Synchronized Phasor Measurement System Technologies for improving Power system reliability

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Presentation Outline

- Review of Past Major Disturbances
- Lessons Learned from Major Blackouts
- What are Phasors / Synchro-Phasors?
- Value of Phasors over SCADA systems
- Use of Phasor Technology by Operators
- Synchro-Phasor Tools for Real Time Monitoring
- EPG Synchrophasor Applications
- Use of Synchrophasor Technology at CAISO
- Conclusions / Summary

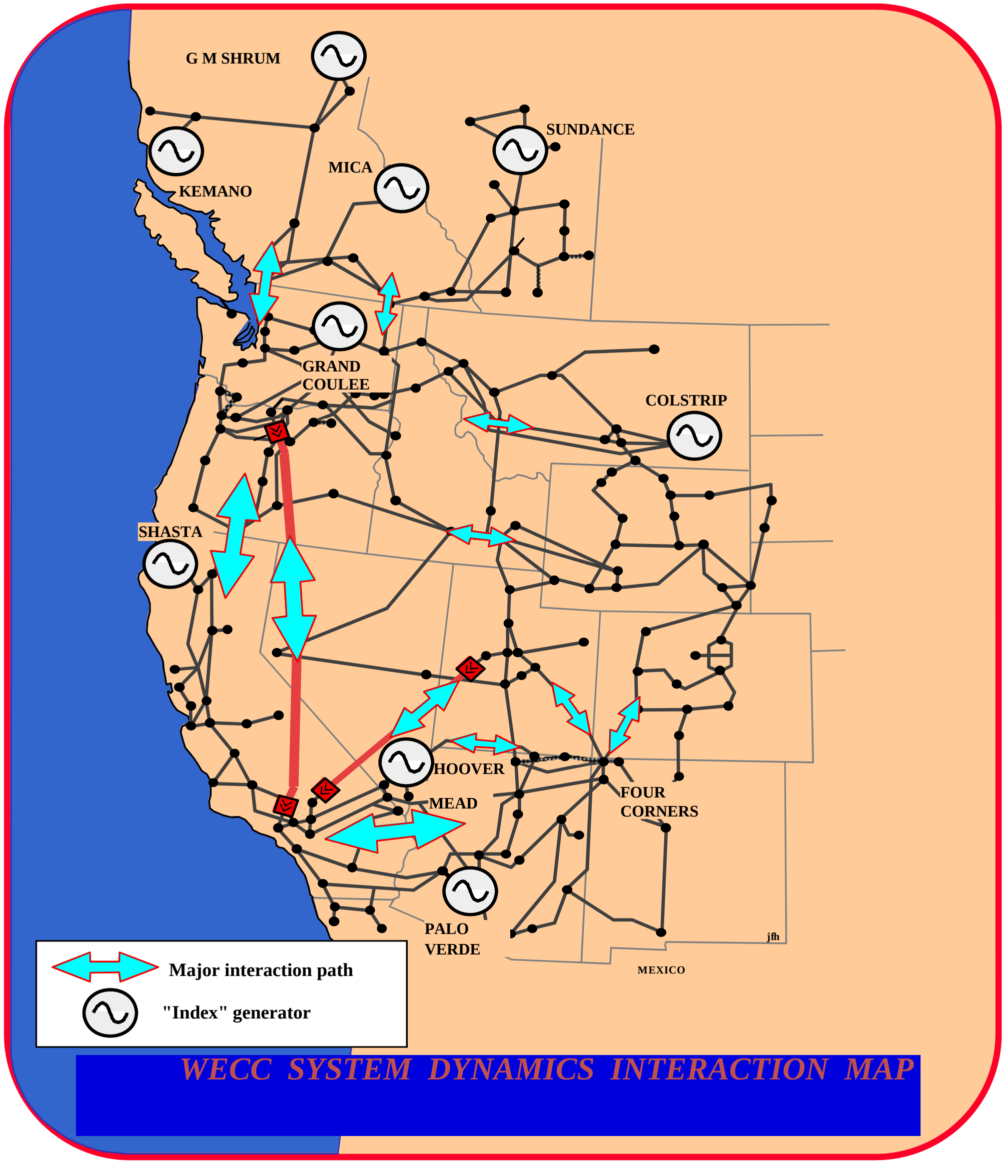
Review of Some Past Major Disturbances

- WECC Disturbance – August 10, 1996
- Eastern Interconnection Disturbance –August 14, 2003
- San Diego/IID/CFE Disturbance – September 8, 2011

WECC (US) Disturbance – August 10, 1996

- Highly stressed system conditions and hot weather
- Transmission lines overload and sag into trees and trip one after the other (cascading outages)
- System weakens but operators are not able to see the weakening of the system – when systems are stressed, the VAR demand on generator increases
- Generators are over-stressed and trip after some time under stressed conditions
- System continues to see increase in stress but no corrective action is taken
- Large growing power swings occur between Northwest and Southwest leading to system separation

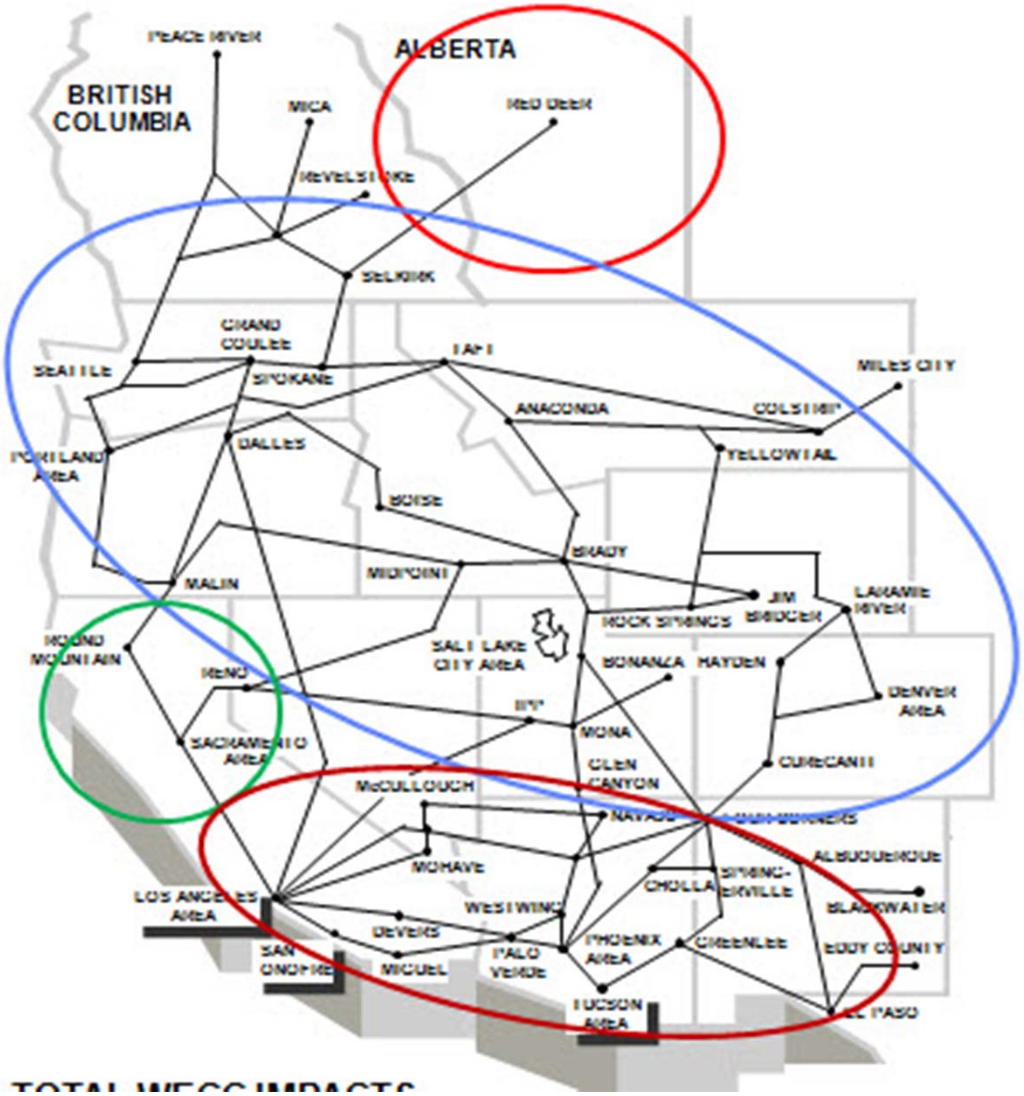
WECC System Disturbance – 8/10/1996



Sequence of Events leading to system break up

1. Large Power Transfers from North to South on AC & DC systems
2. High angle difference between Grand Coulee and Vincent / Devers / Sylmar in South
3. Lines trip resulting in angle increase and high VAR demand on generators
4. Loss of generators result in weakening voltage support near COI
5. System separates because of North-South system oscillations
6. WECC System splits into four islands

WECC August 10, 1996 Event

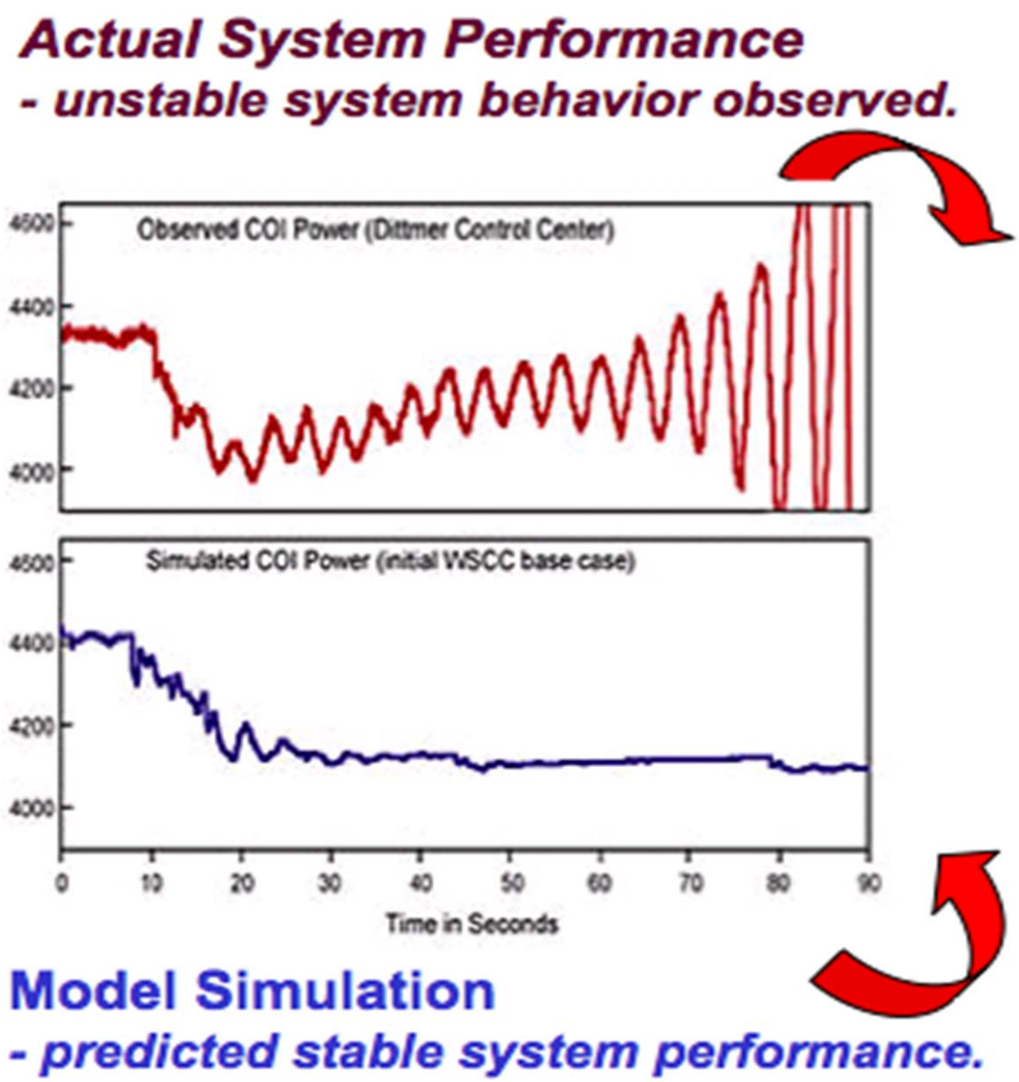


<u>TOTAL WECC IMPACTS</u>

Load lost:	**30,489 MW**
Generation lost:	**27,269 MW**
Customers affected:	**7.49 million**
Outage time:	**Up to 9 hours**

Inaccurate Dynamic Models

WECC 1996 Breakup

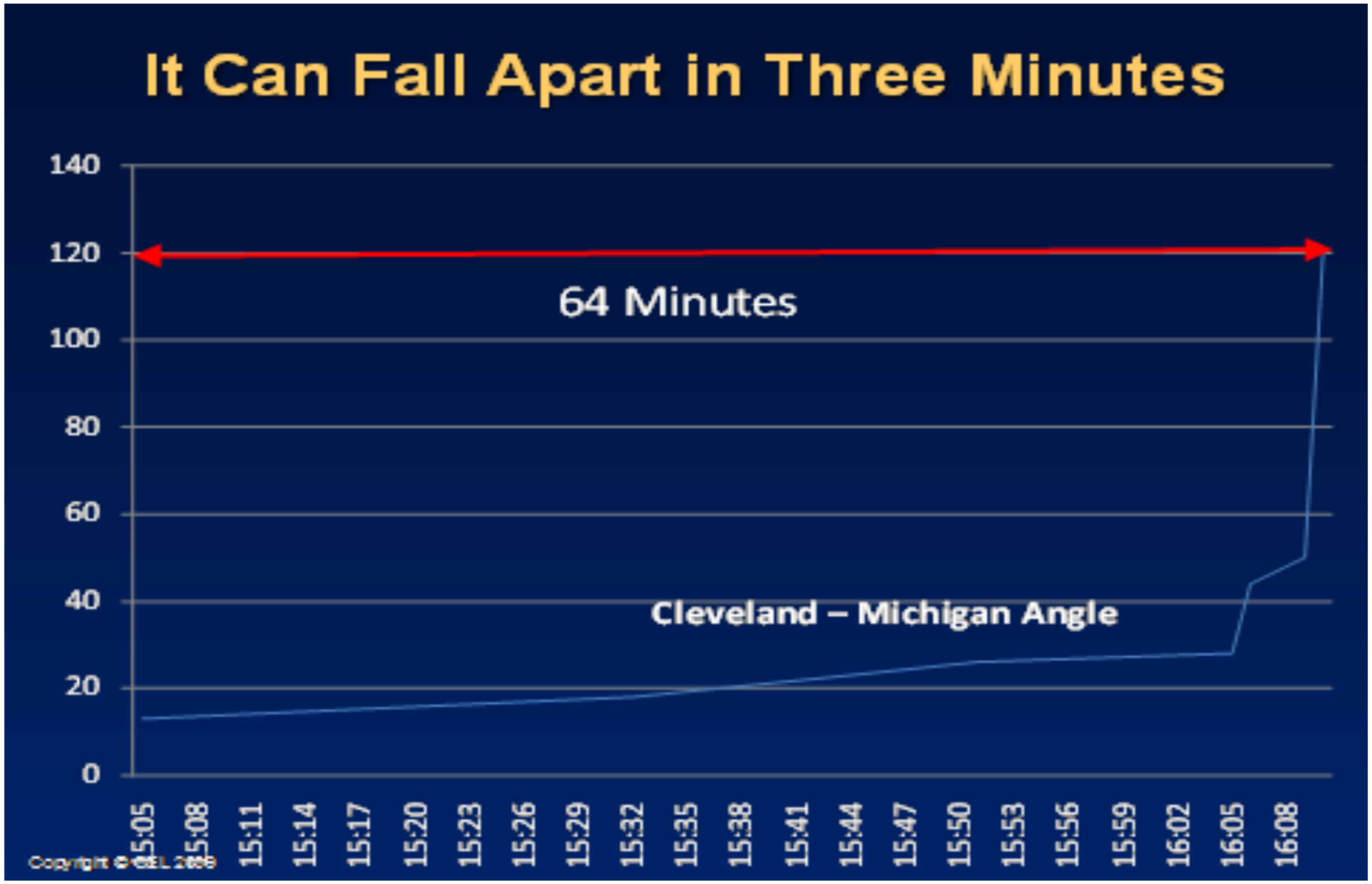


Northeast US-Canada System Disturbance – August 14, 2003

- Highly stressed system conditions and hot weather
- Transmission lines overload and sag in to trees and trip one after the other in Michigan & Ohio
- System weakens but operators are not able to see the weakening of the system
- Generators are over-stressed and trip after some time under stressed conditions
- System continues to see increase in stress but no corrective action is taken
- Large power swings occur between Midwest and Eastern US and Canada
- System is separated and results in blacking out part of Northeast and New York

August 14, 2003 Blackout

Cleveland Separation – Phase Angle Difference Started Increasing 1 hr Prior



Note: Angles are based on data from blackout investigation. Angle reference is Browns Ferry.

Phase Angles Diverged Prior To Blackout

SAN DIEGO SYSTEM BLACKOUT ON SEPTEMBER 8, 2011

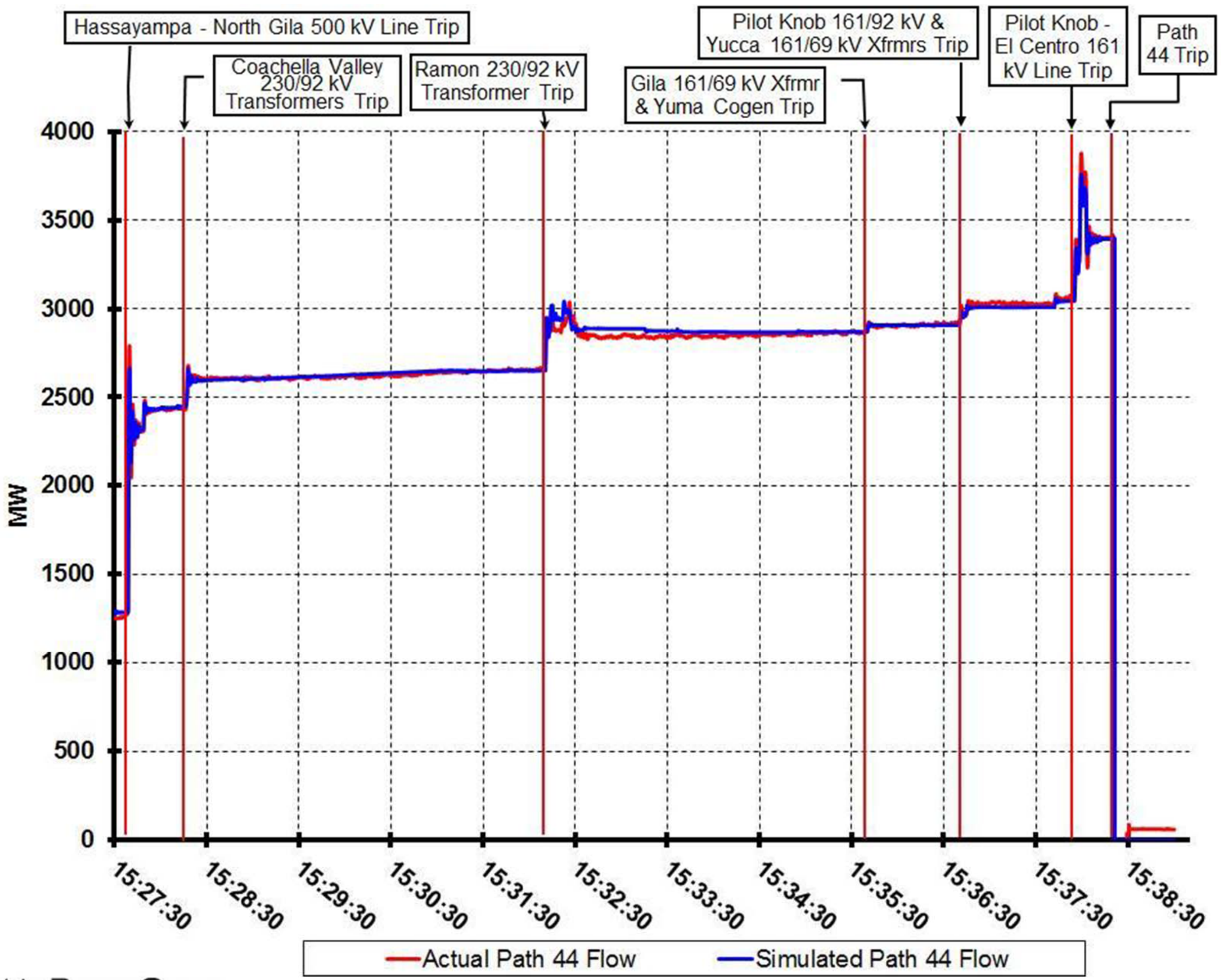
San Diego - WECC Disturbance
September 8, 2011

- San Diego system imports power on two major import paths
  - Hassyampa – N. Gila- Imperial Valley – Miguel 500 kV
  - South of SONGS – Five 230 kV lines (Path 44)
  - Power also flows through the underlying 220/115/92 kV system from Devers bus to IID and Western Administration – Lower Colorado
- SDG E has established individual path ratings
  - Hassyampa – N. Gila – 2200 MW
  - Path 44 south of SONGS – 1800 MW
- SDG&E monitors these through the EMS / SCADA system
- SDG&E may have been operating beyond safe operational limit

San Diego - WECC Disturbance
September 8, 2011 – Sequence of Events

- Heavily loaded and stressed system conditions and hot weather (115 degrees in IID)
- Safe operation and (N-1) criteria requires that loss of a path should not result in exceeding the normal rating of other paths.
- RTCA are generally employed to ensure that the system is operating with in safe operating region and can withstand a contingency
- The Hassyampa – N. Gila line tripped at 15:26 hrs while carrying 1394 MW load due to an operational error
- Loss of this line resulted in increase of power flow on Path 44 from 1302 MW to 2386 MW which exceeded the path 44 rating of 2200 MW
- Units tripped in CFE and transmission lines / transformers in IID resulting power flow on path exceeding 3200 MW resulting in path 44 tripping

Power flow on path 44 after Hassyampa – N. Gila line (from FERC/NERC Report)



Some Lessons Learned from Major Blackouts

- Lack of Wide Area View and monitoring capabilities
  - Operation in unsafe operating zone
  - Inability to take appropriate preventive measures
- Lack of Situational Awareness
  - Metrics of Health of the Grid e.g., Phase Angles
- Lack of Time-synchronized and High Resolution Data
  - Inability to Monitor Grid Dynamics in Real-Time
- System Models Inaccurate and Inadequate
  - Model validation is essential

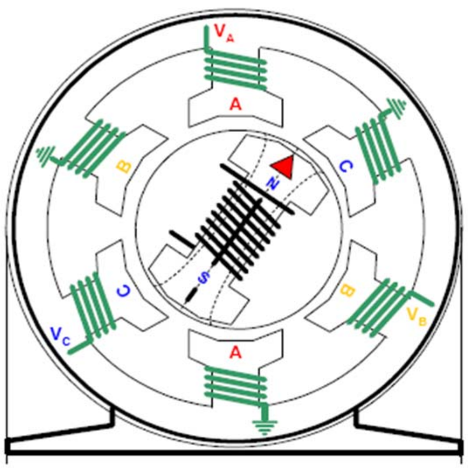
Value of Phasor Technology in Operations and Reliability Management

Synchronized Phasor Measurement Technology can:

- provide monitoring and wide area view of the entire power system
- help in avoiding blackouts and major disturbances
- provide synchronized event recording during disturbances at multiple points
- enable wide area visibility, instantaneous assessment of system performance reliability and stability (Situational Awareness)
- enable quicker restoration of systems after major system disturbances
- increase power transfers on existing paths
- help in determining Available Transmission Capacity in real-time
- provide early warning of growing stresses

What is a Phasor?

- **A phasor is a rotating vector:**
  - **A way to describe AC circuits and sinusoidal waveforms.**
  - **By definition they rotate counter-clockwise (i.e., engineering convention).**
  - **Fully characterized by 'Magnitude' & 'Phase' (e.g. $V_1 \angle \delta_1$).**



AC Circuits

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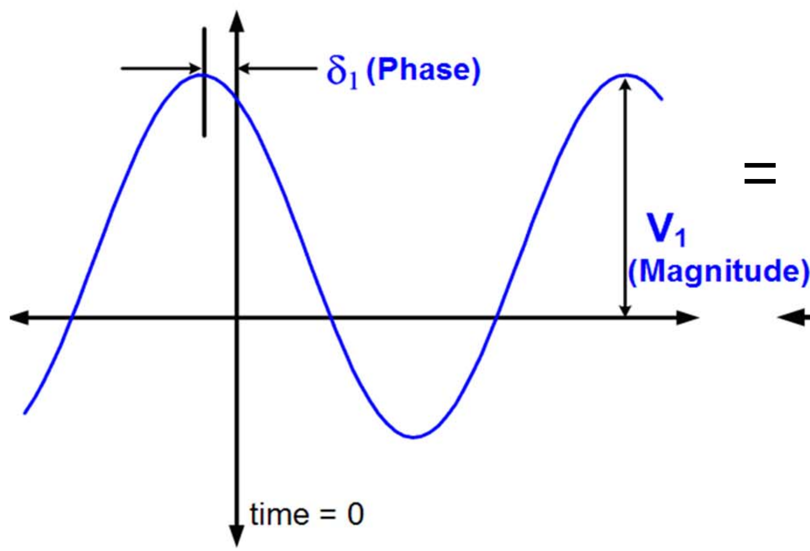

Sinusoidal Waveform

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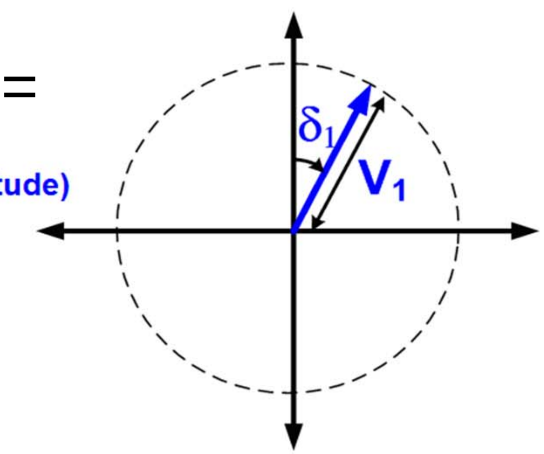
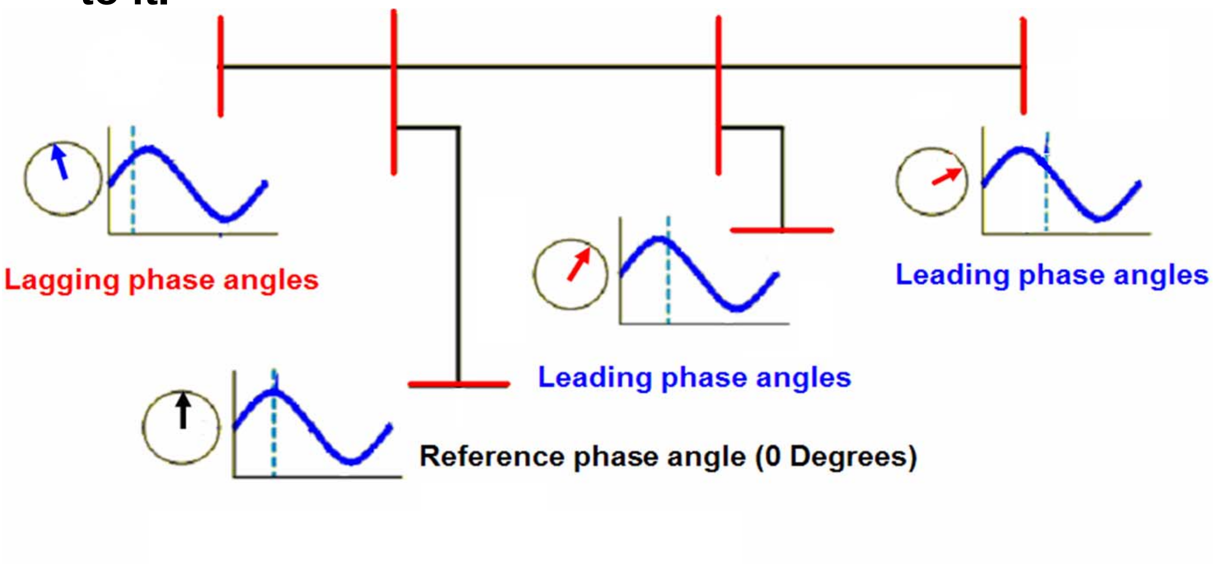
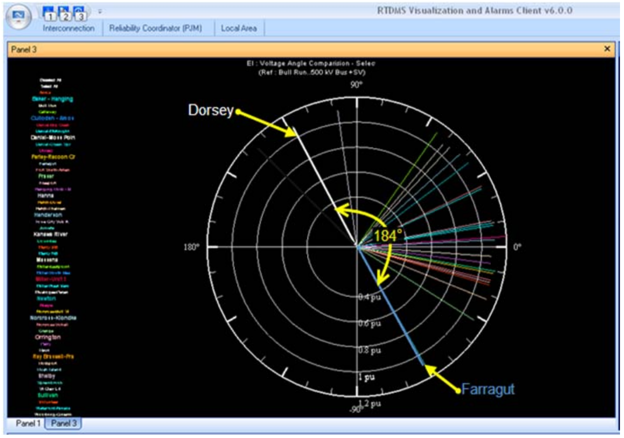


Phasor Representation

Wide-Area Phase Angle Monitoring

- **Phasor technology offers a means of capturing wide-area snapshots of phase angle profiles and comparing them:**
  - **You can pick one point on the grid as a reference and the others can be compared to it.**



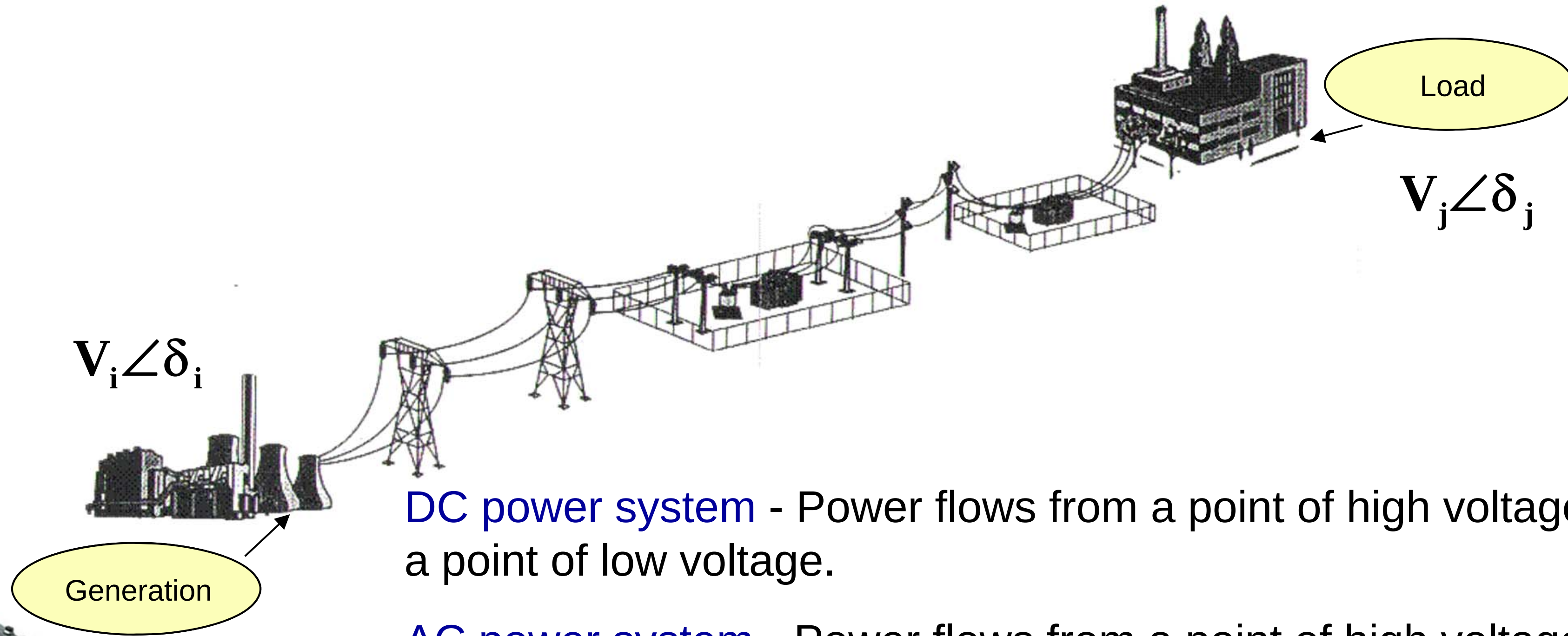


EPG – RTDMS software

Definition: A leading waveform is one that is ahead of a reference.
A lagging waveform is one that is behind a reference.

The phase angle difference between two waveforms of the same frequency are good indicators of grid stress.

What **Causes** Power to Flow on the Grid



DC power system - Power flows from a point of high voltage to a point of low voltage.

AC power system - Power flows from a point of high voltage angle to a point of low voltage angle. The higher the angle the greater the power flow.

Power Flow Equation

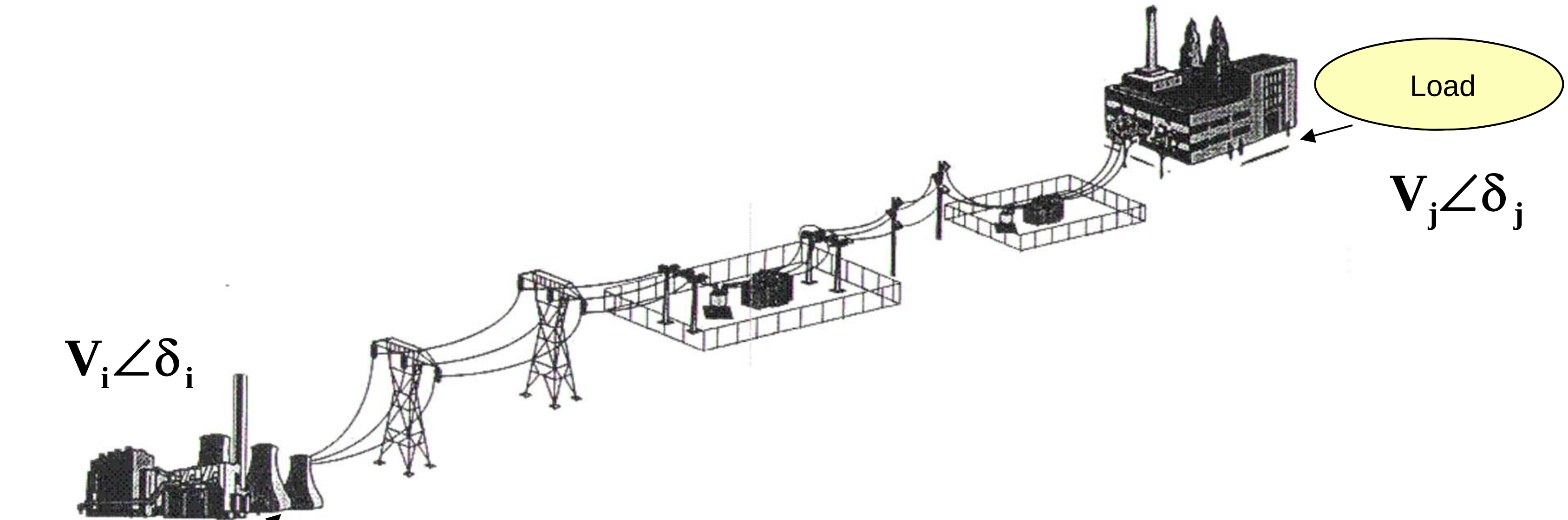
$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j)$$ where

$V_i \angle \delta_i$ is the voltage magnitude & angle at bus ‘i’

$V_j \angle \delta_j$ is the voltage magnitude & angle at bus ‘j’

X_{ij} is the transmission line reactance

What Causes Voltage Angle differences to Increase?



What can cause the voltage angle to increase?

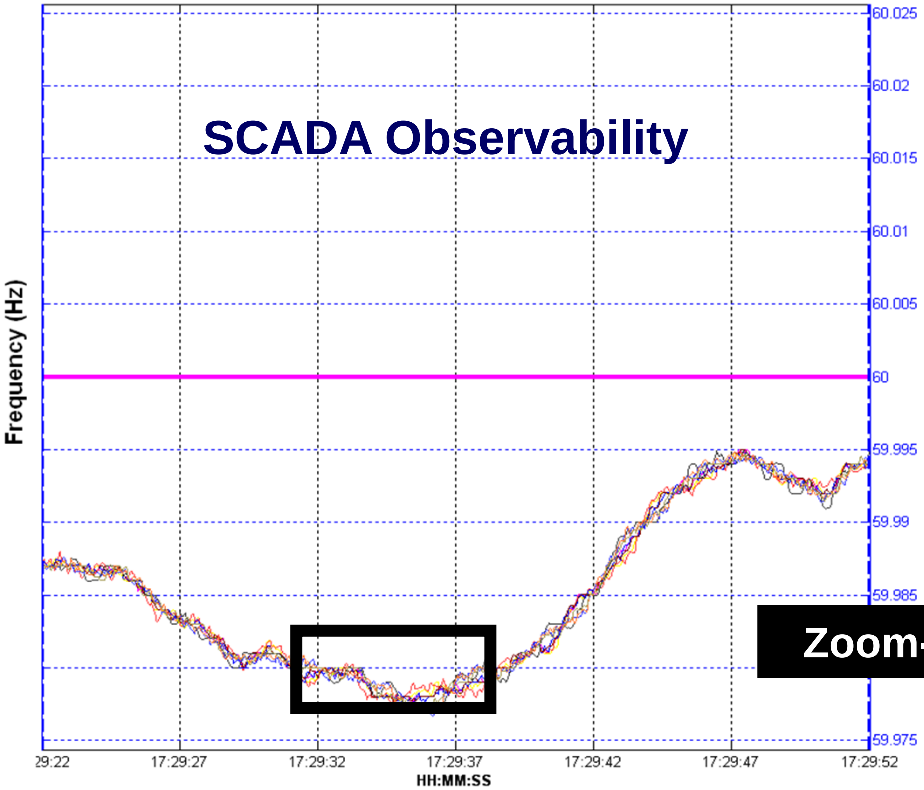
1. Increased scheduled power transfers between source and sinks (increasing the prime mover [e.g., steam] in source. generators and decrease on sink generators).
2. Transmission lines removed (forced or scheduled) from service between source and sink, without adjusting schedules.
3. Loss of generation in the sink area.

Phasor Data Complements SCADA

- **With SCADA we get info on:**
  - bus voltages
  - line, generator and transformer flows (MW, MVAR, and Amperes)
  - generator MW and MVARs (low/high limits, ramp rates)
  - transformer taps and breaker status, as well as other generator parameters (e.g. limits)
  - Frequency measurements
- **Phasor technology provides additional information on:**
  - voltage and current phase angles (monitor angle-of-separation)
  - frequency and rate-of-change (identify generation loss) at all PMU locations
- **And other derived metrics from these measurements, e.g.:**
  - damping for each dominant frequency present
  - inter-area oscillations frequencies
  - measured sensitivities, Voltage and Angle
  - frequency response and df/dt

Observability – SCADA Vs. PMUs

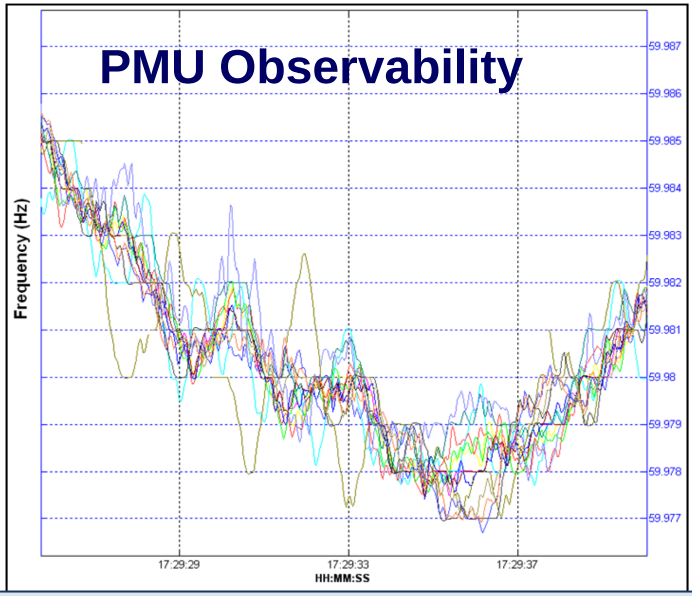
QUESTION: Detection of Frequency Differences Across the Interconnection



No!

Zoom-in

YES!



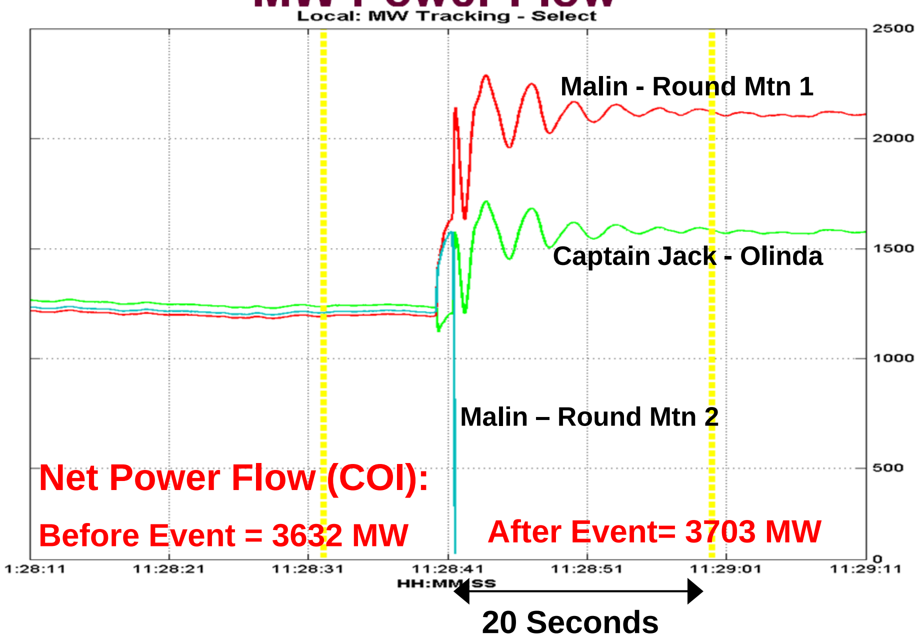
ANSWER 1) The frequency is the same across the Interconnection – almost

2) Frequency measurements from different locations show small variations – associated with inter-area dynamics ('oscillations')

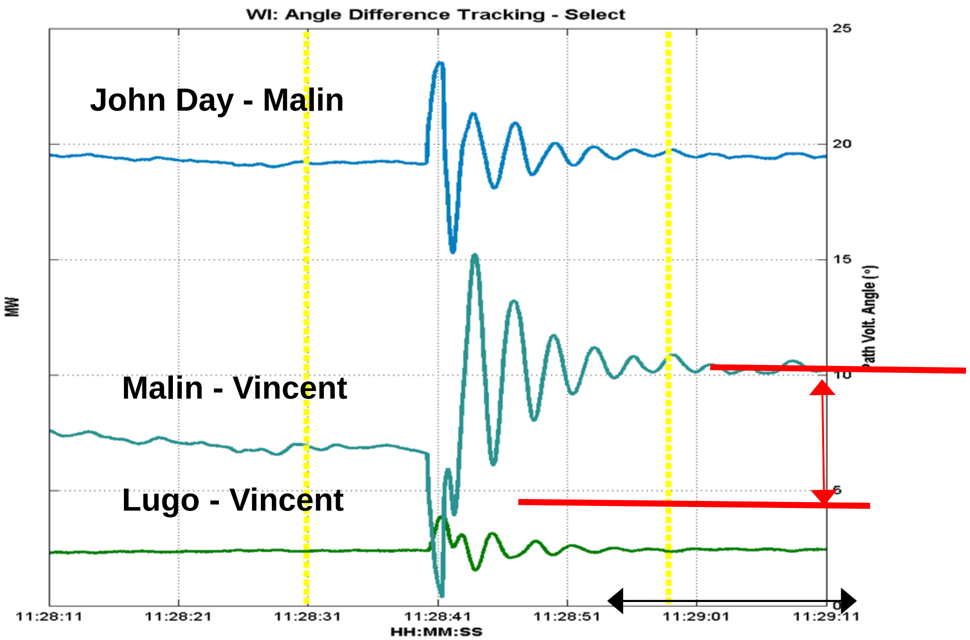
WECC Transmission Outage – Malin Round Mountain Monitoring Flows Alone is Not Sufficient

- **Power flows - essentially unchanged**
- **Oscillations observed - dampens within 20 secs**
- ***Angle Difference across the path increases– indicator of higher stress.***

MW Power Flow



Angle Difference



Net Power Flow Before Event = (1207 + 1190 + 1235) = 3632 MW
Net Power Flow After Event = (0 + 2123 + 1583) = 3703 MW
⇒ Net COI Power Flow did not change to capture Event

Increased stress changed phase angle difference across COI however, net COI flows remained unchanged

Observations

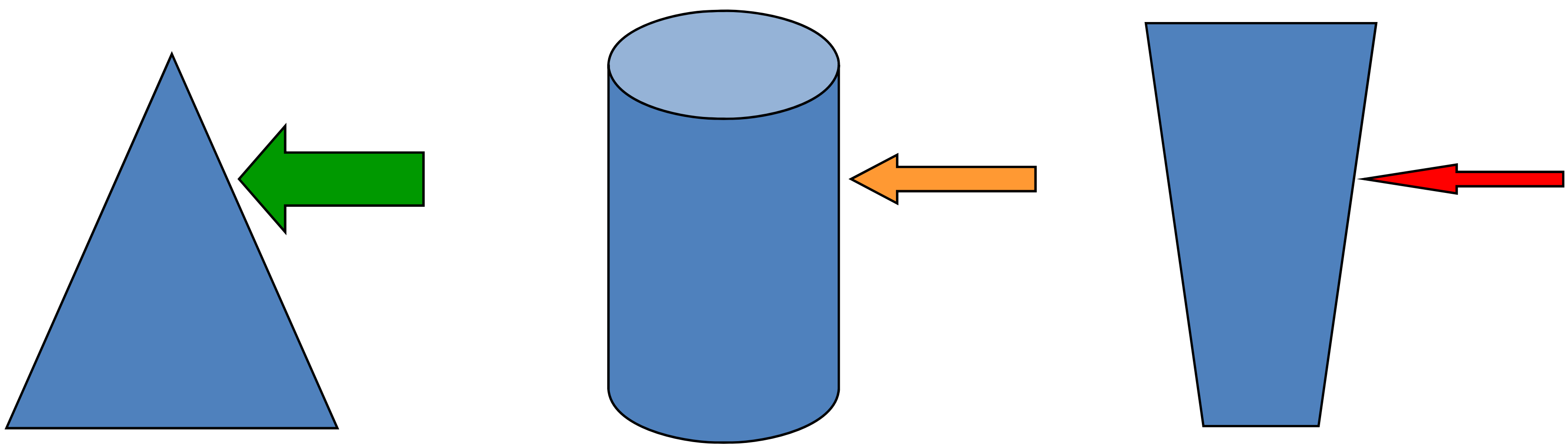
- Power transfer economics and system reliability are competing goals
- Systems are designed considering the worst loading condition scenarios and for loss of one element
- Systems are generally well planned and designed as they withstand outage of one element
- Most disturbances occur, not for loss of one element, but multiple contingencies occurring over an extended time period
- Often, the line loadings and margins are not adjusted when line outages occur outside one's control area
- Tools are needed to monitor Wider Area and for keeping an eye on other systems as well

Use of Phasor Technology by Operators

- Increase use of transmission capacity
- Establish static and dynamic phase angle limits
  - Increasing loadings if margin is there
  - Reducing loading if the safe limits are exceeded
- Compare phase angle measurements with bench marked cases and keeping adequate dynamic margin
  - for critical outages (HVDC, large generation units etc.)
  - Maintaining adequate margins if line outages occur and adjusting phase angles as necessary
- Monitor Modal oscillations frequencies and damping
  - Modal damping should not fall below 7 to 8 percent
  - Modal frequencies should not continue to drift lower
- Monitor voltage support and sensitivities at intermediate locations
  - when operating at large phase angles separations.
- Event reconstruction and model validation

Stability, Phase Angles, and Dynamic Stress

Very Stable | **Oscillatory** | **Unstable**



Low < 60deg.	Medium 60 – 80 deg.	High > 80 deg.
Can take high dynamic stress	Can take medium Dynamic stress	Can take low dynamic stress ONLY

Angles shown above refer to WECC system between GC-Devers

Static and Dynamic Phase Angles from Some Recorded and Simulated Cases

- **500 kV System Events (WECC)**

  Phase Angle separation between Grand Coulee (BPA) and Devers (SCE)

Date	Static Phase Angle Degree	Dynamic Phase Angle Swing Degree	Stability Type
Aug 10, 1996	94 (simulated)	Growing	Unstable - Dynamic
Aug 4, 2000	92	15	Dynamic / Stable
June 6, 2002	74	73	Transient / Stable
July 15, 2002	82	-35	Transient / Stable
June 14, 2004	55	90	Transient / Stable
April 20, 2006	86	-10	Transient / Stable

- **230 kV System Event (SCE Big Creek System**

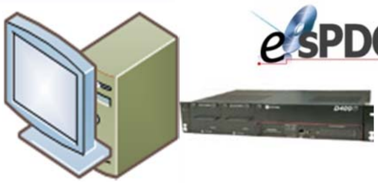
  Phase Angle separation between Big Creek and Vincent

Sept 13, 2000	30	15	Dynamic / Stable

EPG SynchroPhasor Applications

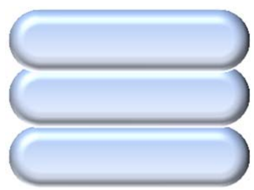
ePDC

esPDC



*e*nhanced PDC

PHASOR ARCHIVER™



PHASOR RTDMS™

Real Time Dynamics Monitoring System Alarming

Phasor Grid Dynamics Analyzer™

Phasor Grid Dynamics Analyzer

EPG Synchrophasor Solutions at ISOs and TOs

- **CAISO**
  - In use since 2003 - 56 PMUs, around 750 phasors at 30sps
  - *e*PDC, RTDMS, Phasor Archiver, PGDA
- **MISO**
  - Currently 35 PMUs with a capability of 400+ PMUs
  - *e*PDC & Phasor Archiver deployed
  - PGDA – selected as the phasor analysis and planning tool
- **PJM**
  - PMUs at 91 substations
  - *e*PDC & Phasor Archiver are deployed in test environment
  - RTDMS & PGDA deployment nearing completion
- **NYISO**
  - Production grade deployment of RTDMS, PGDA, *e*PDC, Phasor Archiver
- **ERCOT**
  - Deployed RTDMS, PGDA, *e*PDC, Phasor Archiver
- **NASPI**
  - In use since 2004 - 123 PMUs, around 1168 phasors at 30sps
  - RTDMS Supports 70+ Web-based clients concurrently
- **TO's – List includes AEP, BPA, SRP, Duke, Dominion, SCE, Ameren, Hydro One, Southern, BCHA, PG&E**

WECC

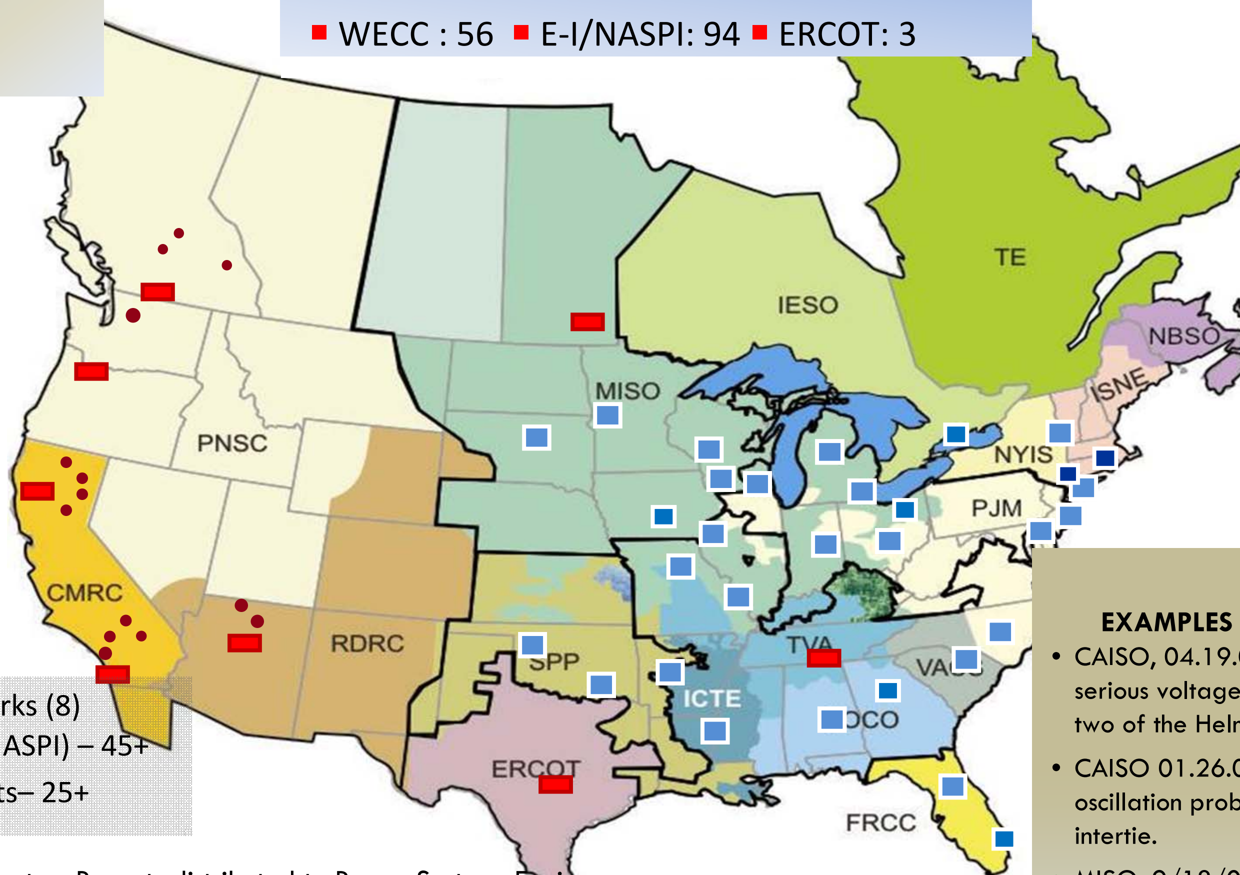
RTDMS Networks at

- CAISO
- Salt River Project
- BCTC

RTDMS® Usage in North America

PMU's Networked

■ WECC : 56 ■ E-I/NASPI: 94 ■ ERCOT: 3



E-I / NASPI

- RTDMS Network for EI has a central server hosted at TVA with web based clients.
- Over **45 real time monitoring** clients connected to central server by secure internet
- **9 Reliability Coordinators**
- **29 Control Center Locations**

- RTDMS Daily System Reports distributed to Power Systems Engineers, Maintenance Engineers, TVA Leadership, Authorized Subscribers
- 5 Training programs conducted. Accredited course at Bismark
- Real time detection and capture with quick turn around analysis for over 20 significant events
- RTDMS Users' Group (www.rtdmsusersgroup.org) formed in 1Q 09. Conducts periodic webcasts meetings etc.

EXAMPLES of RTDMS SUCCESS STORIES

- CAISO, 04.19.06- RTDMS alerts RC to flag a serious voltage problem . Operator action- drop two of the Helms Pumps.
- CAISO 01.26.08- RTDMS alerts operator to oscillation problem, Action: decision to drop DC intertie.
- MISO, 9/18/07 RTDMS provides time-synchronized sub-second data MISO separation,
- 02/28/08 Florida event. Turn around analysis in less than 24 hrs.
- ERCOT: RTDMS used to monitor two oscillatory modes in the grid, not previously discerned or validated by SCADA.

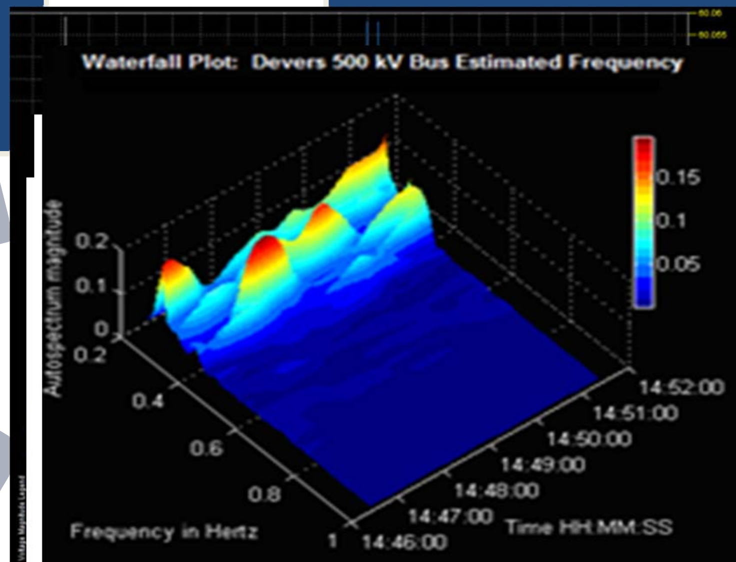
Phasor Technology – Basic and Advanced Uses

- Wide Area Situational Awareness – flows, frequency, voltages
- Grid Stress --- phase angle measurements
- Grid Robustness –damping status and trend
- Dangerous growing Oscillations – low damping
- Frequency Instability – frequency variation across interconnection
- Voltage Instability – low voltage zones and areas approaching nose of the Power-Voltage curves
- Reliability Margin – "How far are we from the edge"–sensitivity metrics

Metrics to Monitor the Health of the Grid

Dangerous Oscillations
Modal Damping & Energy

Grid Stress
Phase Angle Separation



PHASOR RTDMS

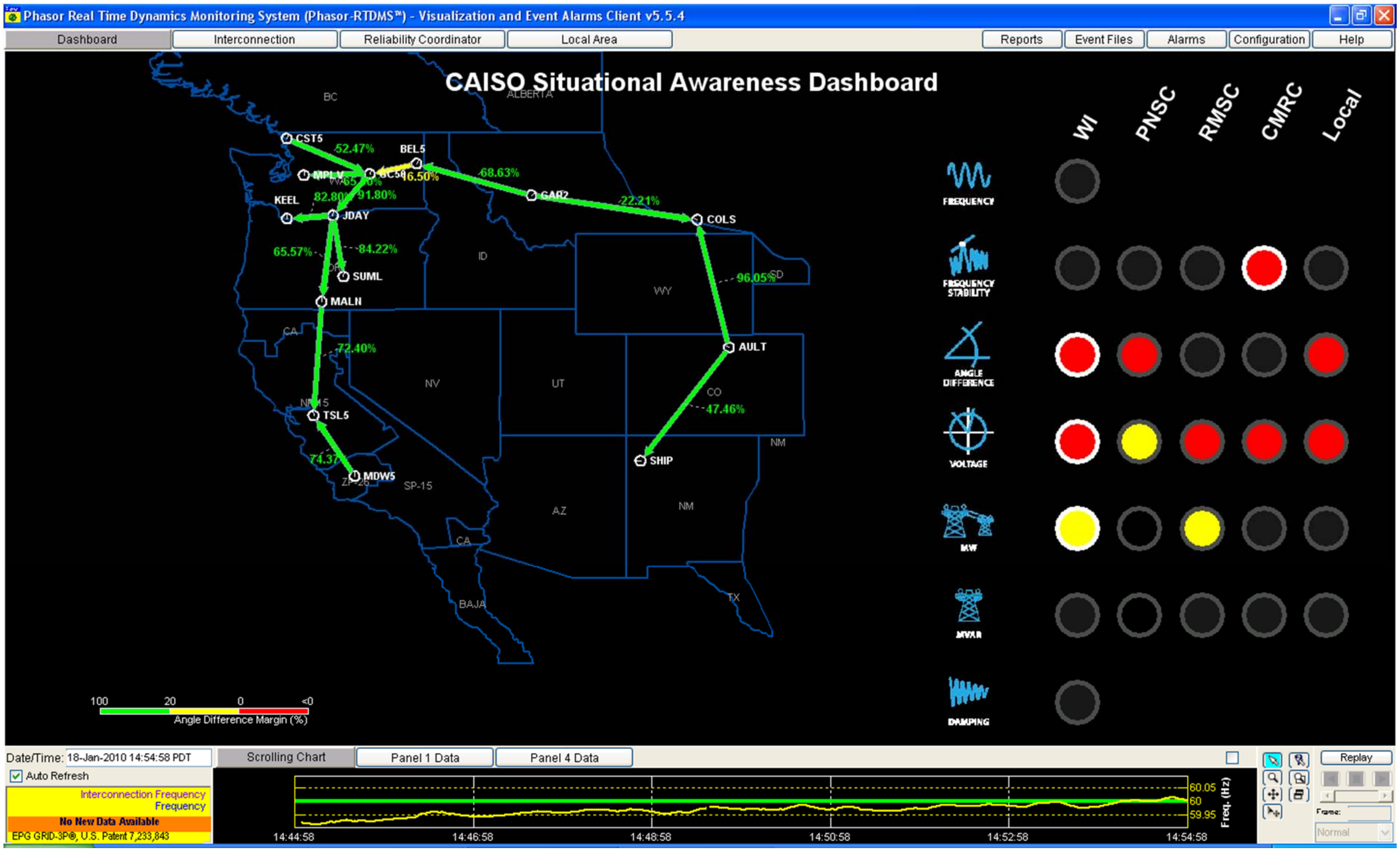
Margin
"How far are we from the edge?"

Angular Stability
Angle Sensitivities

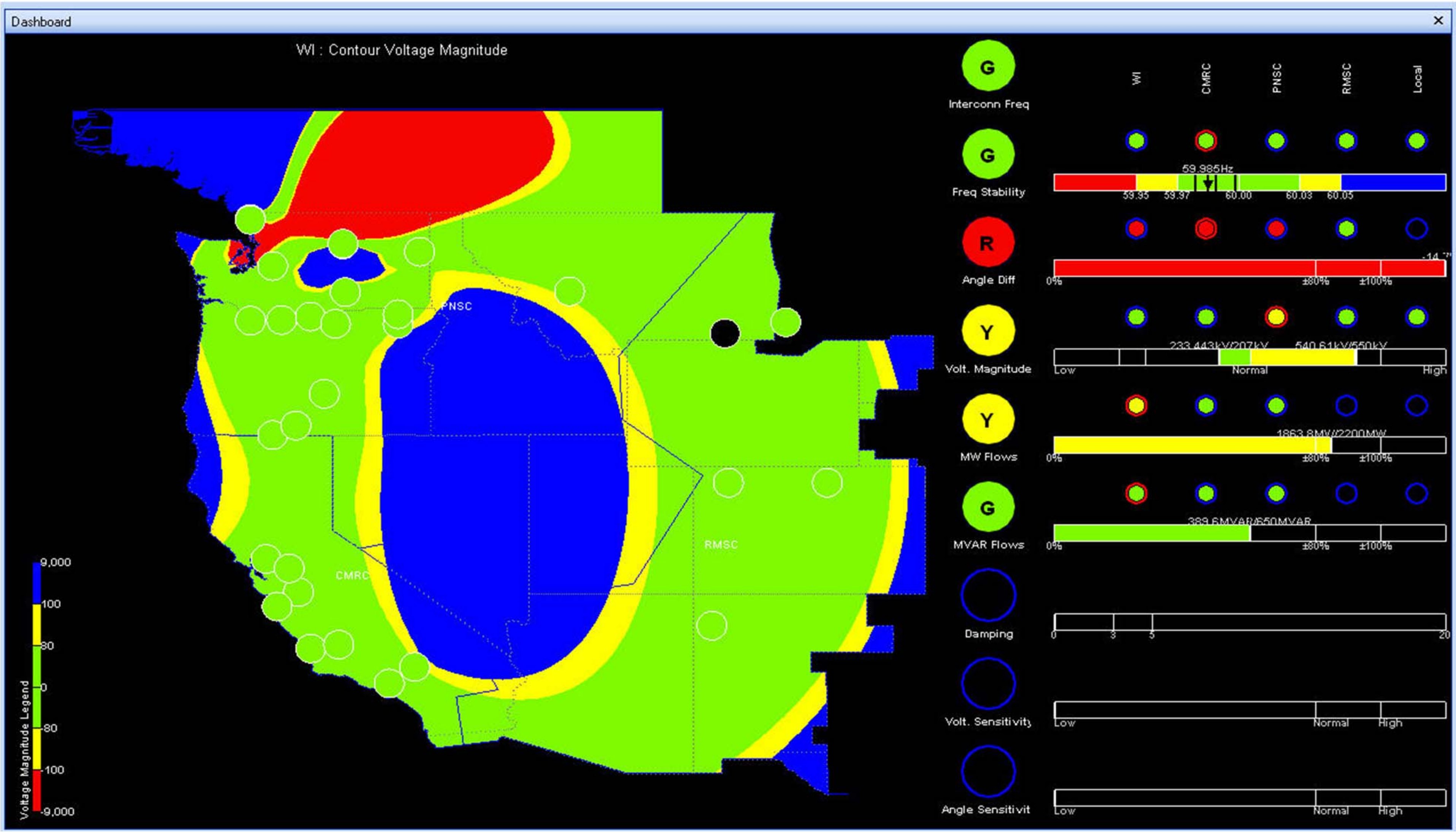
Voltage Stability
Low Voltage Zone

Frequency Instability
Frequency variations across grid

RTDMS Dashboard Display at California ISO



RTDMS Plot Showing
Voltage Contour Plot for WECC System



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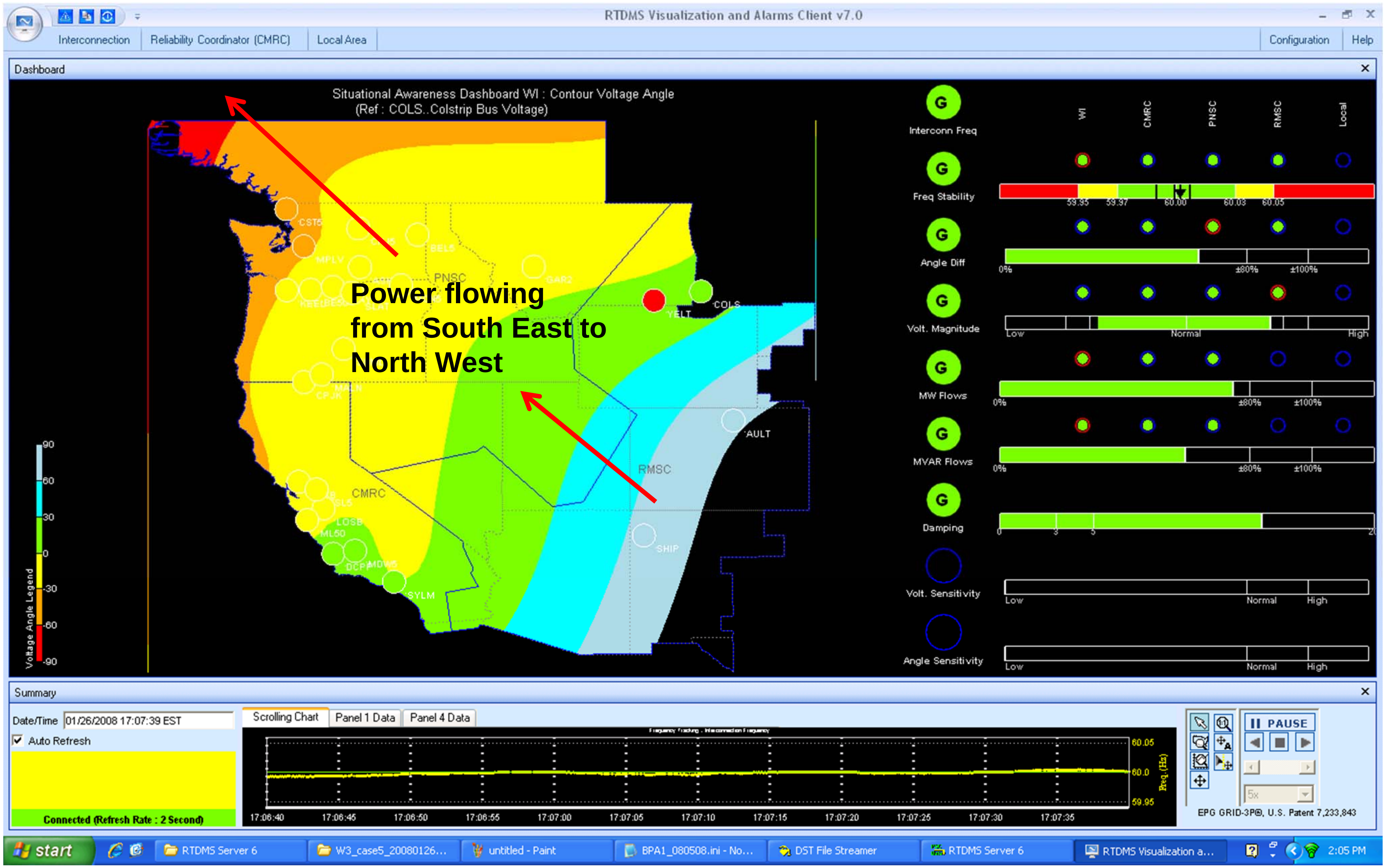
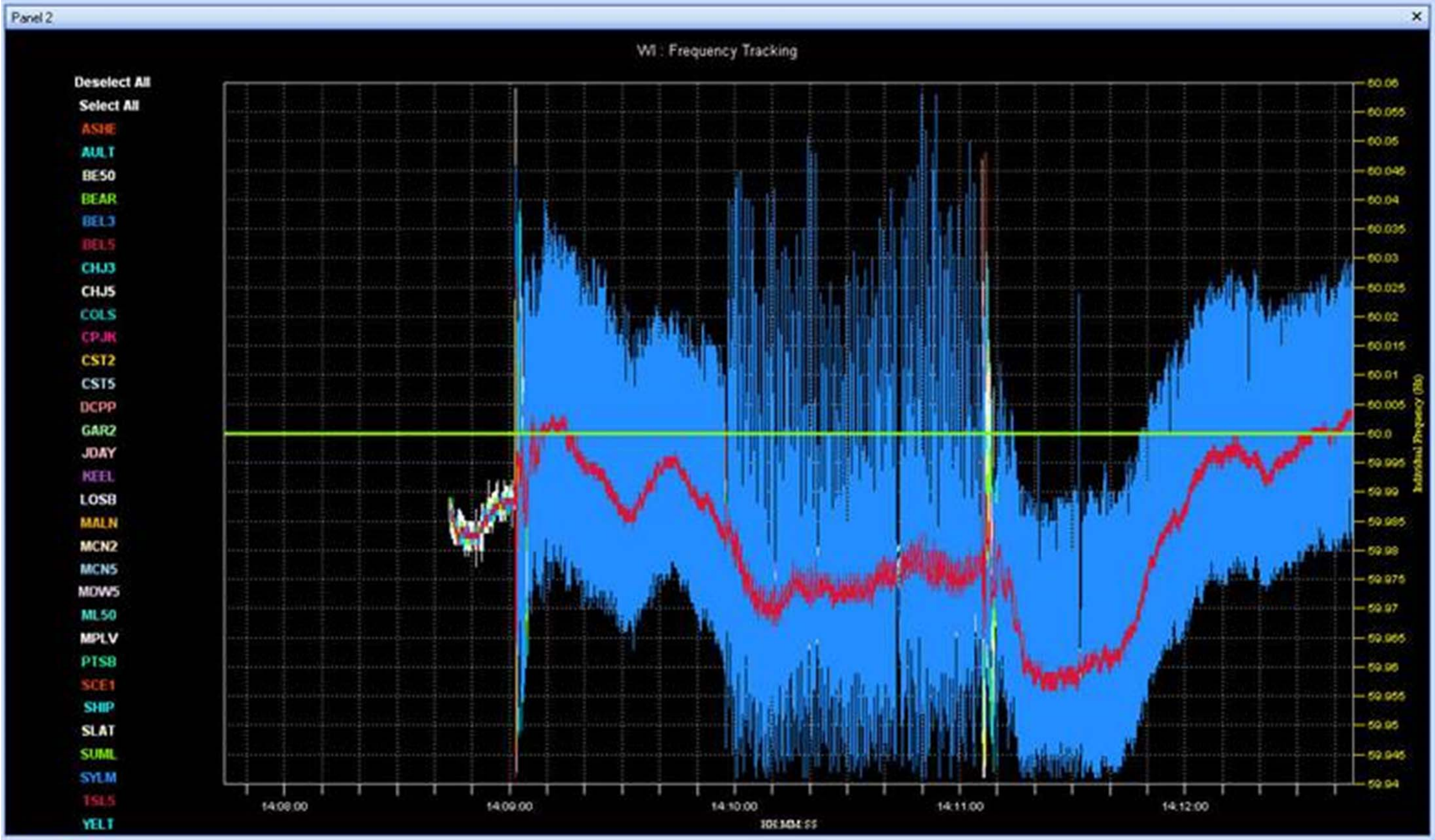
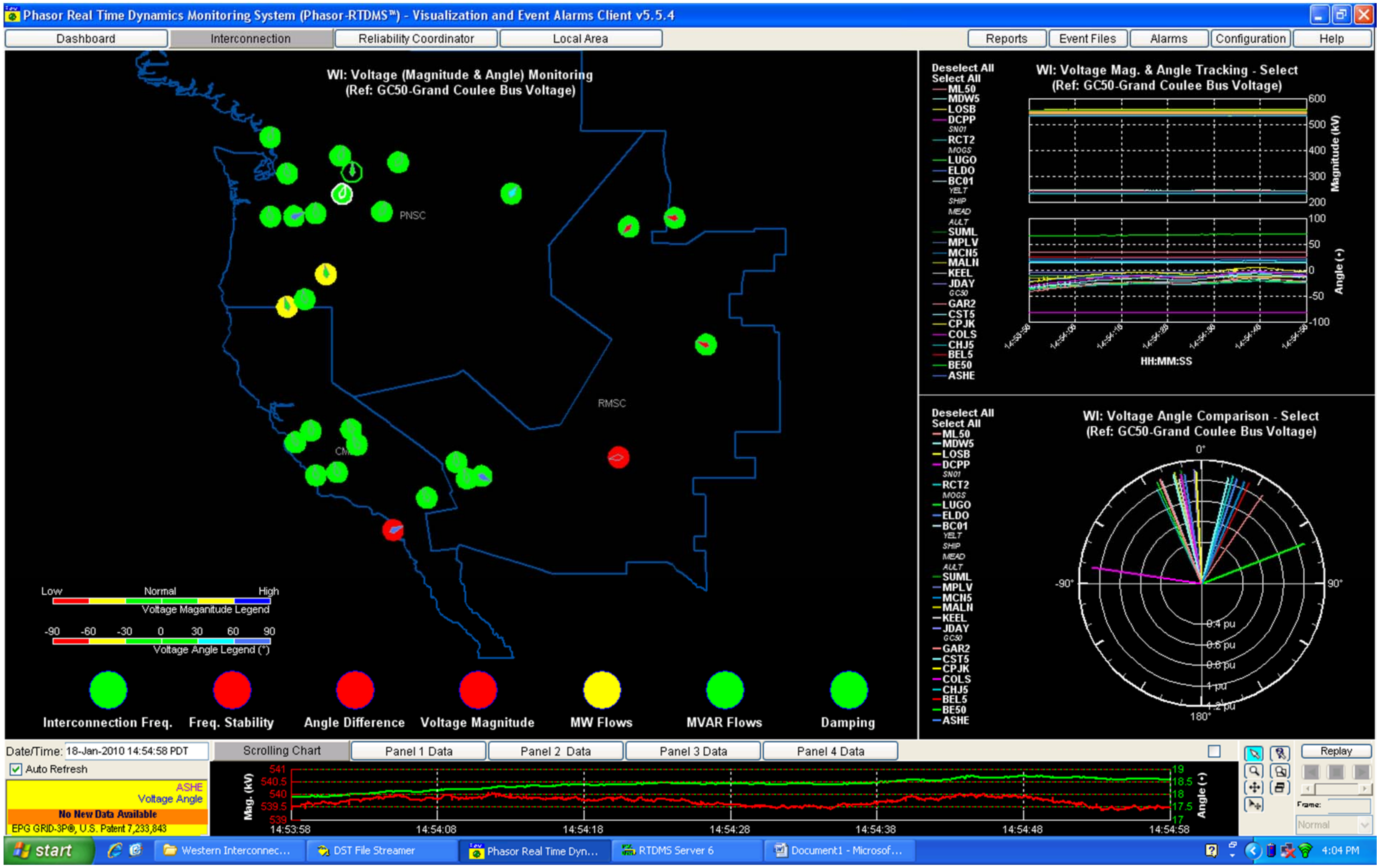
Phase Angle Visualization



Large Frequency Oscillations Detected by RTDMS -- WECC January, 2008



RTDMS Screen Showing PMU Locations and Monitored Voltage Magnitude and Angles



Monitoring Advanced Metrics with RTDMS

- Phase Angle Differences for Wide Area Grid Stress Monitoring
- Damping, Inter-area oscillations
- Voltage Sensitivity
- Angle Sensitivity

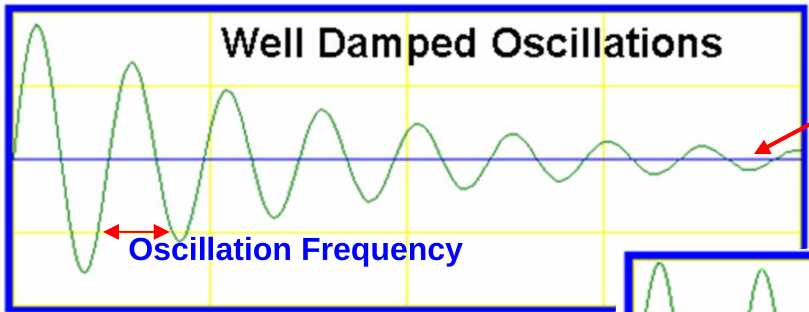
Monitoring wide area dynamics and advanced metrics in real-time is only possible with phasor technology

Characterizing Oscillations –
Freq. and Damping

Oscillatory Frequency & Damping Interpretation

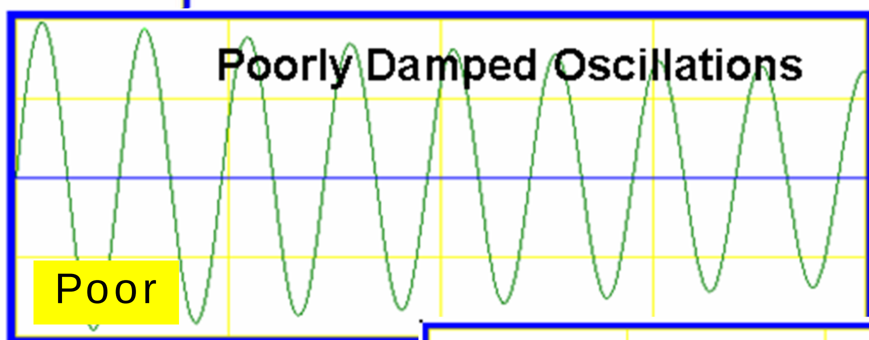
Desirable Condition

Desirable: 10% Damping ⇒ 30 sec decay time; 5% Damping ⇒ Decay in 60 sec

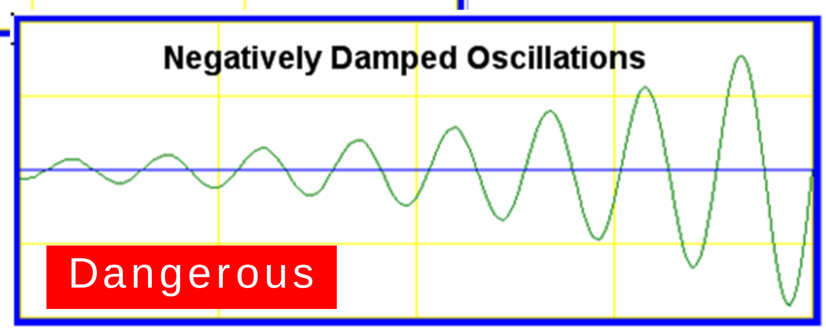


Decay Rate (i.e., Damping)

Poor: Less than 3%



Dangerous- Growing oscillations



Higher Damping ⇔ Greater Dynamic Stability (i.e., Desirable Situation)

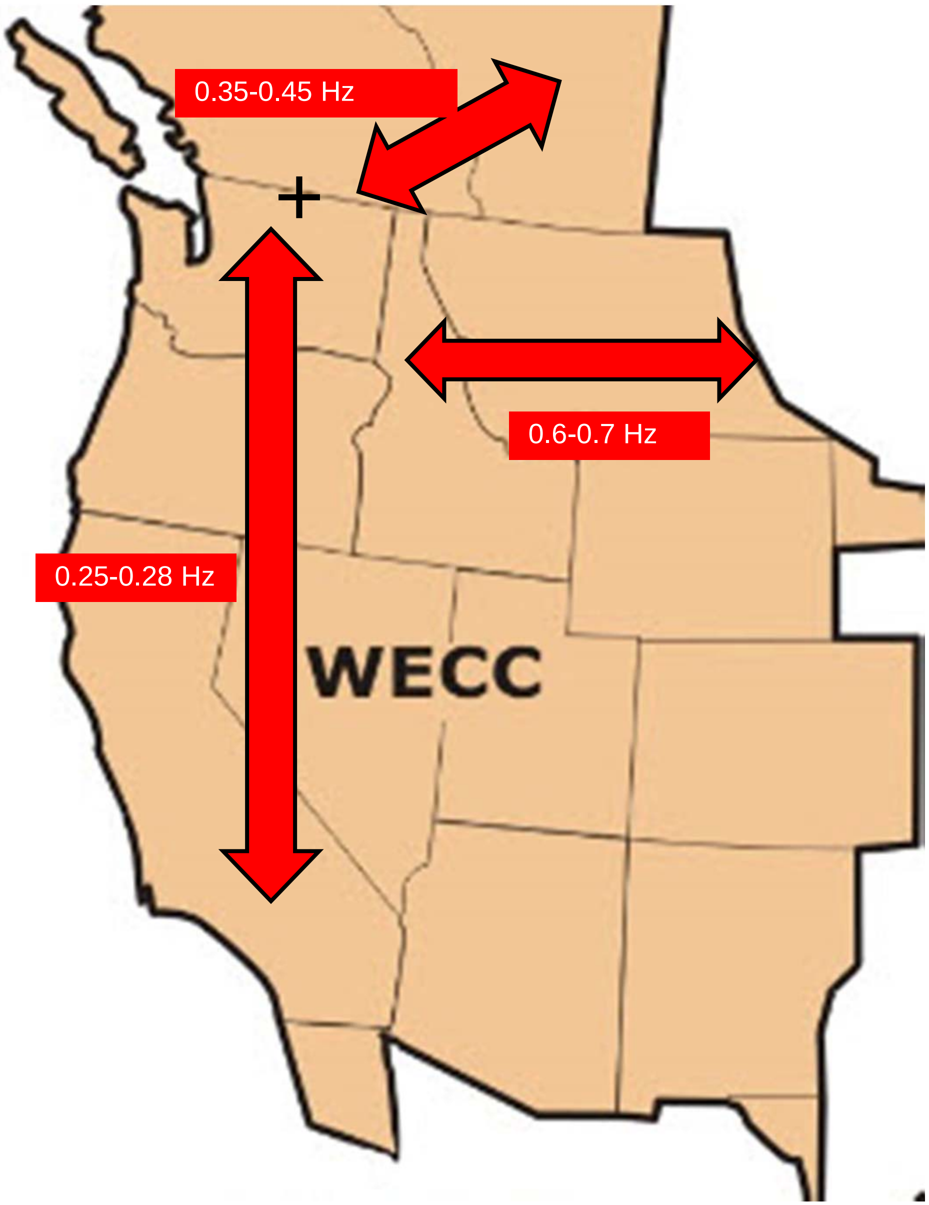
Monitoring Modal Oscillations

- The components of a complex power system are always oscillating with respect to each other
- Under normal conditions, the system oscillations are damped and controlled
- Oscillations, if not damped, lead to instability and system collapse e.g., 1996 WECC break-up
- Damping – Good damping is when oscillations damp out in less than 20 seconds – approx 12% damping. 5% damping means oscillations damped in about 60 seconds
- RTDMS has the capability to monitor oscillations and their damping and can alert if damping falls below the threshold levels

Power System Oscillation frequencies

- Sub-harmonic oscillation frequencies range from 0.01 Hz to below 60 Hz
- Oscillations can be characterized based on frequencies as follows
  - 0.01 Hz to 0.5 Hz – Inter-area power system oscillations
  - 0.5 Hz to 0.8 Hz – sub-regional area oscillations
  - 0.8 Hz to 2.0 Hz Local mode power system oscillations
  - 1.5 Hz to 3.0 Generator control system oscillations
  - 3.0 Hz to 10 Hz Fast acting control system oscillations (HVDC, and other FACTS devices)
  - 5.0 to 55.0 Hz Sub-synchronous system oscillations
  - 60 Hz – System frequency

Identified WECC Modes and Oscillating Areas

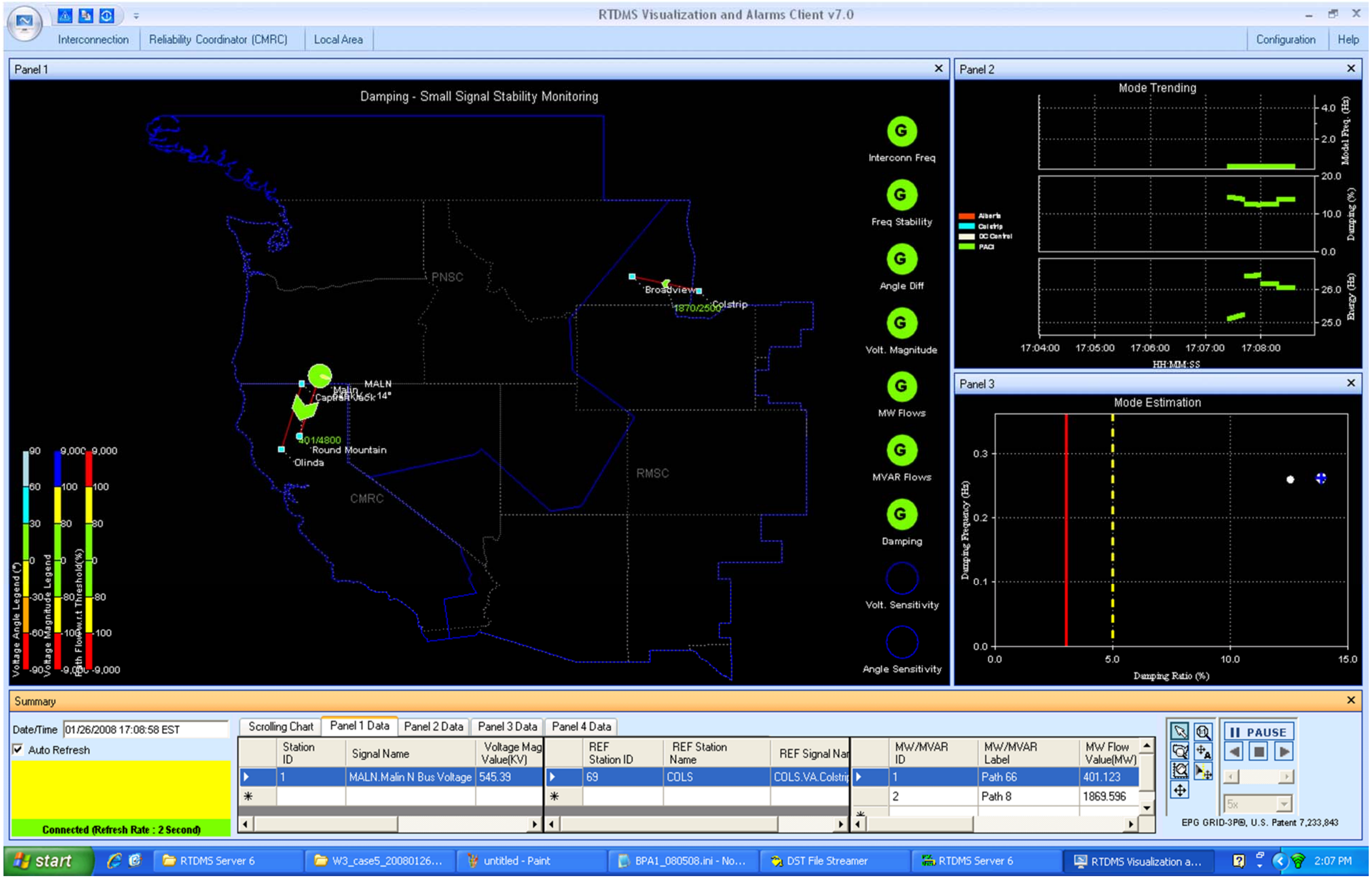


Dominant WECC System Modes

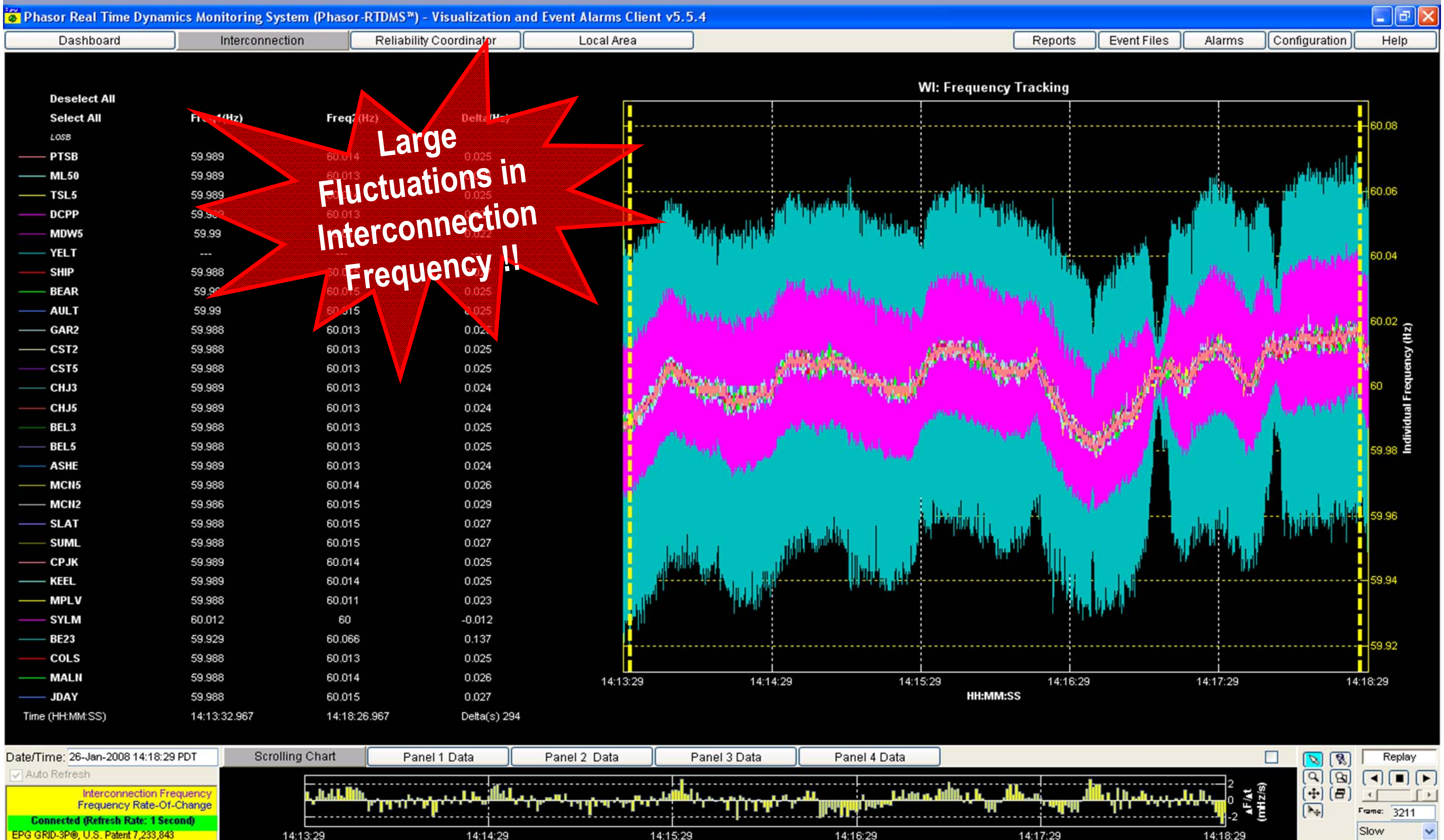
- **With Alberta connected to WECC system we see**
  - **North-South – 0.25 to 0.28 Hz**
  - **Alberta Mode – 0.35 to 0.45 Hz**
- **Colstrip mode 0.6 t0 0.7 Hz**
- **DC Control mode – 4.0 to 4.5 Hz**

(observed when DC Control malfunctioned)

RTDMS Plots Showing Oscillations and Their Damping and Energy Trends



Frequency Tracking using RTDMS



Polar Representation of Phase Angles

Phasor Grid Dynamics Analyzer™

A stand-alone application for offline forensics, enabling power system planners and engineers to perform quick turnaround analysis as well as detailed analysis of system dynamics and validate accuracy of system models.

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5.09.13

What is the Phasor Grid Dynamics Analyzer (PGDA)?

- PGDA is a powerful set of analysis tools that allows users to quickly and accurately analyze phasor data in order to:
  - Assess the health and vulnerability of a power system
  - Identify the root causes and effects of events
  - Determine a power system's ability to withstand events
- Challenging and time consuming tasks like system baselining and modal analysis can be accomplished in minutes
- Visualization tools help to convey meaningful information about complex data

PGDA Features and Capabilities

Data Sources

- Databases like eDNA
- Flat files - phasor files
- .dat, .csv, .dst files etc

Datasets

- Sets of data created by the selection of various metrics
- Data merger assists the creation of datasets

State-of Art Algorithms

- Parametric & Non-parametric techniques
- Significant mode cluster identification
- Modal analysis under ambient & post-event conditions

Plots

- Statistical charts
- Spectral analysis charts
- Modal analysis plots
- Ring-down analysis charts

Spectral Analysis

- Common significant peaks signify oscillatory modes
- Significance of coherency
- Information regarding the oscillating nature of signals

Statistical Analysis

- Time aligned matrix along metrics
- Statistical chart representation
- Signal manipulation i.e. frequency is a derivative of angle
- Variability of the metrics across time intervals

Ambient Modal Analysis

- Analysis under ambient conditions
- Trend of modal frequency, modal damping and modal energy over a period of time

Ring down Analysis

- Modal analysis under fault conditions
- Variation of mode frequency with respect to damping
- Alignment of modes based on phase angle

Capabilities

- Small Signal Stability Analysis
- Event Analysis – Forensic, Disturbances
- Performance Evaluation
- Reliability Assessment
- Data Repair & Preparation
- ***Event Analysis Report generation (New)***
- ***Data base connectivity (New)***

PGDA's Capabilities Include:

Event and Disturbance Analysis	• Quickly determine the causes and effects of power system events like generation and line trips
Dynamic Model Validation	• Verify and refine/re-calibrate dynamic models used in power system simulations to aid in planning and engineering studies
Baselining Analysis	• Examine long-term system performance and establish reliable ranges for voltage, frequency, and other system metrics
Dynamic Stability Assessment	• Evaluate the ability of a power system to withstand and respond to disturbances by analyzing the characteristics of dangerous oscillations and calculating standard reliability metrics like frequency response

Synchro Phasor Technology for Monitoring Power System Oscillations and Control System Performance

- Unusual system oscillations can be caused by control system malfunctions or high system stress conditions
- Synchro Phasor Technology can be used to monitor these oscillations real time and for later analysis of the data
- Tools such as Real Time Dynamics Monitoring System (RTDMS) are available to monitor these oscillations in real time
- Tools such as Phasor Grid Dynamics Analyzer (PGDA) can be used for detailed off-line analysis of the events
- Following examples of unusual oscillations caused by control systems or high system stress that have occurred in WECC and were detected by Synchro Phasor technology are being presented
  - November 30, 2005 (Caused by the governor at Nova Jaffre, Alberta)
  - January 26, 2008 (Caused by DC controls)
  - August 4, 2000 (Caused by high system stress)

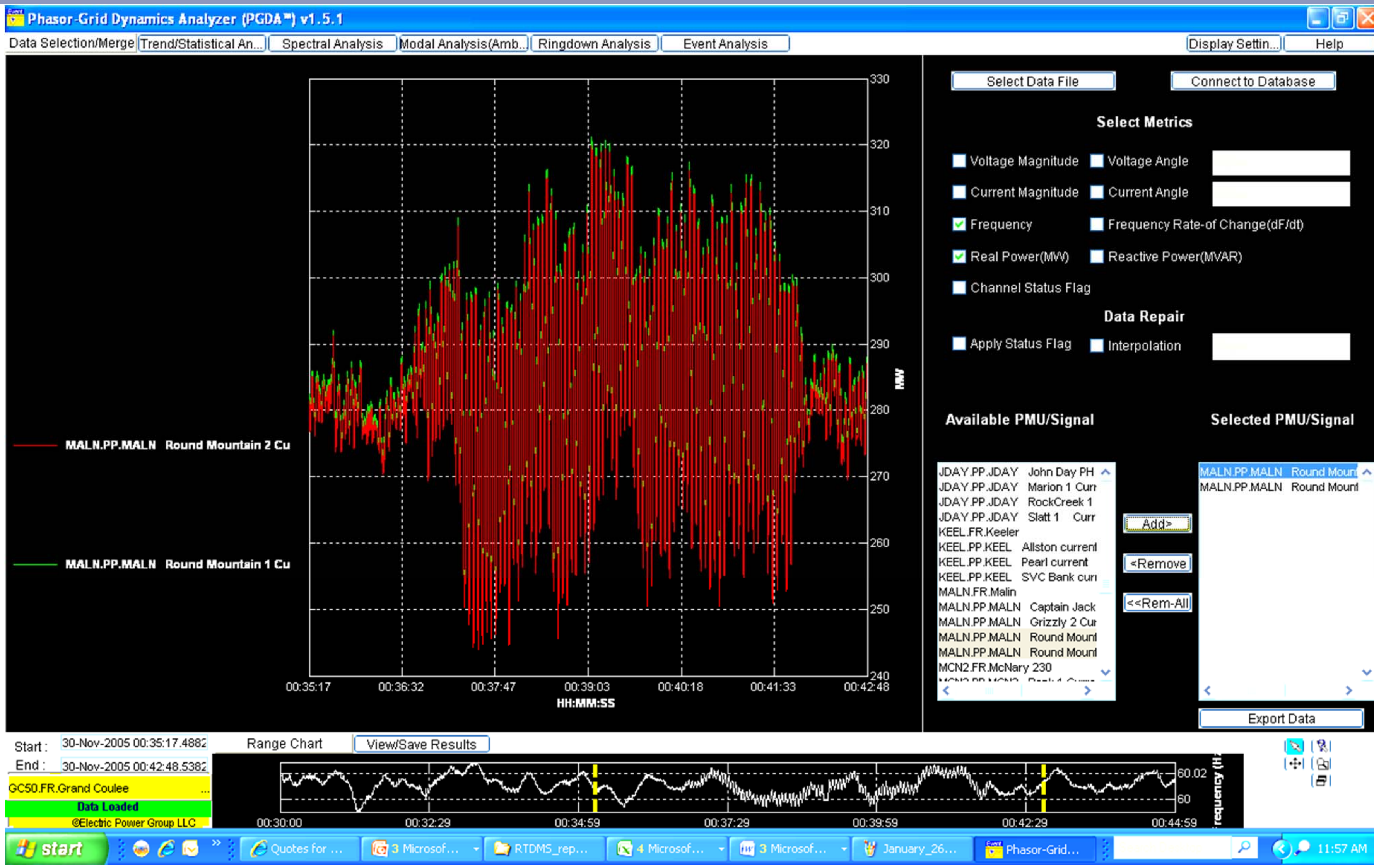
WECC Event on November 29, 2005 at 23:45 PM

Event description:

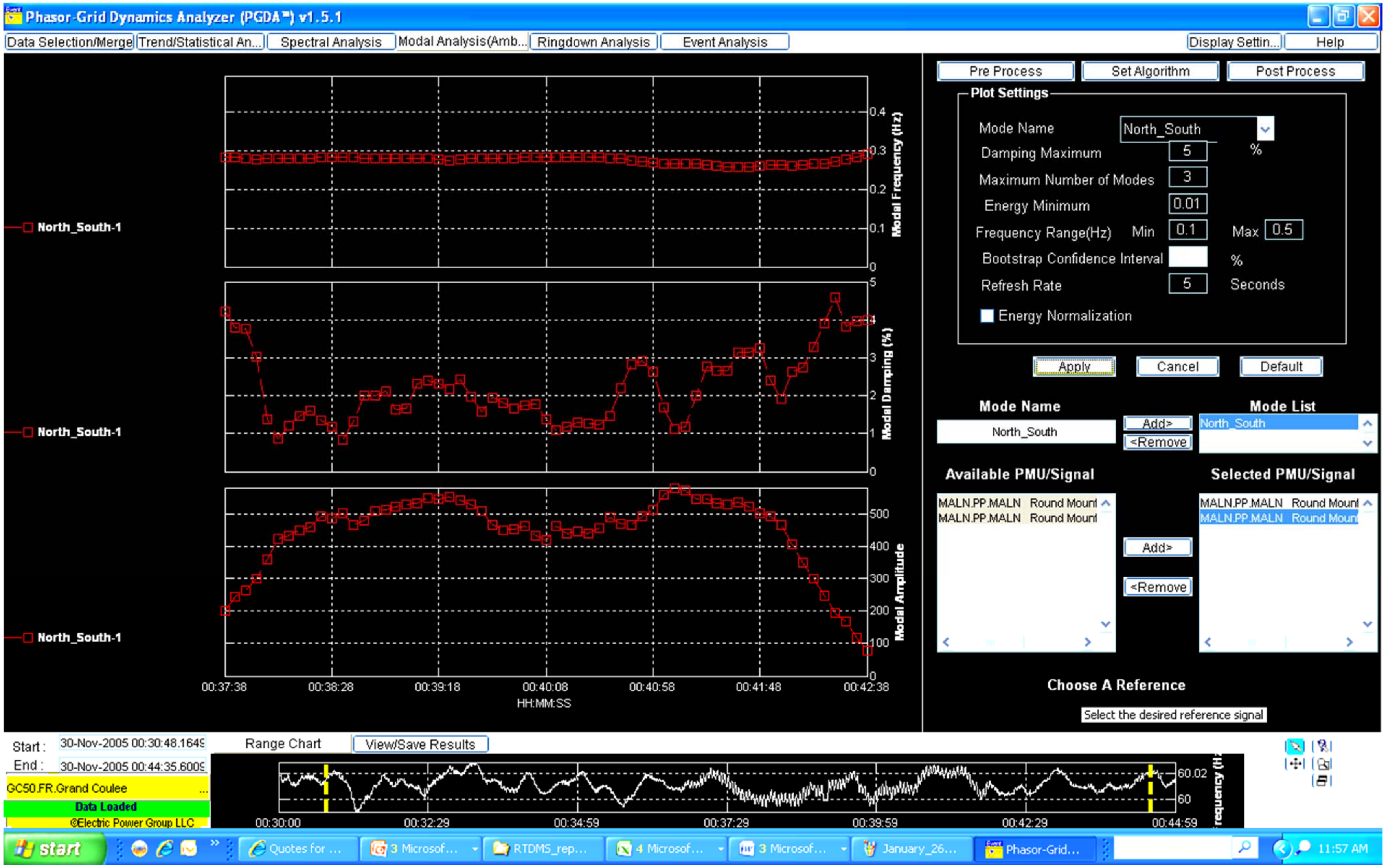
- Event caused by a 20 MW generator unit governor malfunction (Nova Jaffre) in Alberta, Canada
- Oscillations caused by the unit at the North-South WECC mode
- Large power oscillations (About 70 MW on each Malin-Round Mountain line) observed on California-Oregon lines
- Oscillation frequency at about 0.28-0.29 Hz
- Damping drops to 1-2 percent when oscillations are occurring
- Oscillations were detected and finally stopped when the units were taken off-line
- This is a classical example of tail wagging the dog

  – excitation at a resonant mode

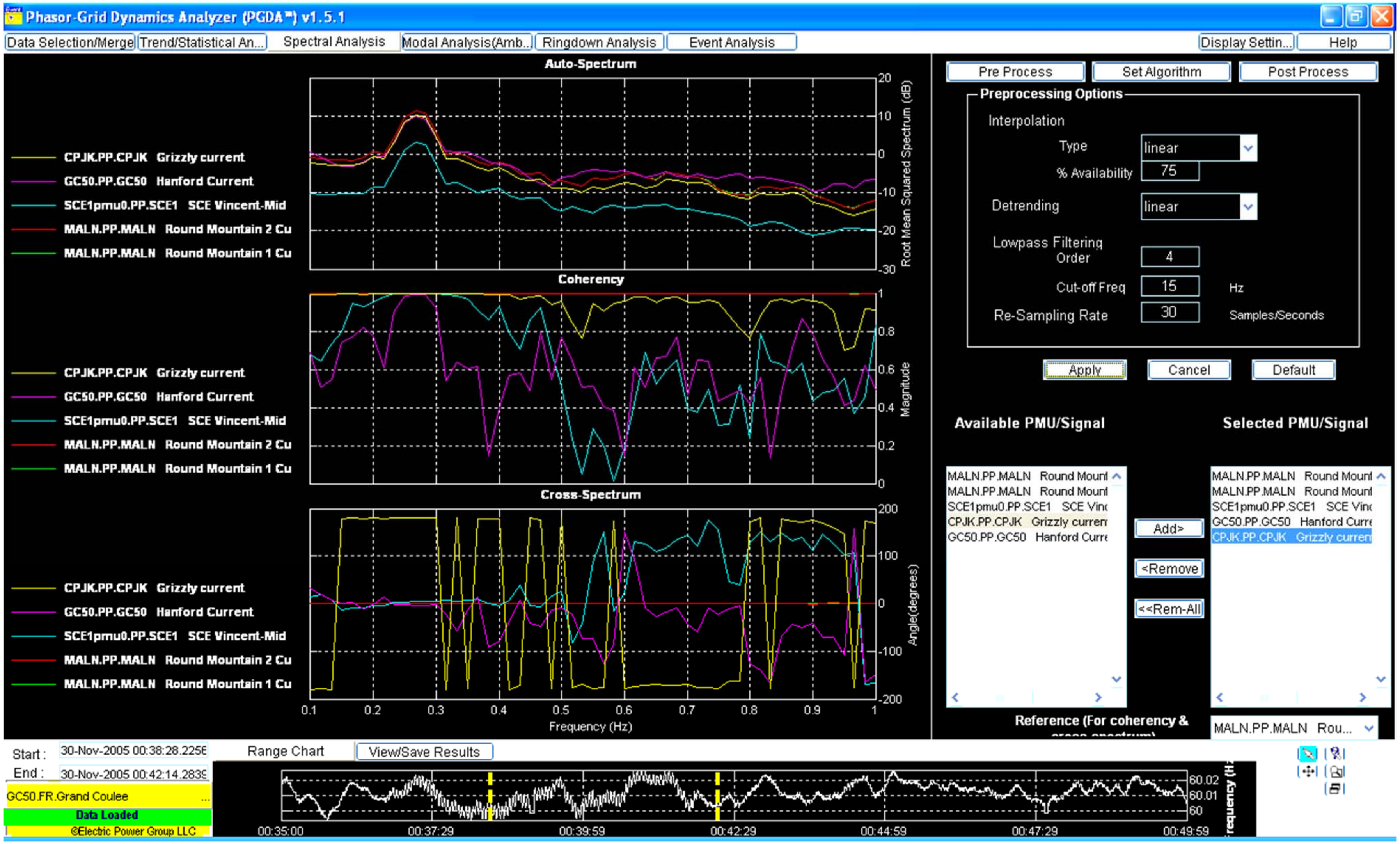
Power Flow Oscillations on Malin-Round Mountain (COI) Lines



Modal analysis (Mode Meter) of power flows on Malin-Round Mountain lines



Spectral Analysis of November 29, 2005 WECC Event

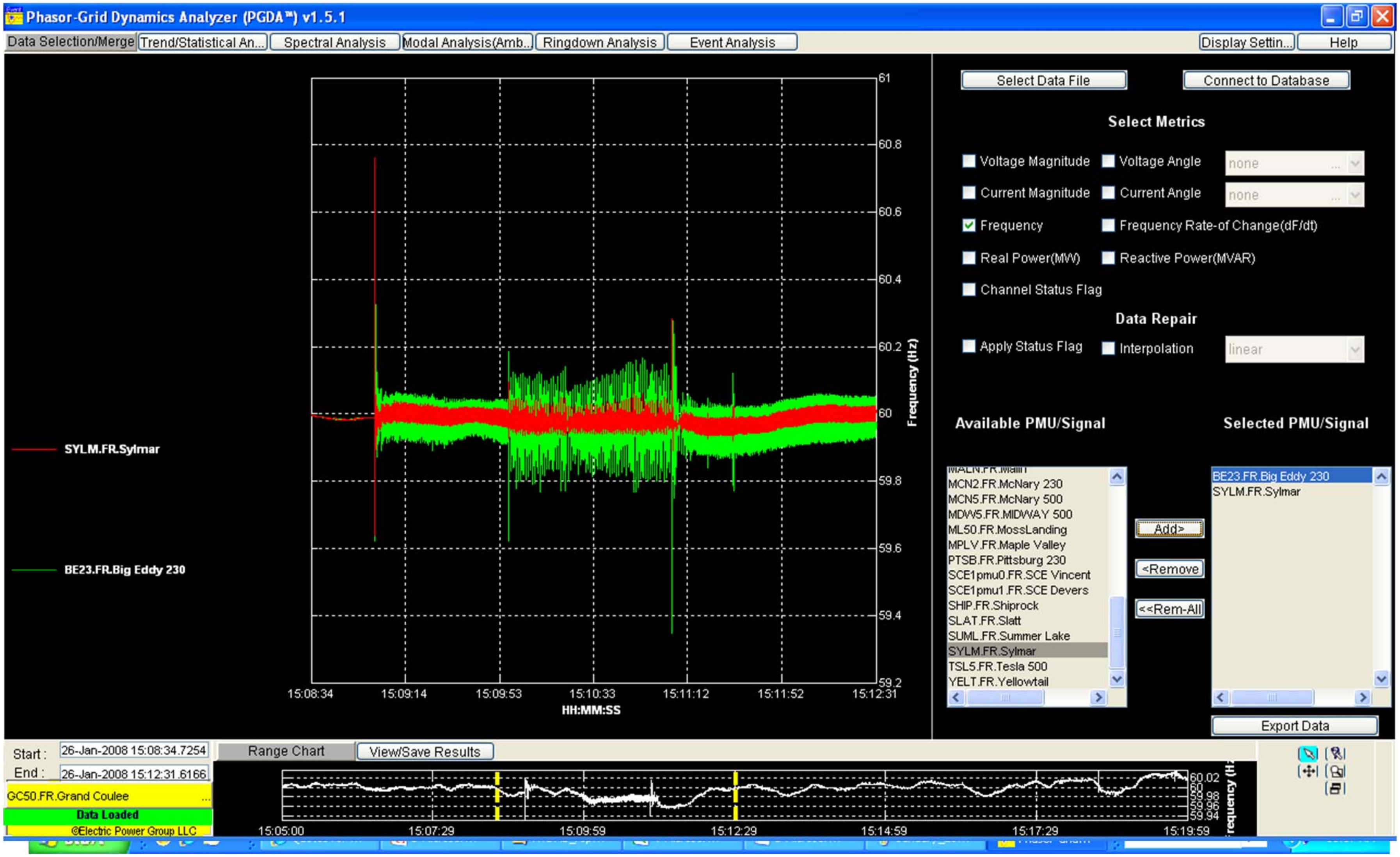


WECC PDCI Event on January 26, 2008 at 14:09 PDT

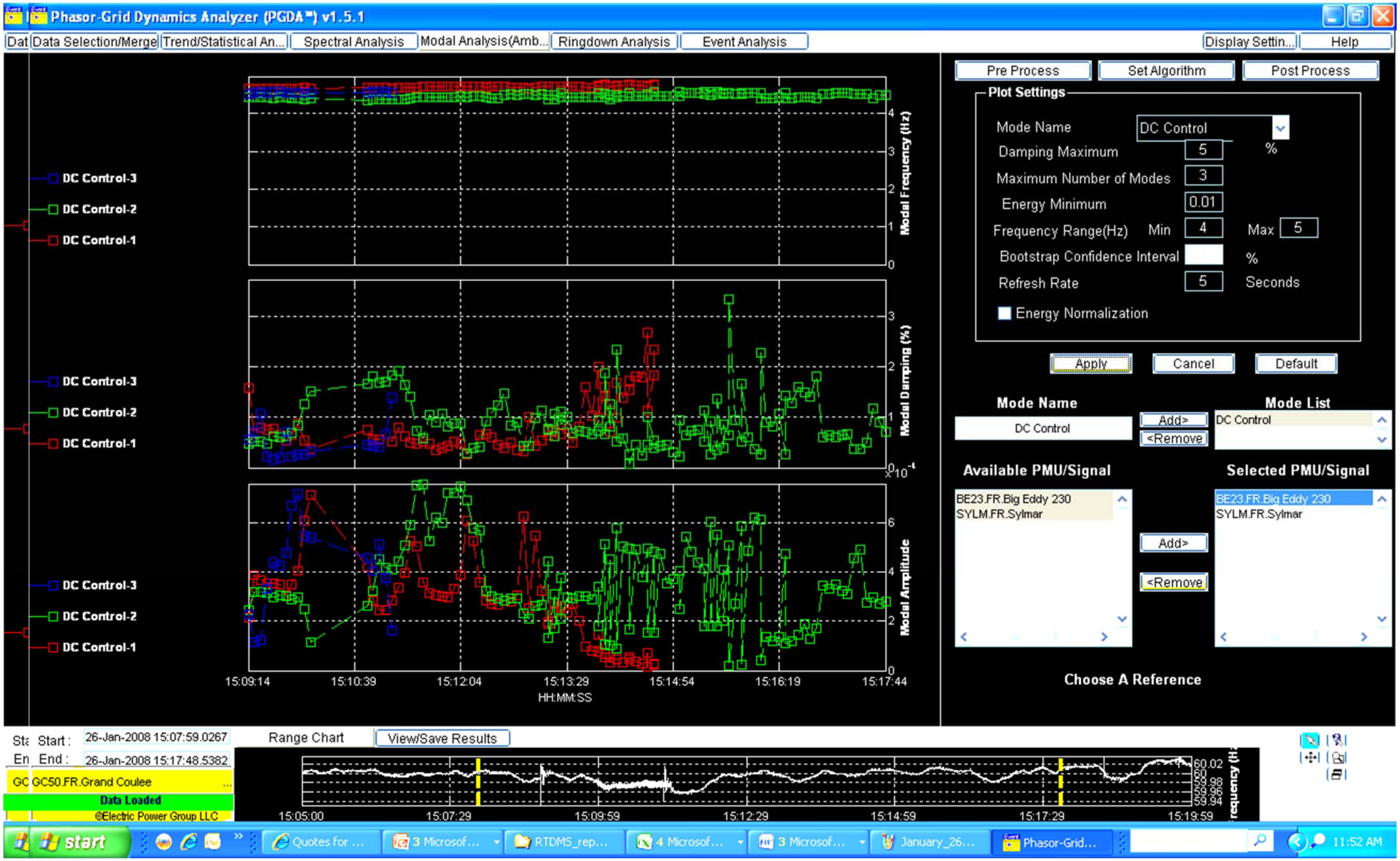
Event description:

- Event was triggered by the loss of the three 525/230 kV transformers at Big Eddy – near Celilo bus (Northern PDCI terminal) at 14:09
- Loss of transformers resulted in separation of 500 & 230 kV busses at Big Eddy substation.
- High frequency oscillations occurred at HVDC 230 kV bus at Celilo and Sylmar busses – the two ends of the PDCI line.
- Oscillation frequency varied between 3.6 to 4.4 Hz.
- Damping drops between 1-2 percent
- Oscillations were detected and finally stopped at 15.05 PM when the DC line power was switched off.

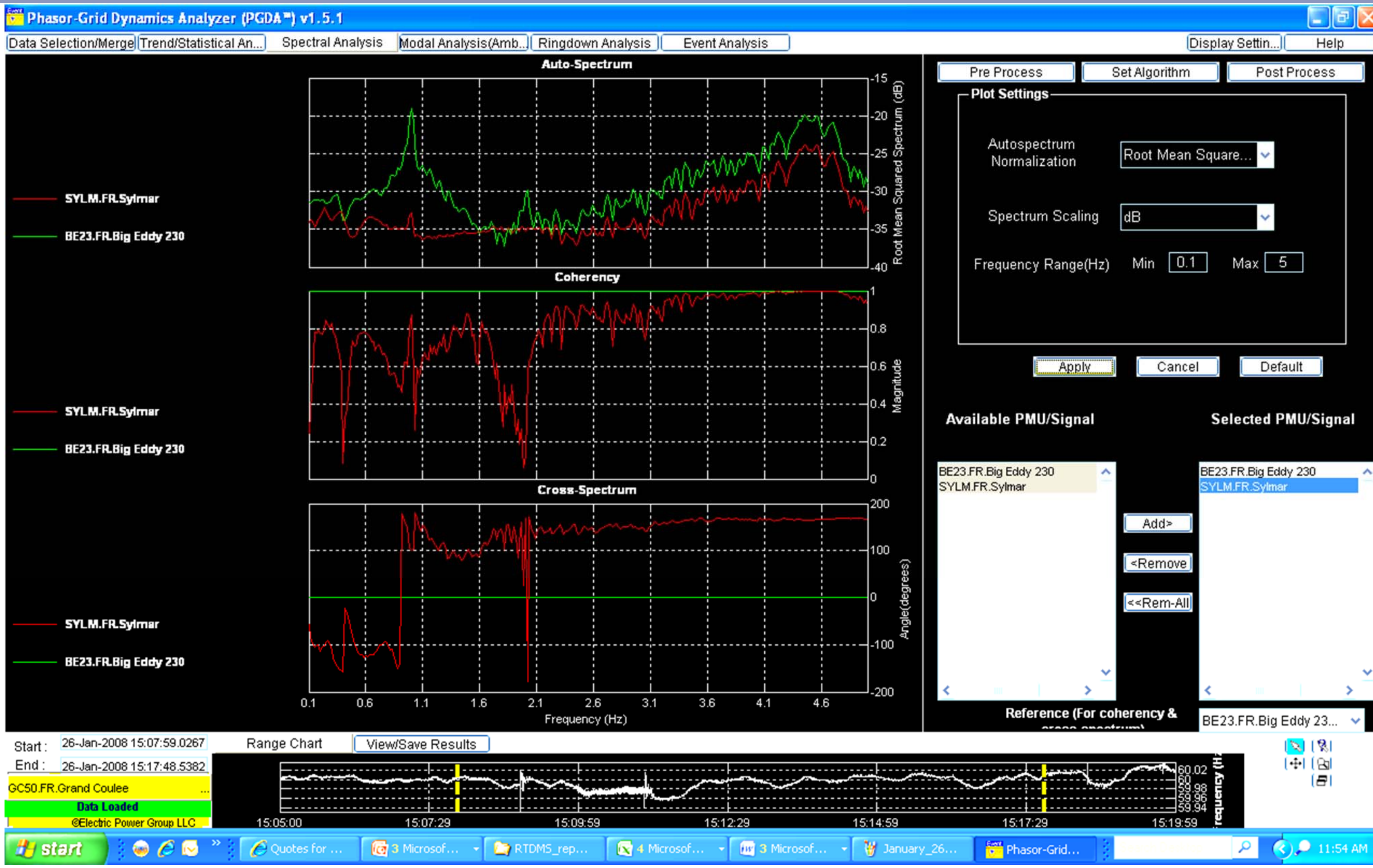
Large Sustained Frequency Oscillations Occurring at Celilo and Sylmar - January 26, 2008



Large Sustained Frequency Oscillations Occurring in the System - January 26, 2008



Spectral Analysis of January 26, 2008 Event



Use of Synchrophasors Technology at CAISO

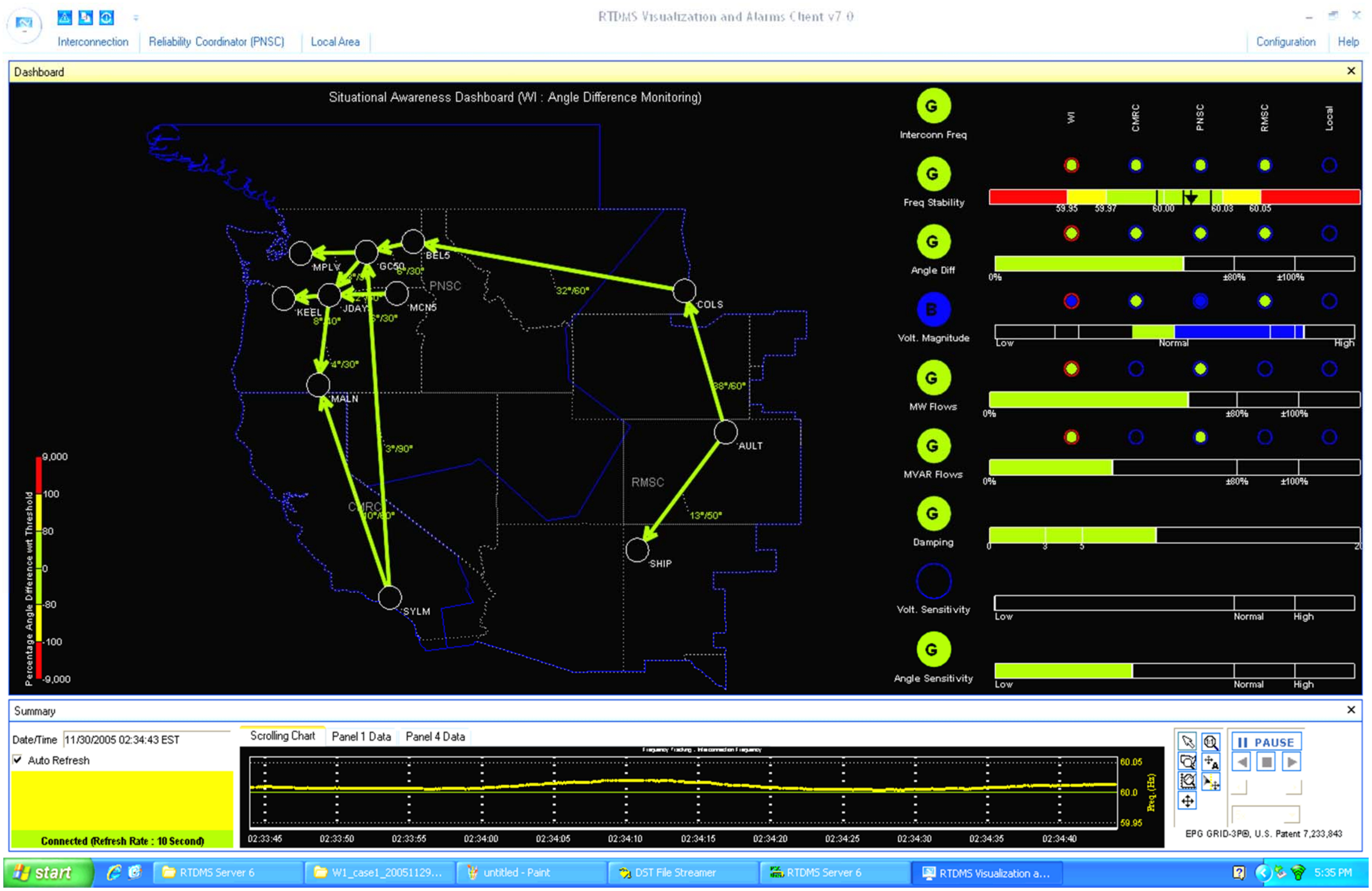
- CAISO Phasor Initiative began in September 2002 with the installation of a PDC
- Initial data from 14 BPA PMUs
- Followed by data from WAPA, SCE, PG&E came online
- Applications developed by EPG

The Goal:
Real-time, Wide-area Situational Awareness
for Improved Reliability

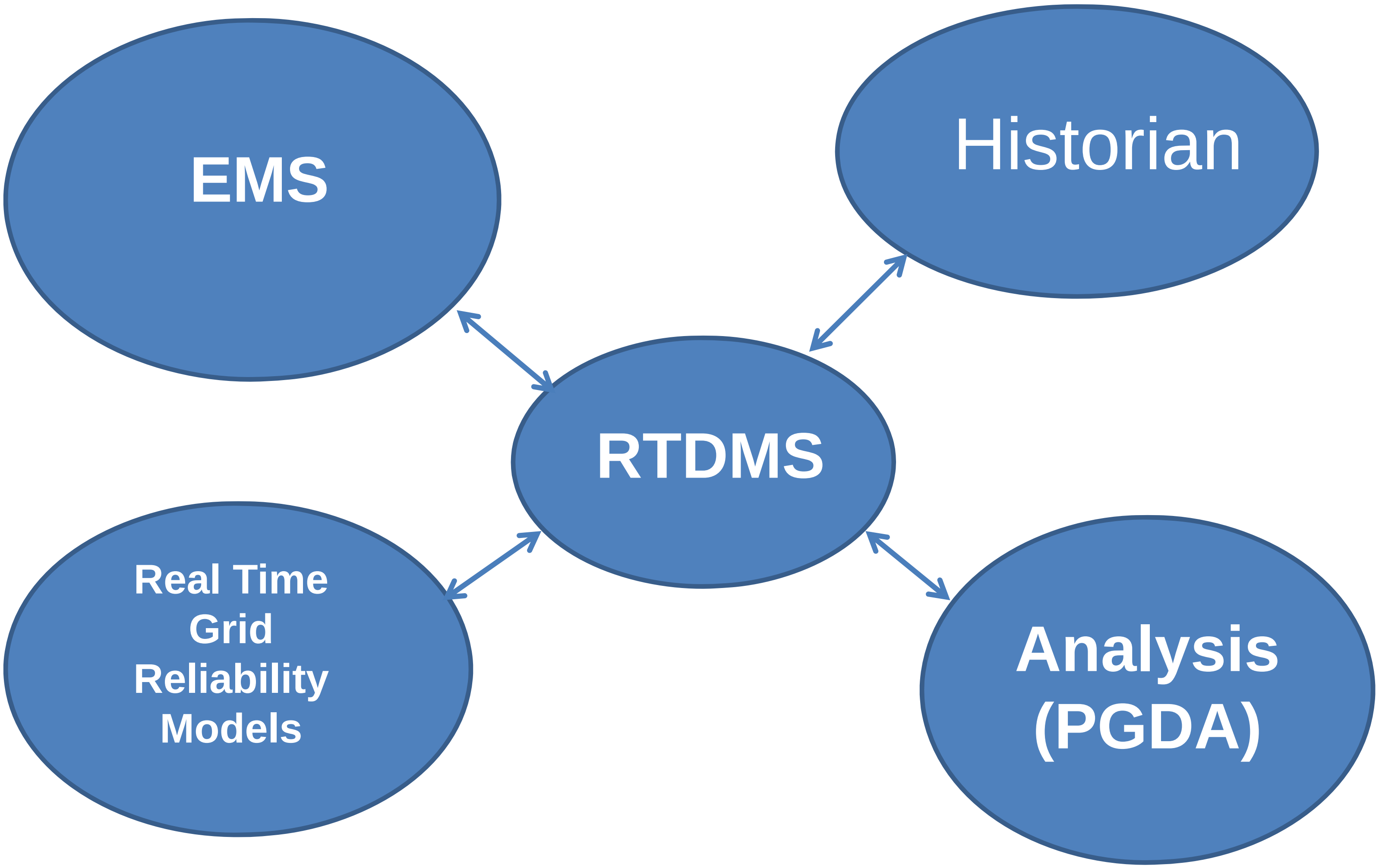
From Concept to Control Center

- Started with a simplistic visualization of the synchrophasor data with RTDMS
- CAISO's phasor application functionality rapidly evolved
  - Event detection & archiving, Alarms, Dynamic Monitoring....
  - Adapted visualization to the requirements of operating staff
  - Dashboard for CAISO centric operations
- RTDMS migrated to control center in 2008

RTDMS Monitoring system displaying WECC system Dashboard



INTEGRATING SYNCHROPHASOR TECHNOLOGY



Summary / Conclusions

- Power systems have become very large and have complex dynamics
- Lack of Wide Area Situational awareness has resulted in system disturbances and black outs
- We need tools to understand the power system complexity, wide area situational awareness and be prepared to take appropriate actions
- Synchro phasors tools are available and their use by system operators can help improve system operations and avoid disturbances and blackouts
- Having a Fire Extinguisher is not enough, you need to know how to use it when need arises
- Several Utilities, System Operators and Reliability organizations are implementing Synchro Phasor technology in control rooms in US and other parts of the World

Wide Area Visualization on your Desk Top
Closed Circuit Television for your Power Grid

THANK YOU.

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