.



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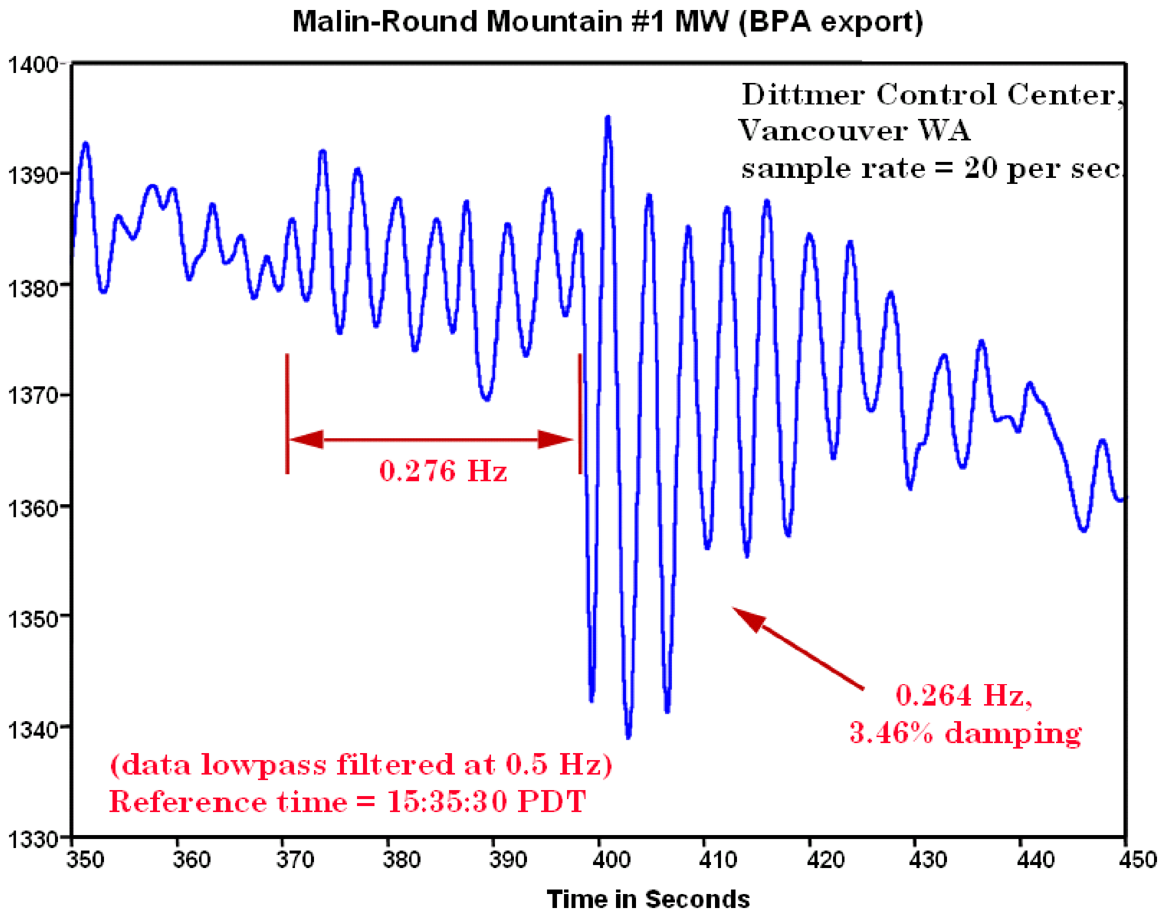
Aug 10 1996 MW oscillation – Source DOE Report

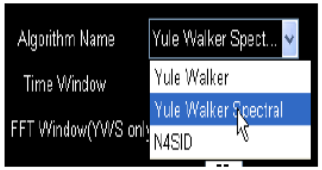


Small Signal Stability Algorithms from Montana Tech – Source RTDMS

- Performs modal analysis on **ambient data**

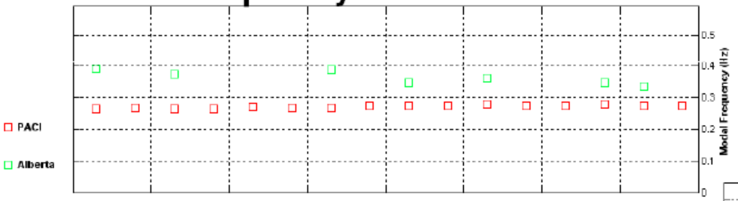
  ----User defined mode observability clusters

  ----Choice of three algorithms *1. Yule Walker*
  2. Yule Walker Spectral
  3. N4SID



- Provides ***three*** plots for ***each*** modal estimate:

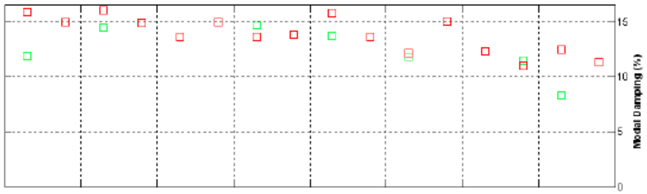
1- Modal Frequency Trends



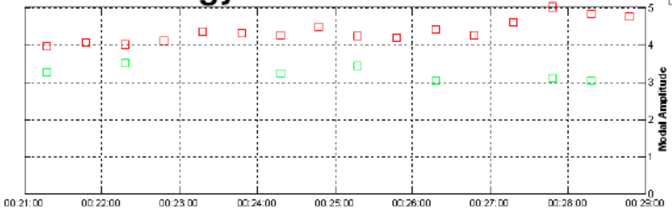
Shows the trend of modal frequency over a period of time.

2- Modal Damping Trends

Shows the trend of modal damping(%) over a period of time.



3- Modal Energy Trends

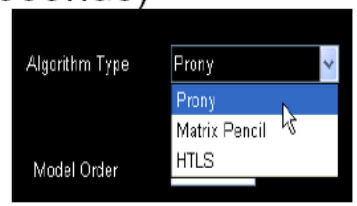


Shows the trend of modal energy over a period of time.

Small Signal Stability Algorithms from Washington State – Source RTDMS

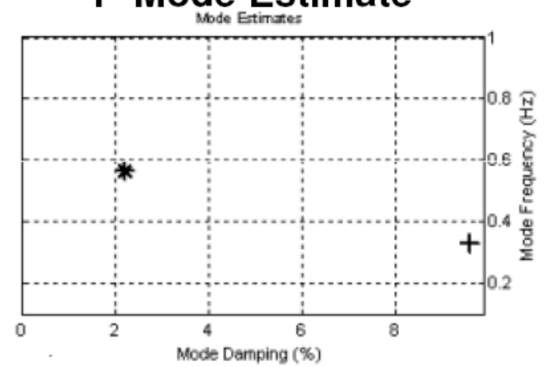
- Modal analysis on **post-event data (**~10-20 seconds)

-----Choice of three algorithms *1.Prony*
2.Matrix Pencil
3.HTLS



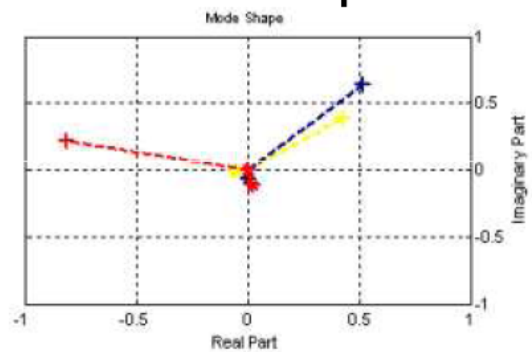
- Provides ***three*** plots:

1- Mode Estimate



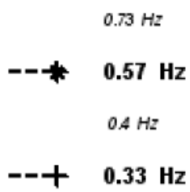
Shows plot of mode frequency versus mode damping.

2- Mode Shape



Shows phase angle information i.e. which modes are out of phase and which are in phase.

Modal Frequencies



Different symbols are used for different frequencies or modes.

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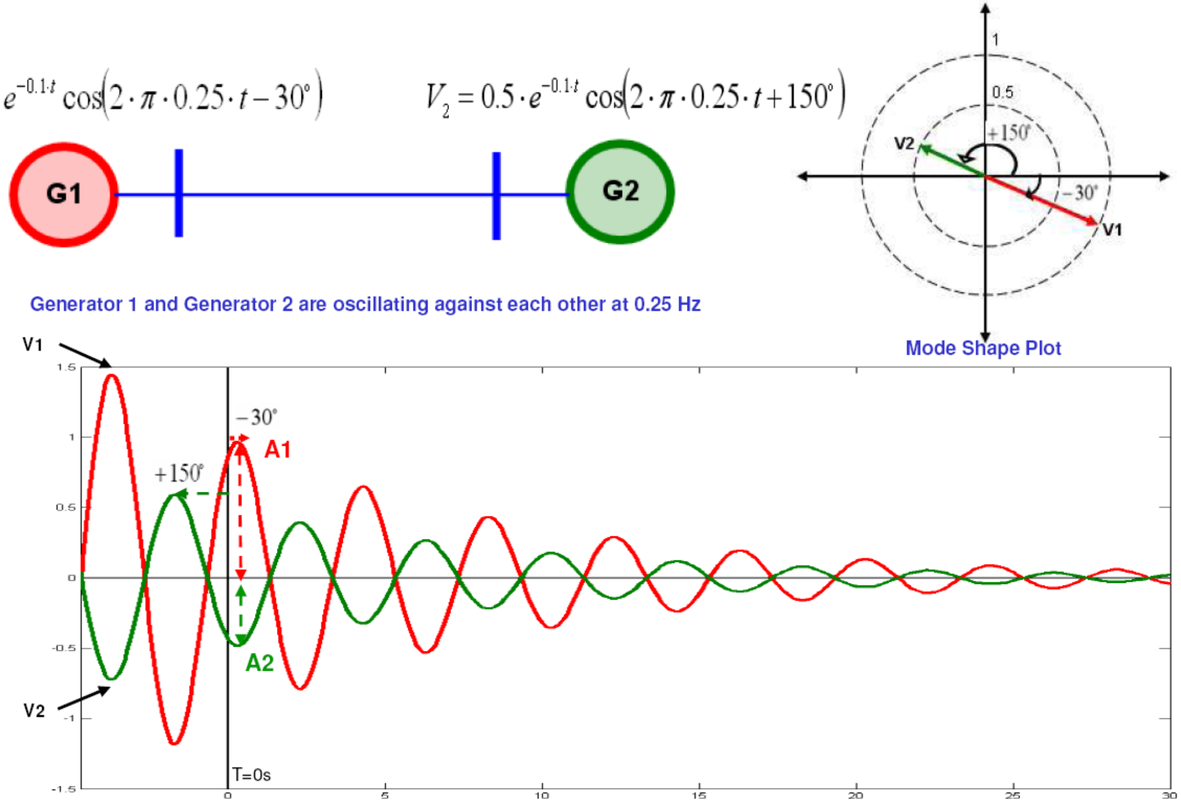
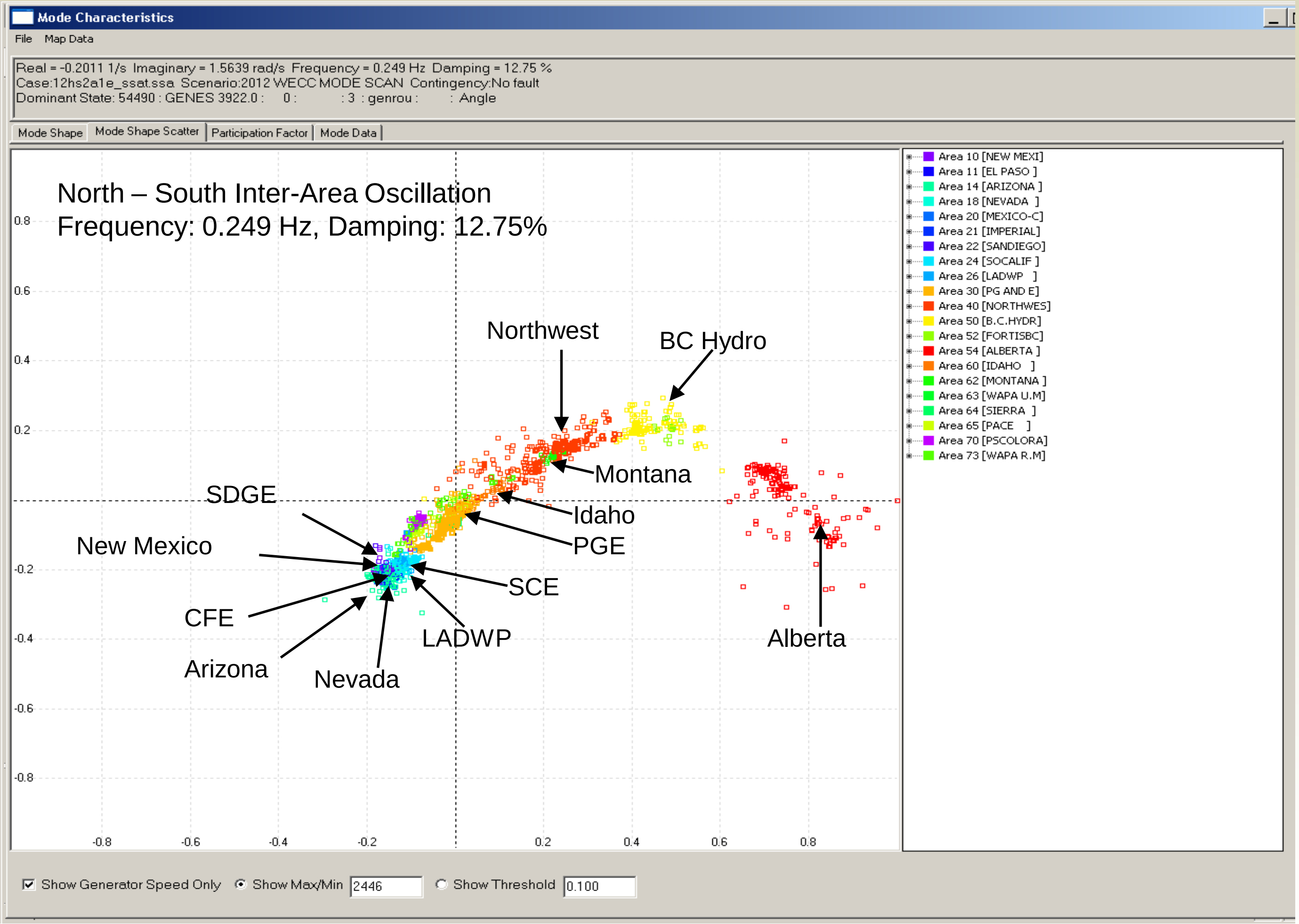
The simplest model that has a 180 degree mode shape – Source EPG

Mode Shape

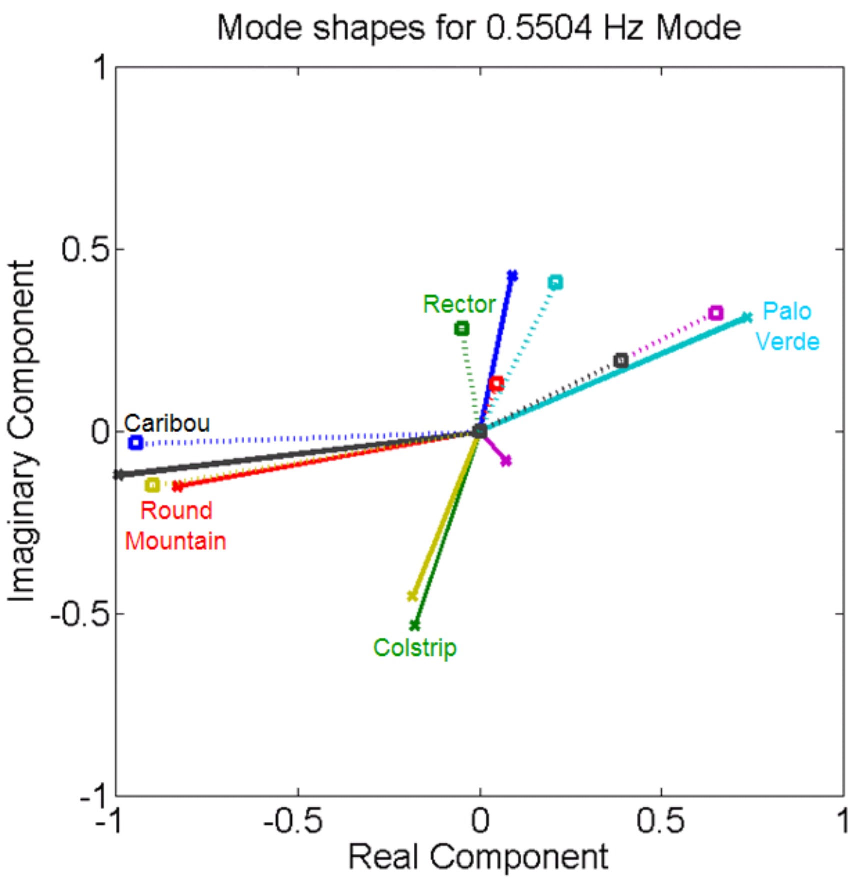
$$V_1 = 1 \cdot e^{-0.1 \cdot t} \cos\left(2 \cdot \pi \cdot 0.25 \cdot t - 30^\circ\right) \qquad V_2 = 0.5 \cdot e^{-0.1 \cdot t} \cos\left(2 \cdot \pi \cdot 0.25 \cdot t + 150^\circ\right)$$



Example of Mode Shapes in WECC – Source Powertech SSAT



Example of Mode Shapes in WECC – Source PNNL



Pacific Northwest NATIONAL LABORATORY

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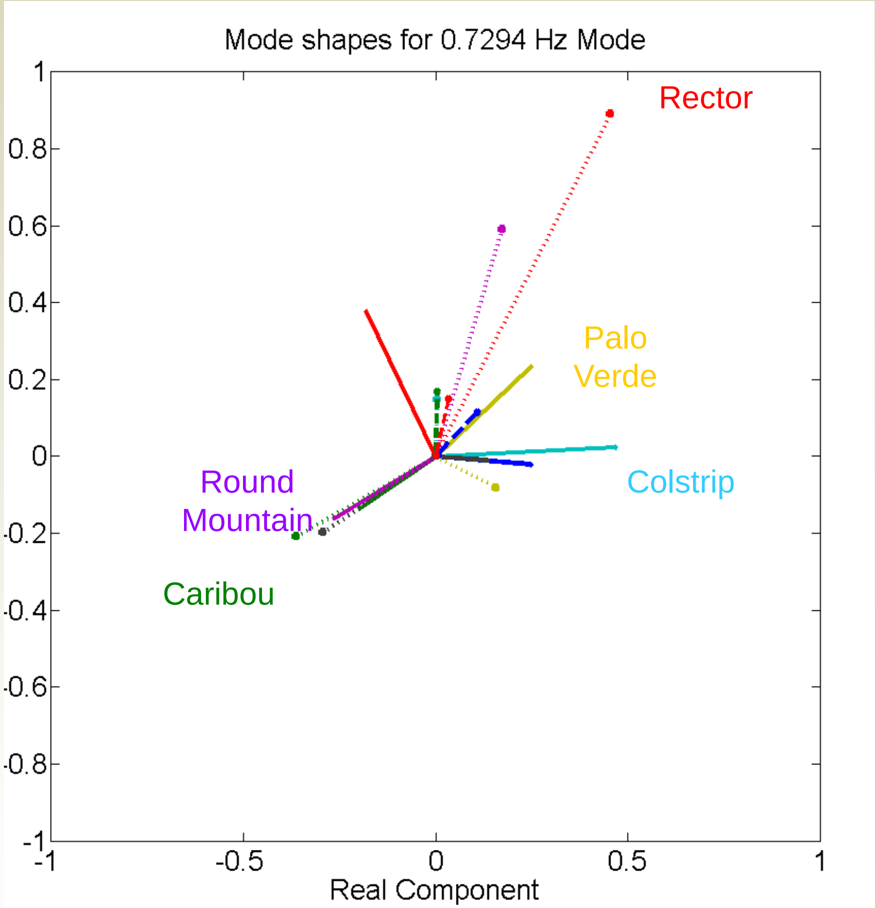
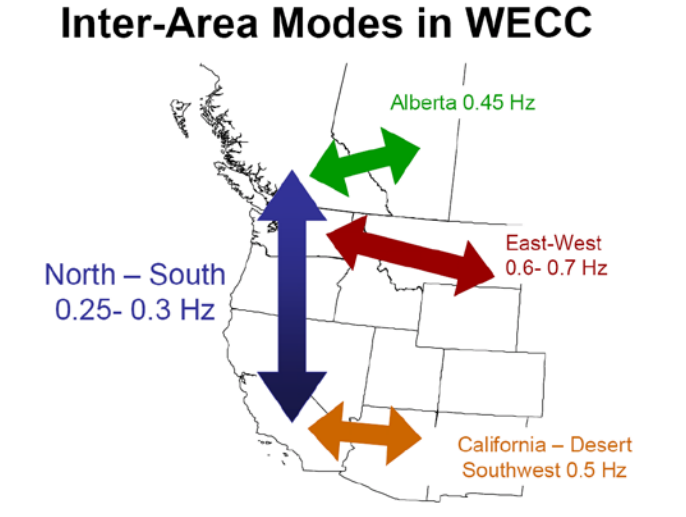
Example of Mode Shapes in WECC – Source PNNL



Controls for Oscillation Damping – Some Solutions

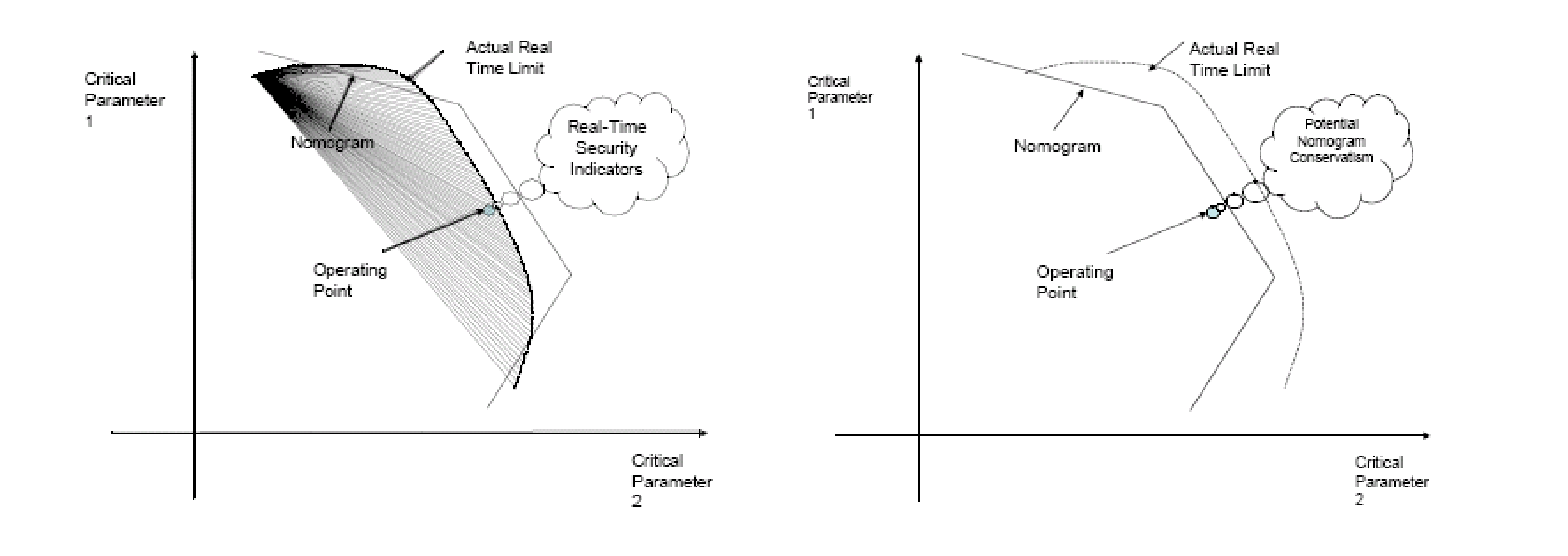


- Small Signal Stability applications with mode meters for damping & eigenvalue calculation.
- HVDC modulation control has significant potential to dampen oscillation.
- Major imports of energy from renewable resources in Pacific NW and Wyoming by 2014.
- 100 MW injections from Thyristors at either end of the COI lines will dampen the oscillations.
- Bottleneck is latency of communication between North & South end of COI.

Reduced Dynamic Equivalents for Angle Differences

- Make a list of all “reasonable pairs” of PMU locations.
- For each PMU pair archive the MW-Angle sensitivity for several weeks.
- For a two area system, zero MW-Angle sensitivity implies angular instability.
- So if MW-Angle sensitivity changes sign without collapse reject the two area equivalent.
- Either need a reduced three area equivalent or a new two area equivalent.
- Repeat System Studies with different operating conditions and contingencies.
- Such studies will validate reduced dynamic equivalents of two or three area systems.

SynchroPhasor Nomograms



Potential “hole” in the nomogram & Potential “conservatism” in nomogram

Plot is courtesy of http://certs.lbl.gov/pdf/phasor-feasibility-2008.pdf

Optimal PMU Placement

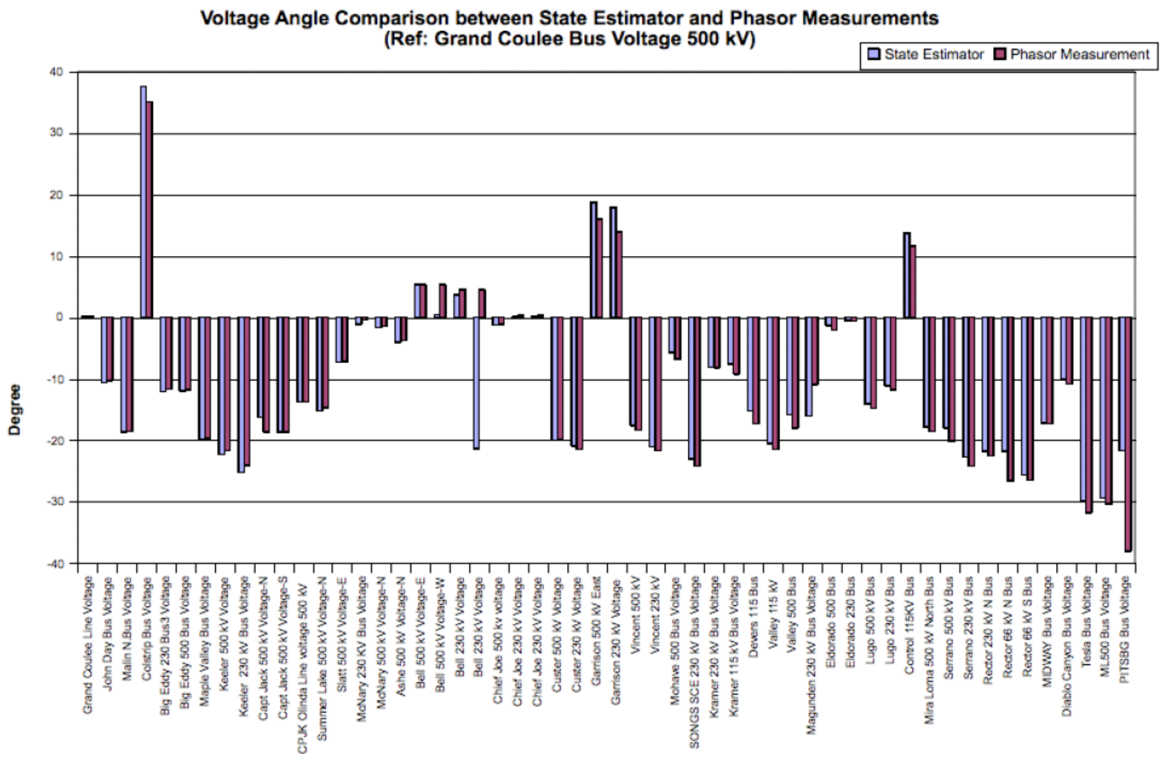
- Objective of the placement problem is that the entire network is a single observable island
- Case studies carried out by PSERC at TVA using only PMU telemetry
- With only one third of the system buses, the entire system can be made observable
- Also zero injection buses will significantly reduce the required number of PMU devices
- Optimization scheme may yield different sets of optimal solutions
- Same minimum PMU number but at different locations – Need additional objectives
- PMU telemetry will enhance bad data detection and identification

Phasor Data & State Estimation Data

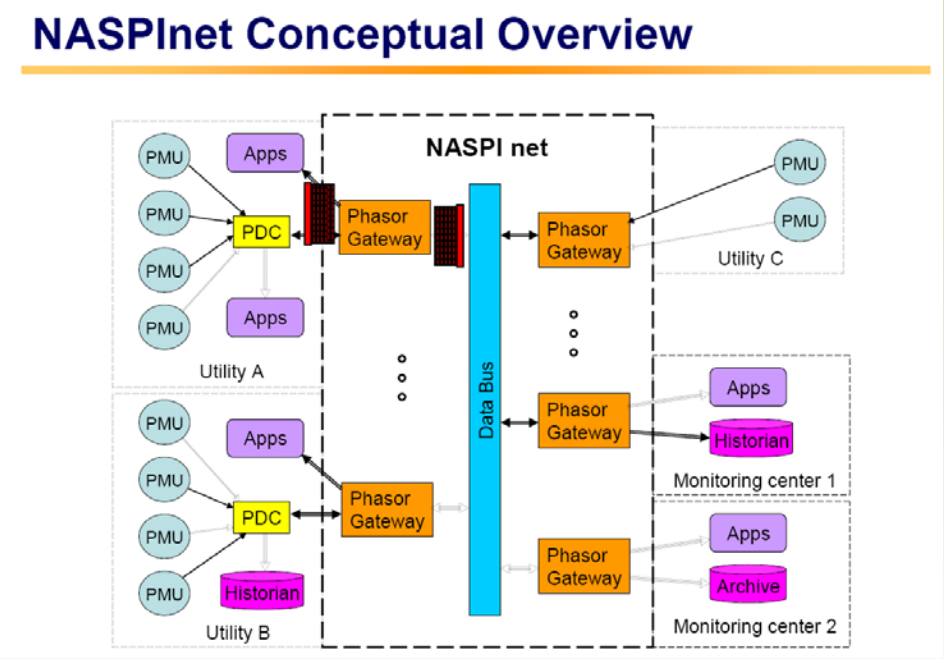
- Key state variable in state estimation is the voltage phase angle
- This was not available as a measurement before
- Direct measurement of voltage and current phase angles
- The improvement on state estimation depend on
  - PMU locations
  - Number of PMU devices
  - Calibration of PMU devices
  - PMU measurement accuracy
  - Related SCADA data accuracy
  - Synchronization between PMU data & SCADA snapshots

Phasor Data and State Estimator Data Comparison

Voltage Angle Comparison *(in degrees)*



R&D - NASPInet and Phasor data repository



- NASPInet overview - courtesy of http://www.quanta-technology.com/
- An entity in WECC will store 5 years of regional frequency data
- NERC has not yet set a data retention standard for phasor data
- 6 weeks is a reasonable period unless there has been a significant event
- Then the retention period is 120 to 180 days

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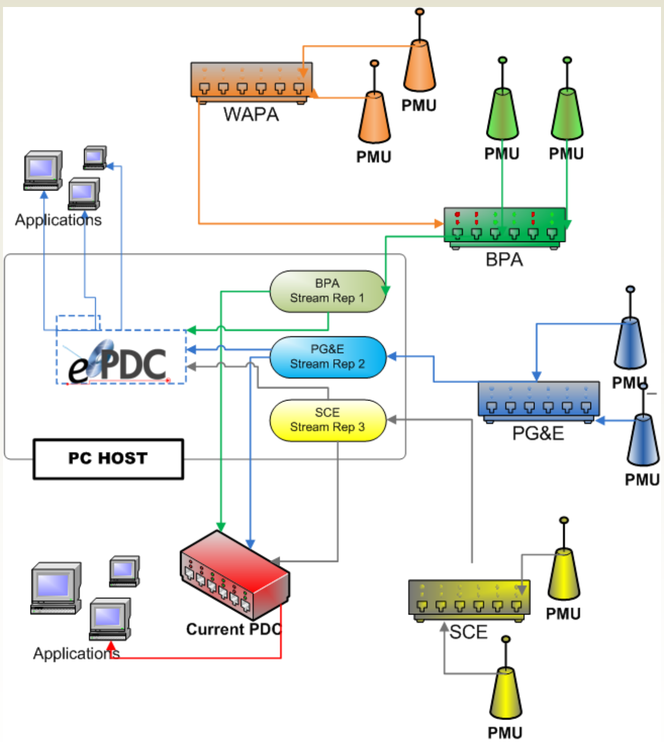
R&D - ePDC Beta Parallel Acceptance Test

- Data feeds to CAISO using UDP/IP protocol
- Routing to PDC by IP address and port number
- Communications are over T1 private leased line
- Addressing and routing are setup and managed by IT
- Schematic – courtesy of http://electricpowergroup.com



Acknowledgements

David Hawkins	California ISO
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Vikram Budhraja	Electric Power Group
Damir Novosel	Quanta Technology
Ken Martin	EPG & Quanta