Training Operators in Synchronized Phasor Measurement Technology by Simulating Major WECC System Events

Prepared by

Armando Salazar

Southern California Edison

And

Bharat Bhargava

Advanced Power System Technologies, Inc.

www.advancedpstinc.com

April 25, 2018

Synchronized Phasor Measurement Technology (SPMT)

SPMT is a new technology that can enable operators to

- Monitor the entire power grid control area in real-time
- Receive data from far-off locations, process and view in less than tenth (0.1 second) of a second
- Forewarn operators and thus help them in avoiding a minor system event cascading in to a major disturbance
- ***Are we doing these ?***

Synchronized Phasor Measurement Technology

Basic causes of some of the Past major disturbances:

- **SDGE** – September 8, 2011 – Path Overloading and Large angle difference across the breaker restricting reclosing the line
- **India Northern Grid** – July 30/31, 2012 – Protection Zone Encroachment
- **Europe** – November 6, 2004 – High wide area angle stress and growing Oscillations
- **Western America** – August 10, 1996 – High Angle stress and growing oscillations
- **Eastern US and Canada** – August 14, 2003 – Growing and diverging angles difference between Cleveland and West Michigan

Synchronized Phasor Measurement Technology

SPMT has the capability to monitor and forewarn operators if the system experiences:

- High Wide Area Angle stresses – Static and Dynamic
- High Angle sensitivities
- Poor Voltage profiles and high voltage sensitivities
- Poorly damped or growing modal oscillations
- Path overloading
- Protection Zone encroachments

Synchronized Phasor Measurement Technology

SPMT is a new, powerful Technology

Operators need to be trained in

- use of SPM technology and
- how to recognize threatening situations

An easy way to train operators is using

- Past recorded system events
  - Limits the training to only the recorded events
- Using simulated events
  - Provides the flexibility to train operators on any severe system condition

SCE Power System Outlook and SMART Programs

SCE Power System Outlook and SMART Programs

- Programs are simple to use
- Require minimum training
- Easy to install and operate
- PSO program has been distributed freely by SCE and presently has about 80 users
- PSLF Simulation plot files can be converted to dst (IEEE 1344) format and viewed using PSO and SMART programs
- The dst files can be stored as permanent record and viewed and played any time.
- For PSO program information, please contact Mr. Armando Salazar at armando.salazar@sce.com or call Phone number (714) 934-0819

SCE Power System Outlook and SMART Programs

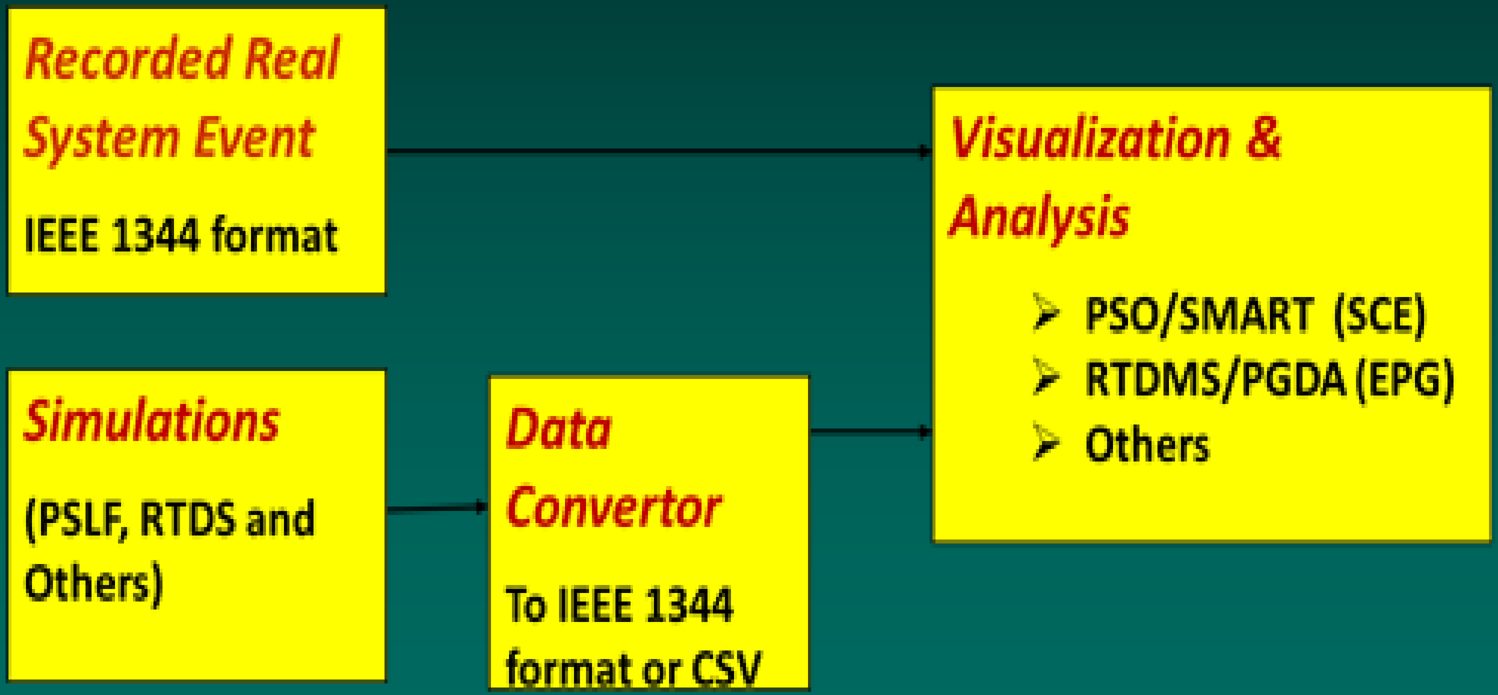
SCE Power System Outlook Program

- Developed by SCE in 1998-2006 Time period
- Can be used to visualize SPMS data
- Takes 3 minutes to 15 minutes long dst (IEEE1344) files
- Presently limited to 30 PMUs
- PSO need to be upgraded to use C37.118 format and higher number of PMUs

SCE SMART Program

- Developed by SCE in 2005-2008 Time period
- Can be used to visualize SPMS real time streaming data
- Takes 3 minutes to 15 minutes long dst (IEEE1344) files
- Limited to 30 PMUs presently
- Can be upgraded to use C37.118 format and higher number of PMUs

Simulation and Validation of Events using PSLF Simulation with PSO and SMART and Comparison with Real Events



Simulation of San Diego Gas and Electric System Blackout on September 8, 2011

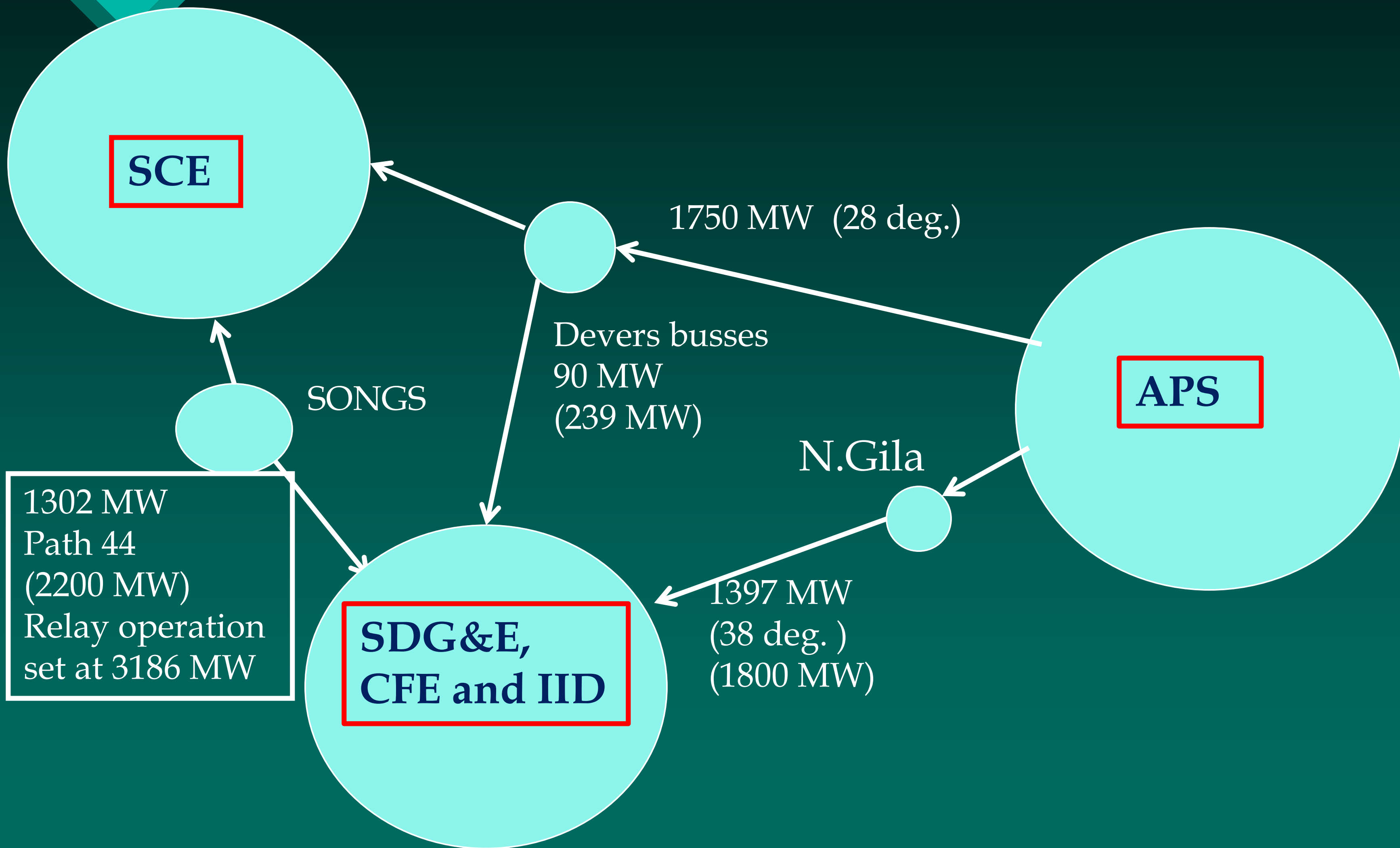
San Diego Gas and Electric System Blackout on September 8, 2011

- **San Diego system imports power on two major import paths**
  - Hassyampa – N. Gila- Imperial Valley – Miguel 500 kV line
  - South of SONGS – Five 230 kV lines (Path 44)
  - Power also flows thru the underlying 220/115/92 kV system from SCE Devers bus to IID and Western Administration – Lower Colorado
- **SDG & E had established individual path ratings**
  - Hassyampa – N. Gila – 2200 MW
  - Path 44 south of SONGS – 1800 MW
- SDG & E monitors these thru the EMS / SCADA system
- The (N-1) criterion requires that other system components should not overload for loss of a line/component

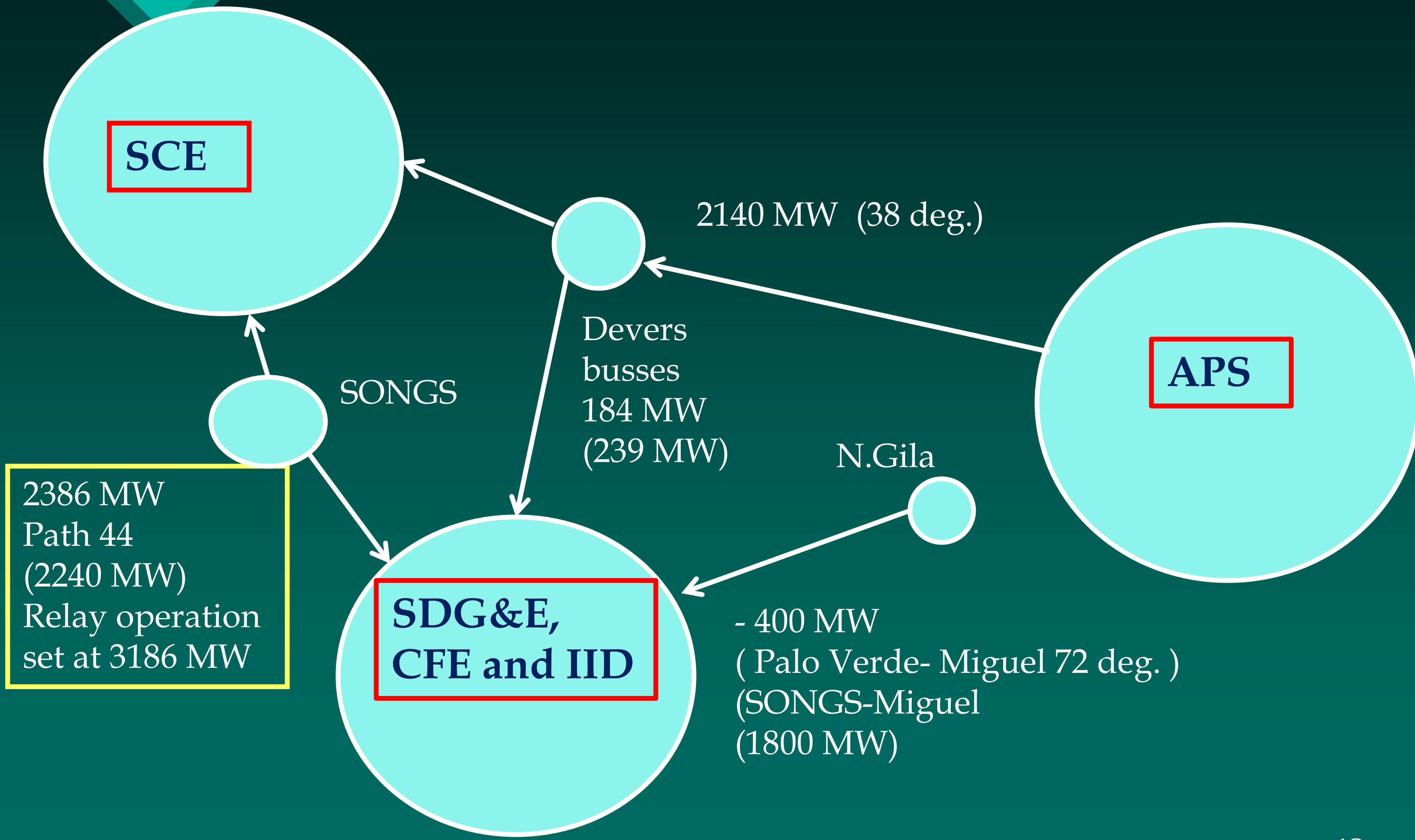
San Diego Gas and Electric System Blackout on September 8, 2011 – Sequence of Events

- Heavily loaded system and stressed system conditions with 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
- 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 increased power flow on Path 44 from 1302 MW to 2386 MW which exceeded the path 44 rating of 2200 MW.
- This indicates that SDGE may have been operating beyond the safe operational limit

Power Flows to SDG&E, CFE and IID before the N. Gila – Hassyampa line trip



Power Flows to SDG&E, CFE and IID after the N. Gila – Hassyampa line trip



Study / Simulation Process

- Match and tune power flow case and dynamic files (Received from SCE)
- Developed switching sequence based on the FERC/NERC report
  - Simulation done based on six defined switching phases
- Conducted simulations for 10 minutes (15:25 to 15:35 PM)
- Compared current / power flows on different flow gates including South of SONG (Path 44)
- Identified stress locations during the disturbance
  - Voltage angle and magnitude, power flows and currents
- Stress locations identified:
  - Low bus voltages at Devers, Mira Loma, Serrano and SONGS
  - High bus voltages at Miguel, Imperial Valley and N. Gila
  - Power flow on Path 26 and on Palo Verde-Devers line - close to its rating
  - High Voltage angles across Palo Verde-Devers, Hassyampa-N. Gila, Mira Loma-SONGS, Miguel-SONGS, and Devers-SONGS
  - Power flow on South of SONGS (Path 44) exceeded the path separation setting

Sequence of Events* - 1

- **Pre-Disturbance Conditions (Before Hassayampa-North Gila line tripped)**
  - Hot, September day, with some generation and line maintenance outage
  - High loadings: Hassayampa-North Gila (H-NG) = 78%; Coachella Valley (CV) transf. = 83%; Ramon transf. = 68%
  - H-NG line series cap. bypassed due to phase imbalance; during switching sequence, APS technician forgot to bypass cap. bank before isolating it at H-NG line
  - Flow in H-NG = 1391 MW
  - Path 44 (South of SONGS) loading ≈ 3250 amperes (Rating = 8000 a**mperes)**

* As identified by FERC & NERC in its report

Sequence of Events - 2

- **Tripping of Hyssampa –N. Gila 500 kV line (15:27:39 – 15:28:16)**
  - H-NG trips at 15:27:39; large phase angle difference (> 60 degrees) prevents breaker/line re-closure
- **Tripping of CV 230/92 kV Transformers (15:28:16 – 15:32:10)**
  - At 15:28:16/17, CV 230/92 kV transf. trip; CV-Ramon 230 kV “KS” line carrying 41 MVA open-ended at CV
  - Path 44 loading ≈ 6600 amperes (Change ≈ 400 amperes)

Sequence of Events - 3

- **Tripping of CV 230/92 kV Transformers (15:28:16 – 15:32:10)**
  - At 15:28:16/17, CV 230/92 kV transf. trip; CV-Ramon 230 kV "KS" line carrying 41 MVA open-ended at CV
- **Tripping of Ramon 230/92 kV Transformers (15:32:10 – 15:35:40)**
  - At 15:32:10, Ramon 230/92 kV transformers trip
  - Between 15:32:11 and 15:33:46, 444 MW of IID's load tripped; nearly half of the load shed within 10 sec. of Ramon transf. trip and Loss of IID generators:
    - IID's Niland Gas Turbine (generating 45 MW)
    - IID's CV Gas Turbine 4 (generating 20 MW)
    - Independent power producer Colmac's unit (generating 46 MW)
    - IID's drop 4 unit 2 hydro-generator (generating 10.3 MW)
- **Separation of San Diego, CFE and IID system at 15:37:45**

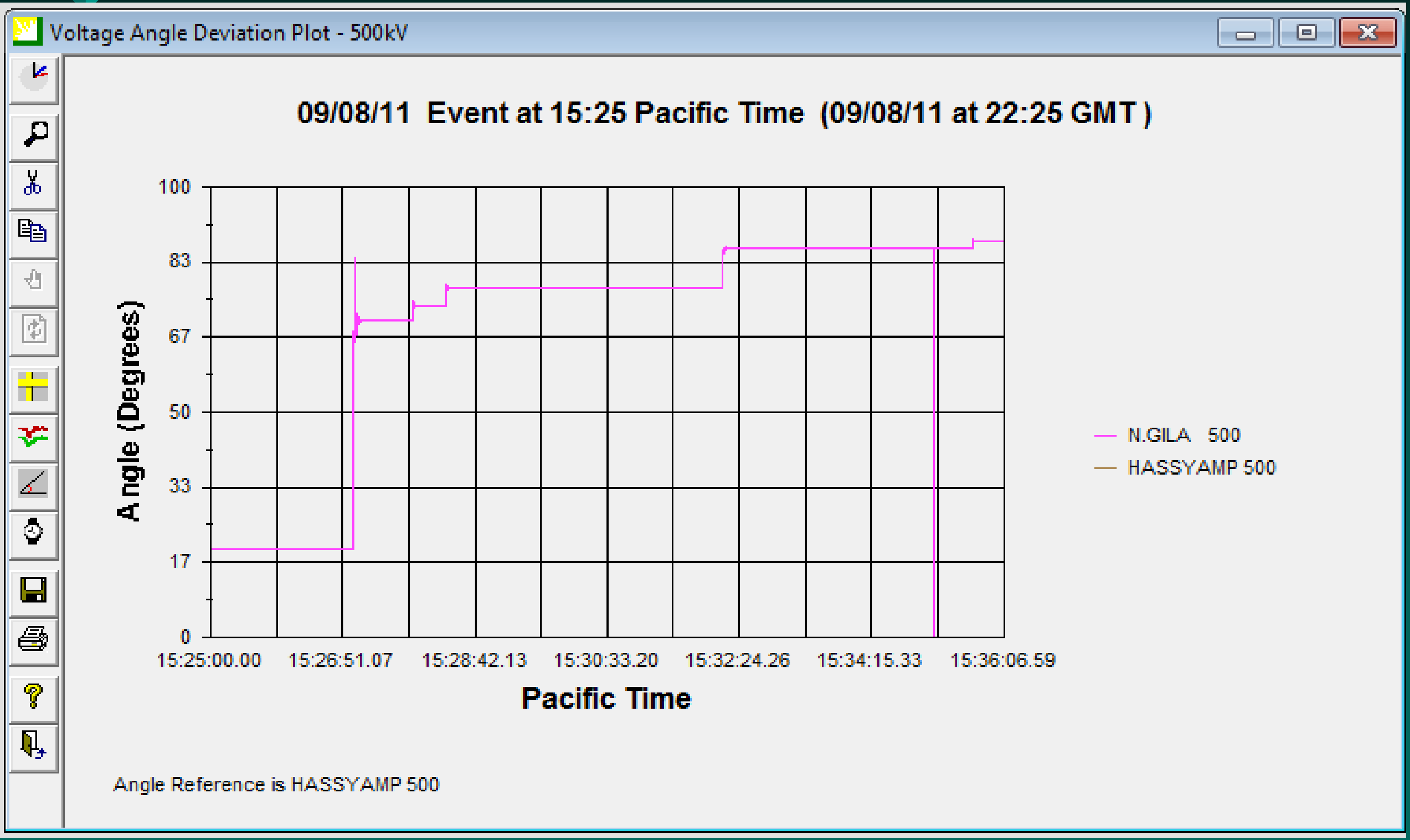
Synchronized Phasor Measurement Technology

SDGE, CA ISO and WECC Could have monitored using SPMT

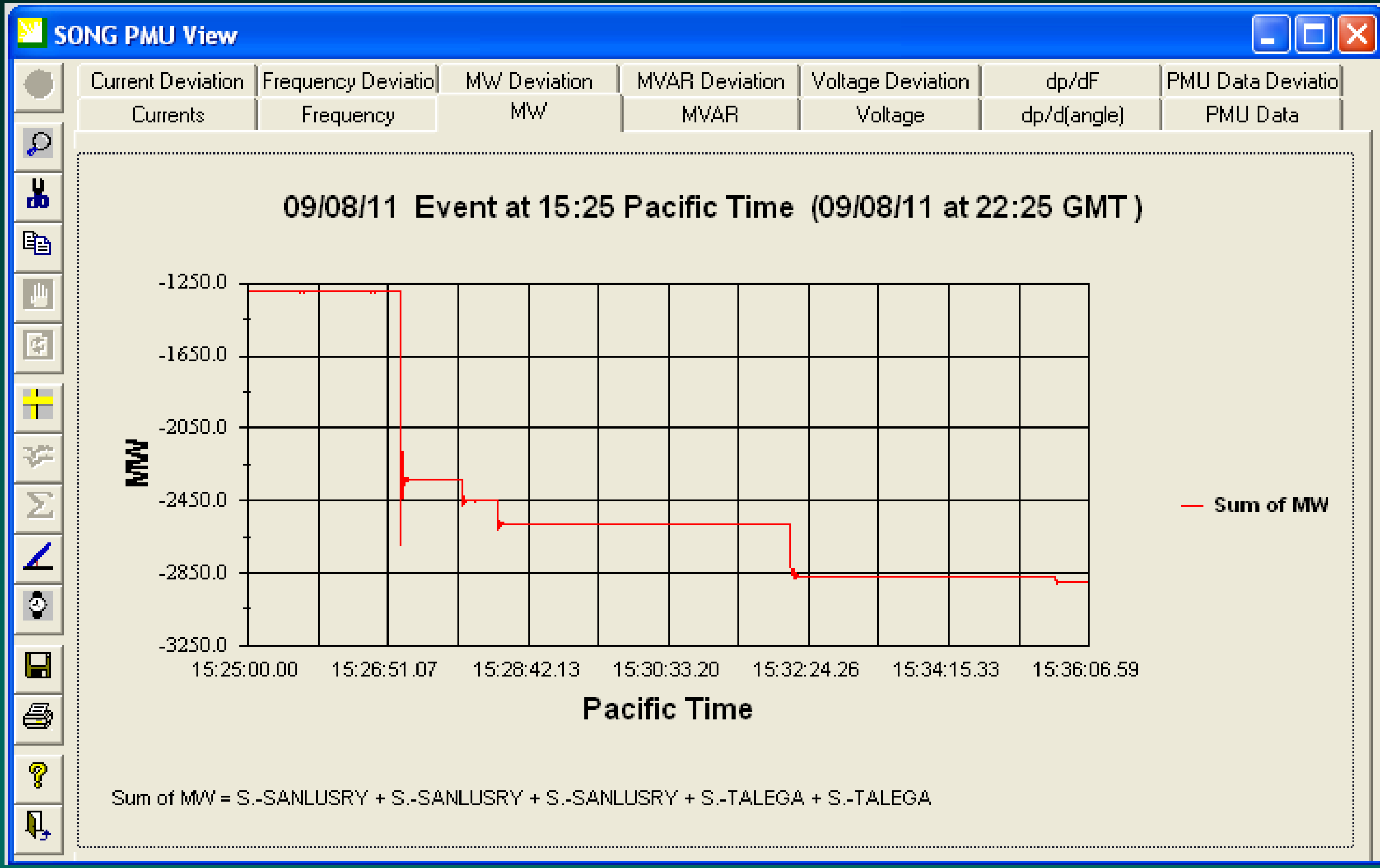
- Angle Differences
  - Hassyampa – N. Gila
  - SONGS - Miguel
  - Palo Verde – Miguel
  - Palo Verde – Devers
- Power Flows
  - Path 44
  - N.Gila – Imperial Valley
  - Palo Verde – Devers
- Voltages at
  - Miguel
  - Imperial Valley
  - Devers

Angle Difference (Hassyampa – N. Gila)

(Increased to more than 60 degrees after N. Gila – Hassyampa line trip)

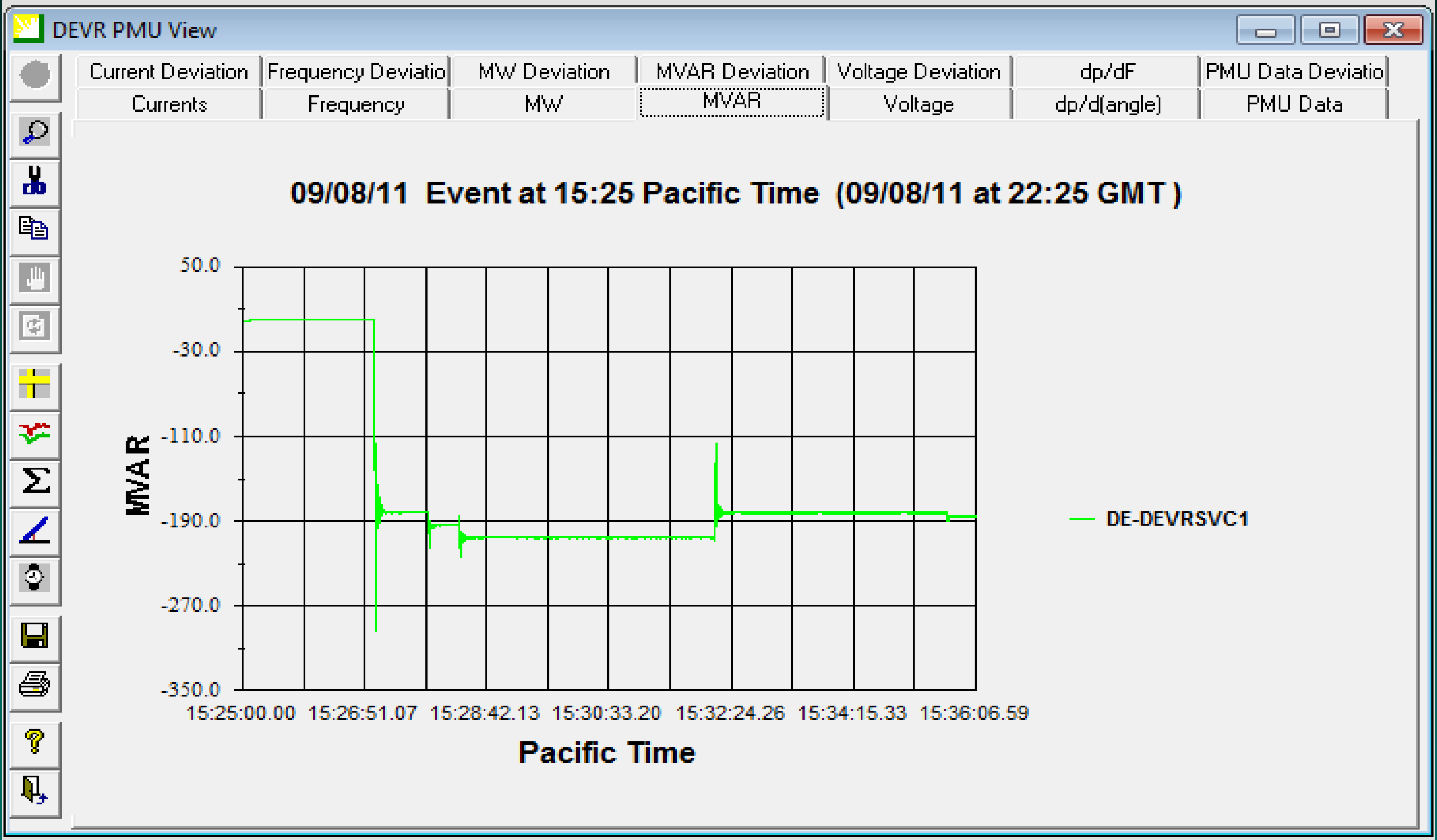


Power Flow on Path 44 (South of SONGS to SDGE)

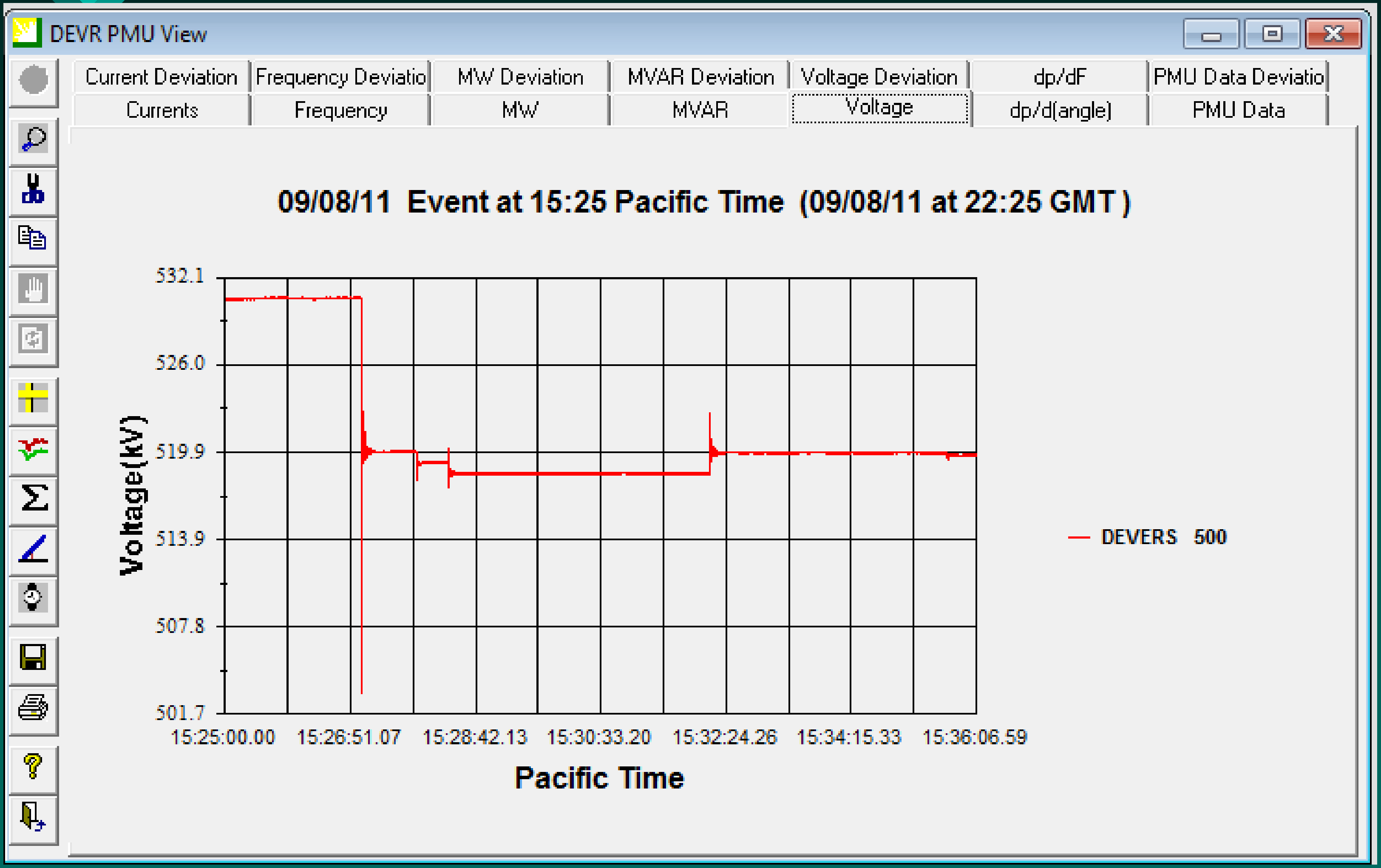


Megavar Flow at Devers Substation SVC

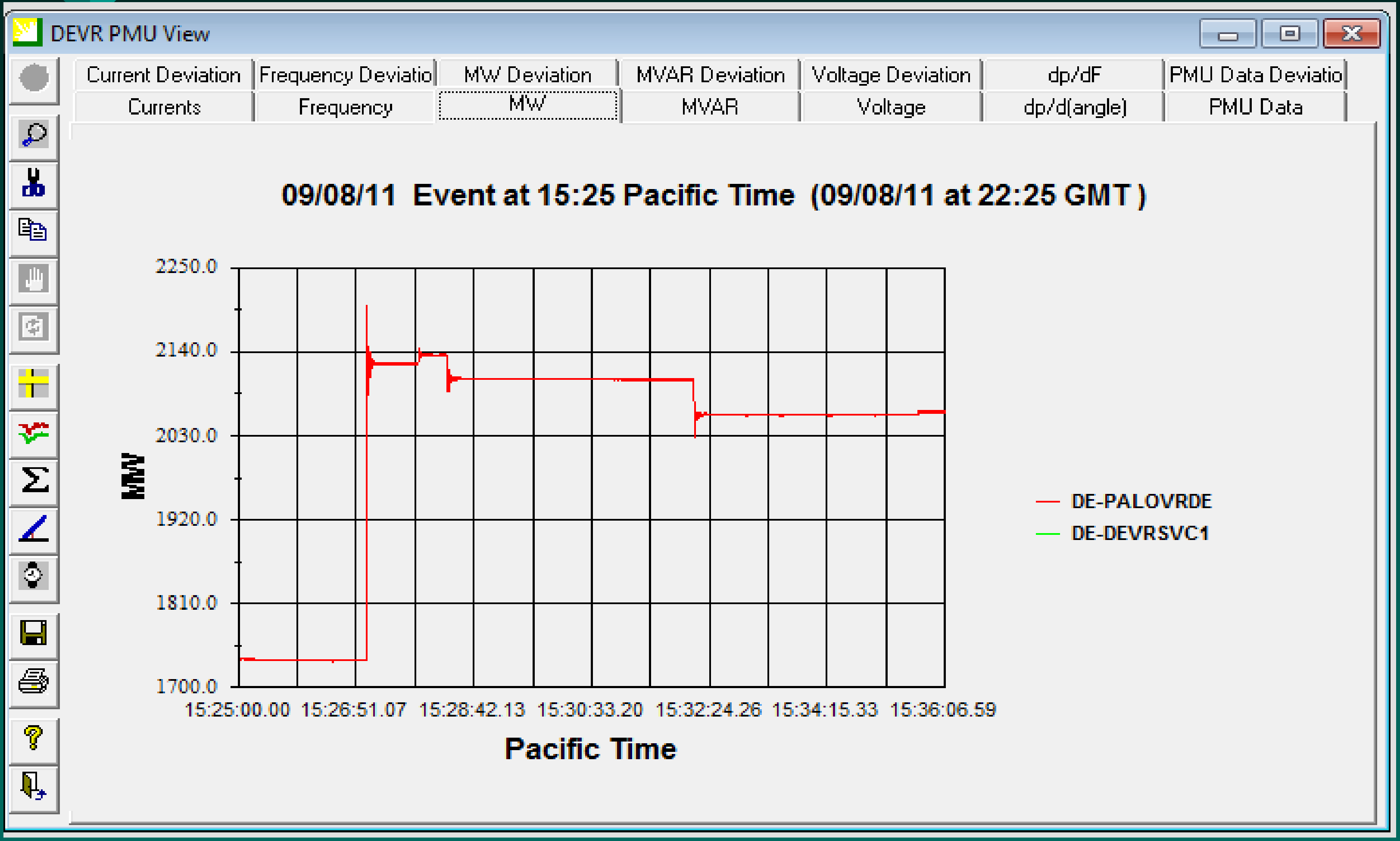
(Provided the much needed VAR support at Devers)



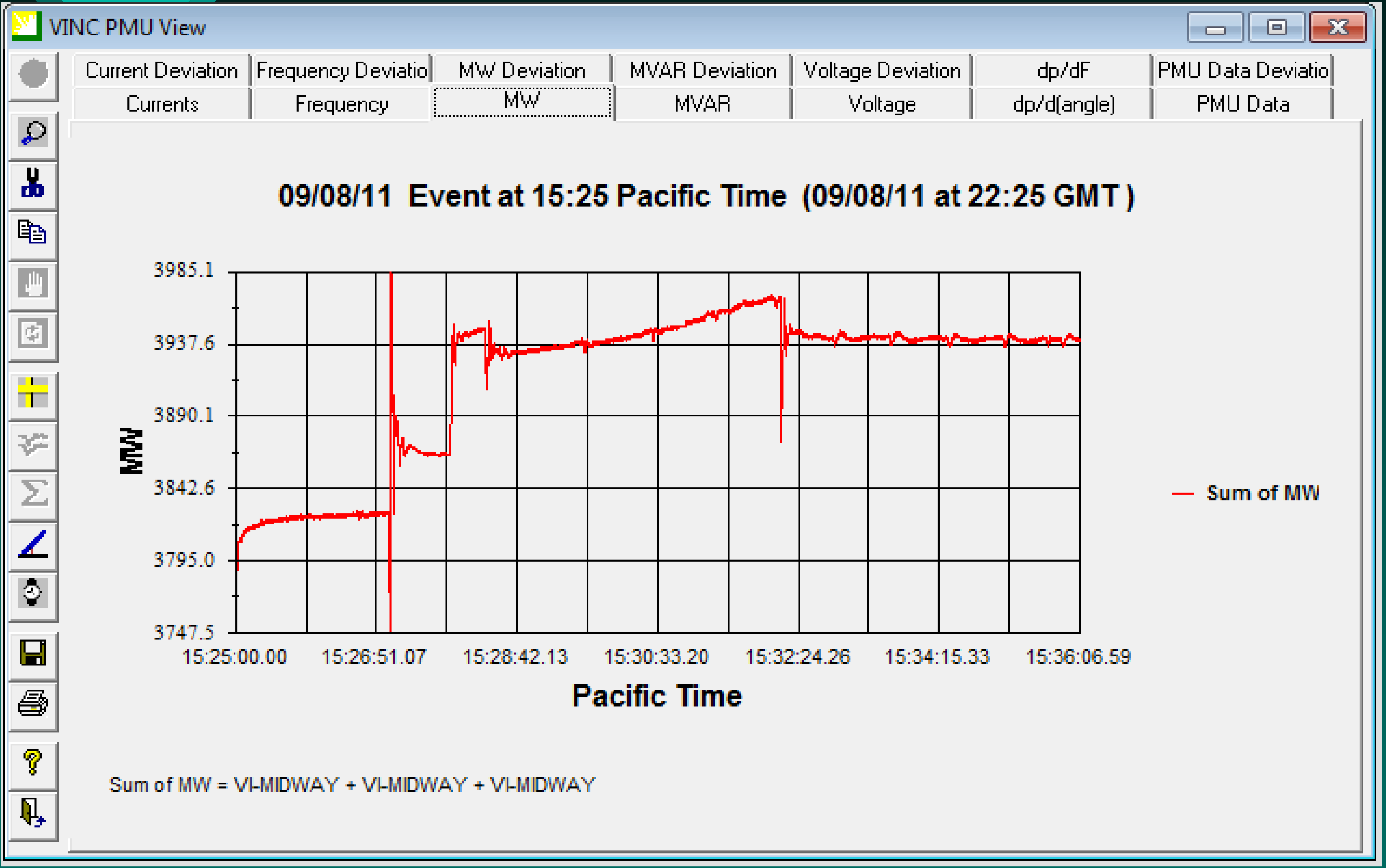
Voltage at Devers Substation
(Voltage maintained around 520 kV by SVC)



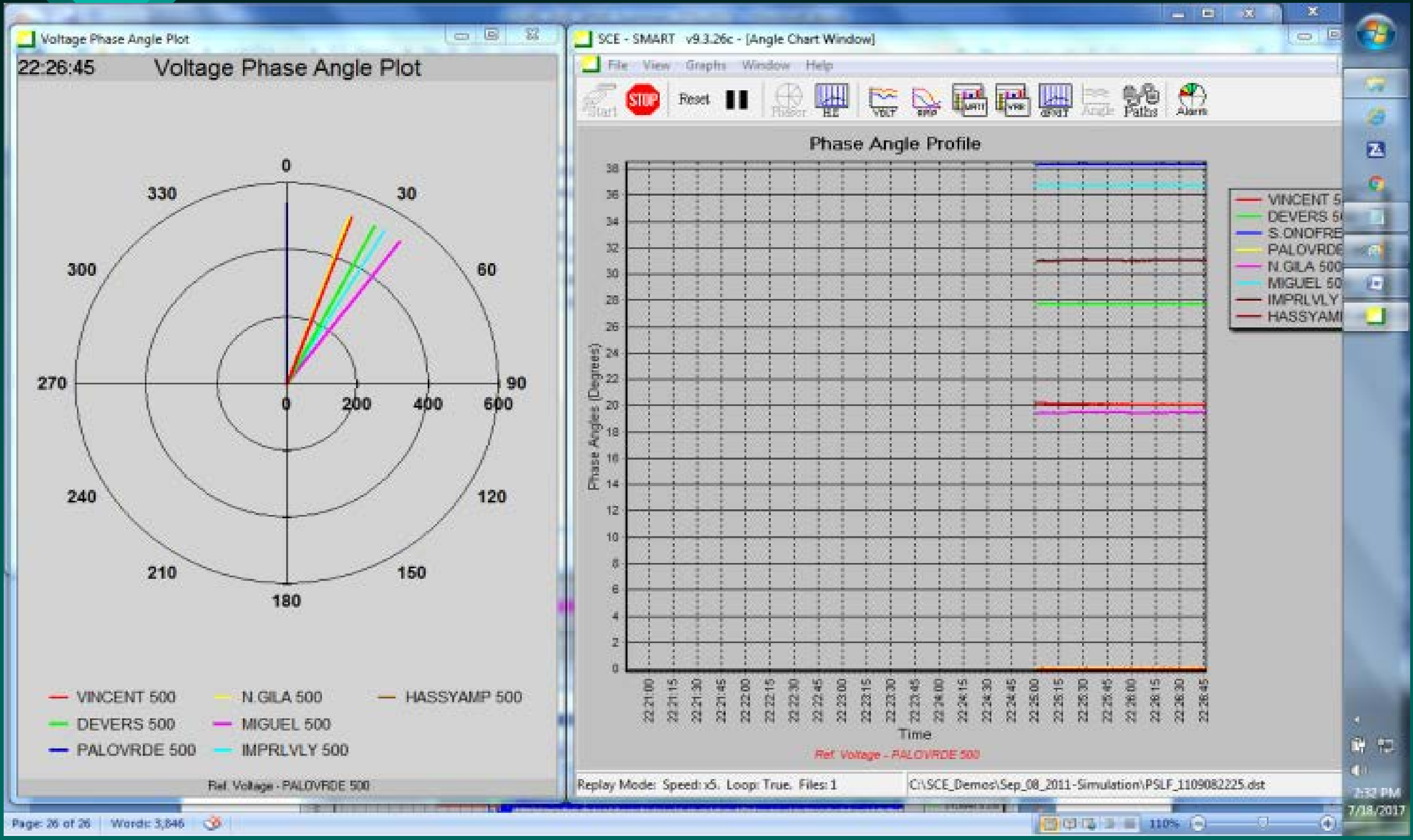
Power Flow on Palo Verde - Devers line



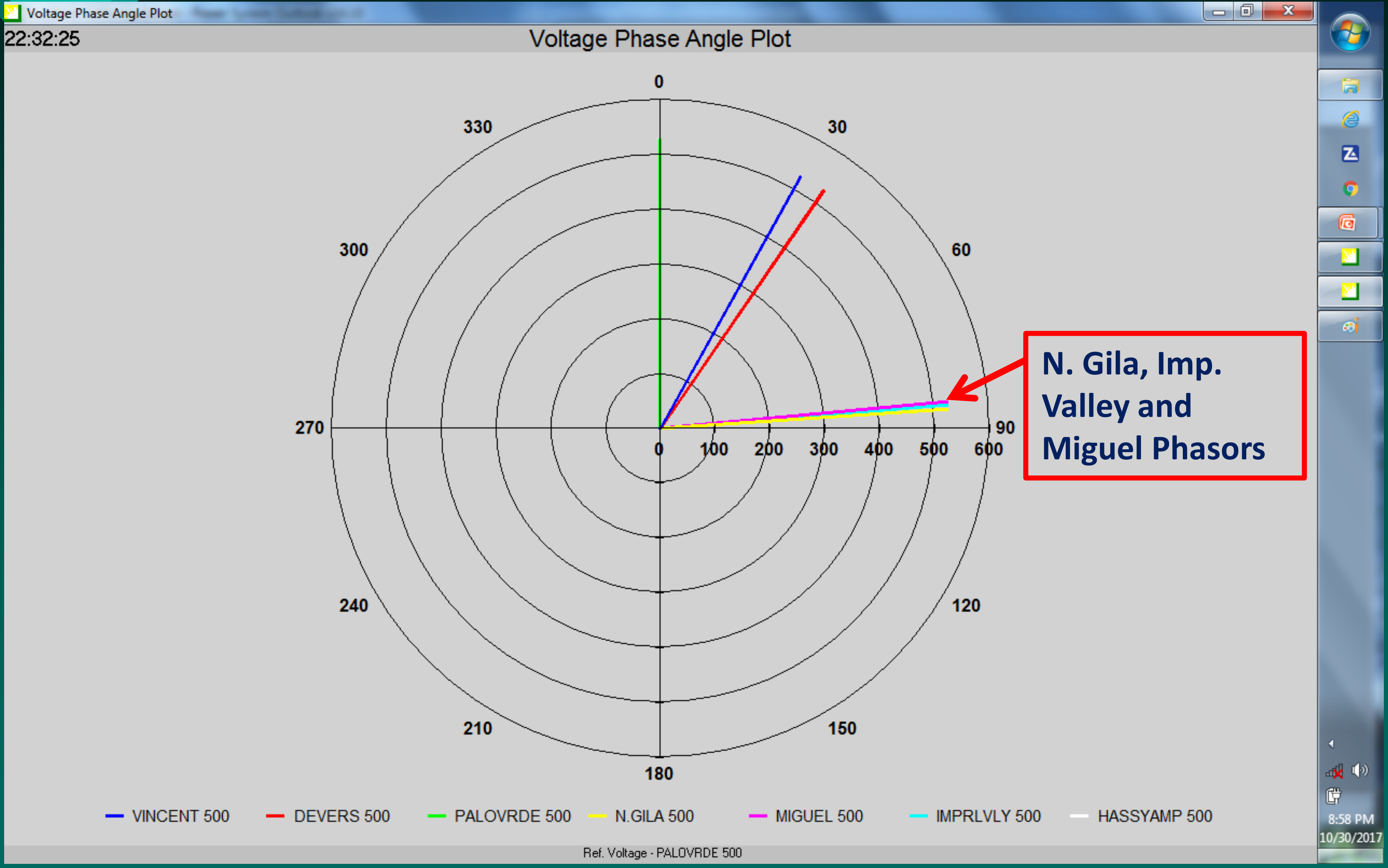
Power Flow on Midway-Vincent lines (Path 26)



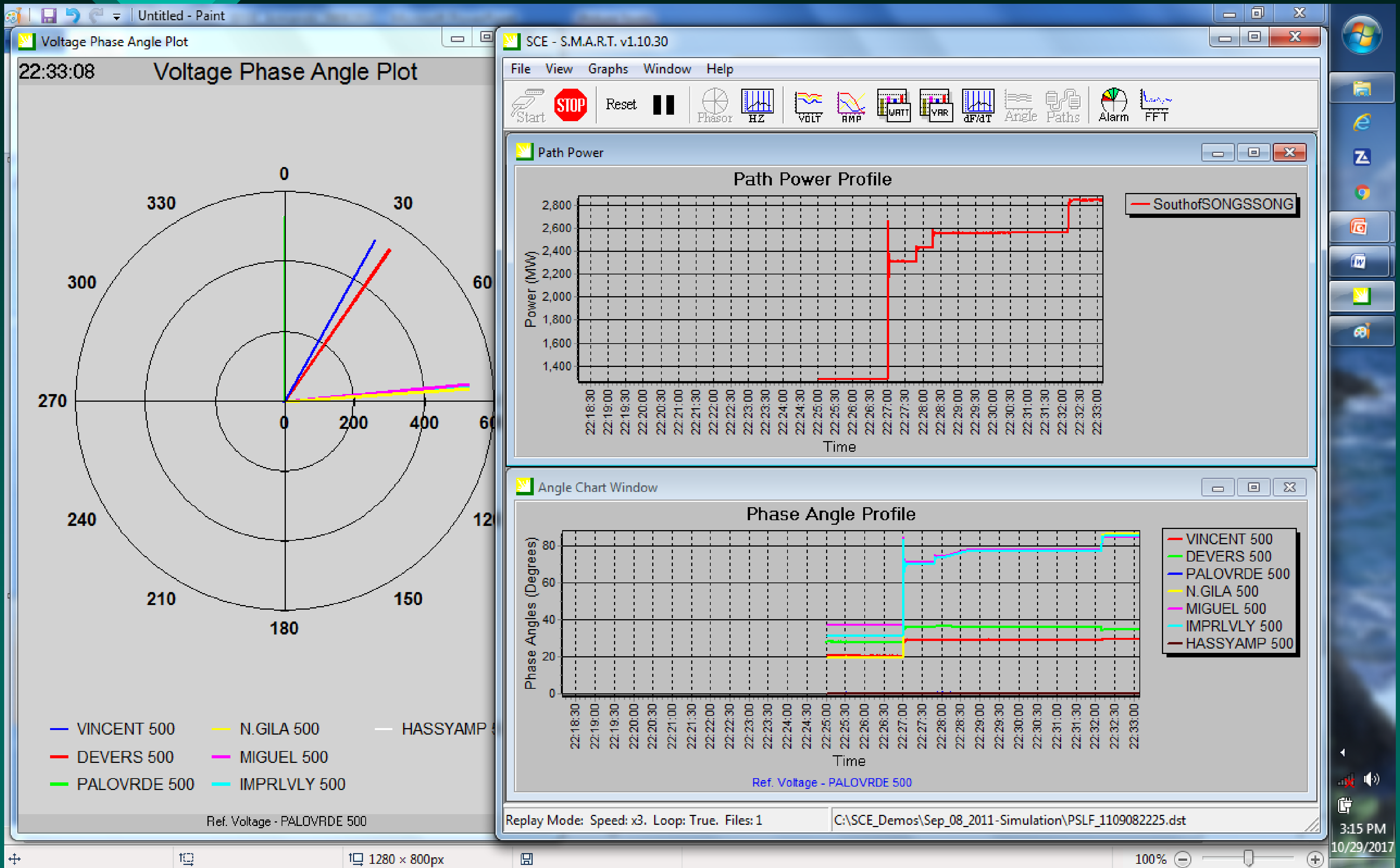
Angle –Difference (SONGS-Miguel) (SCE's SMART Program at 15:26:45)



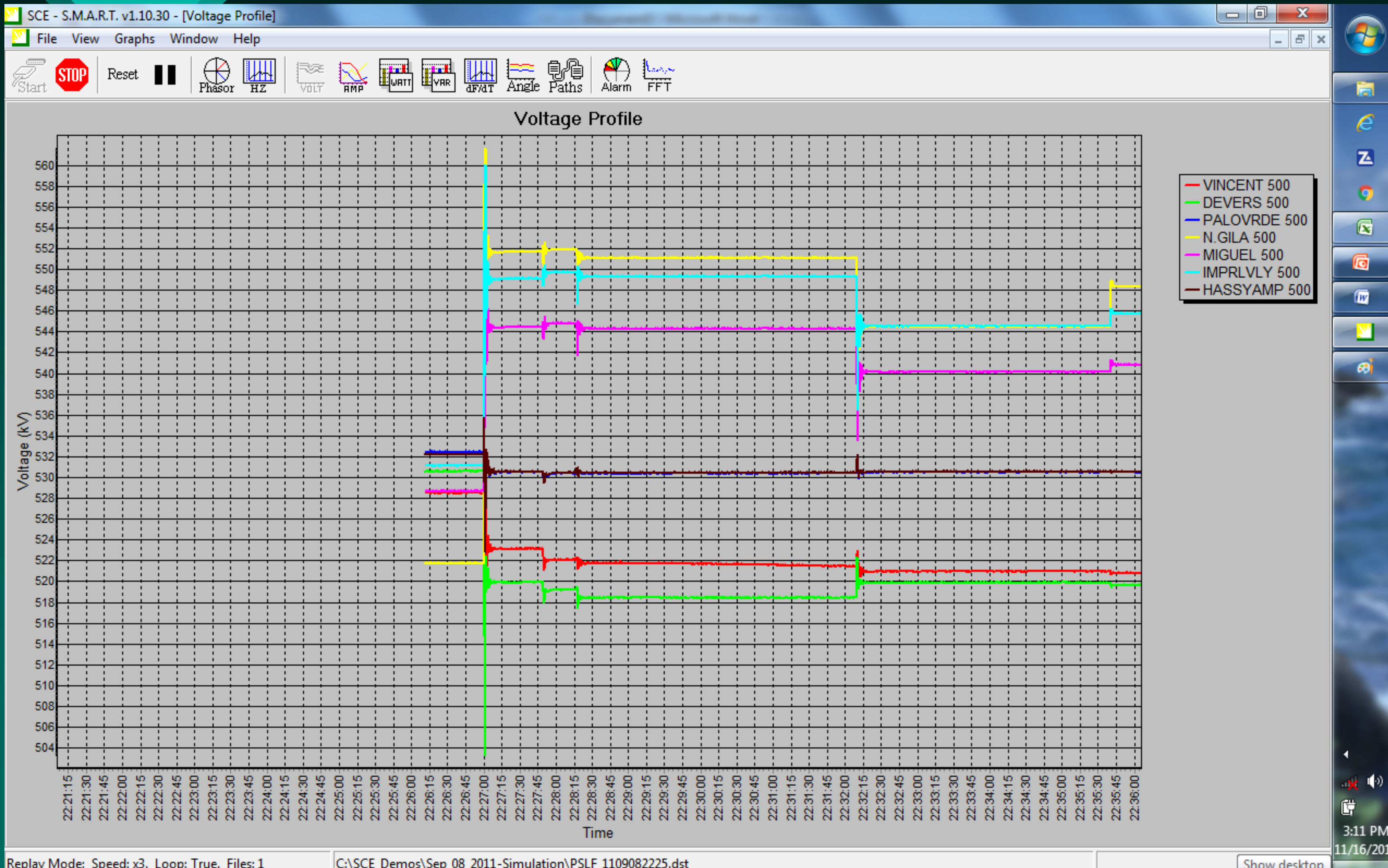
Angle –Differences
(SCE’s SMART Program at 15:32:25)



SCE's SMART Program showing Phasor plot, Angle Differences and Power profile at 15:33:08



SCE's SMART Program showing Voltage plots for some substations



Findings and Conclusions

- **PSLF Simulation resulted in a good event model that compares well with "Actual Event" based on the FERC/NERC report**
- **Use of Synchrophasor technology and "Real Time Wide Area Visualization" could have enabled the operators to observe**
  - Increasing Phase Angle Differences at key locations
  - Power flows on key paths
  - Low/high voltages at different busses
- **Alarm settings on all the above indicators can be used to alert operators of worsening system situation**
- **Cascade was stressing the system at several other SCE locations**

Findings and Conclusions (contd.)

- Cascade and collapse could have worsened if:
  - Devers SVC was not there or tripped i.e. No SVC at Devers or Tripping of SVC at Devers
  - Path 26 (Midway-Vincent lines) tripped
  - Additional generation tripped in CFE/IID/SDGE/Arizona/SCE area
- Simulated Event replay in real time can be seen using the SMART program – video to be attached
- Recommended next steps: simulations to identify vulnerabilities and guide operating, planning and investment decisions at SCE

PSLF Simulations of HVDC System Disturbance of January 26, 2008

Sequence of Events for HVDC System Oscillations Event on January 26, 2008

1409:01 the arcing caused a flashover on the 500 kV bushing operating the 500 kV Tie Line protection. At the same time the 500/230 kV Transformer #5 500 kV Tie Line protection also operated (improperly) due to a mismatch transformer CT ratio. Celilo 500 kV Converter #1 (previously out of service) de-energized at this time also. The transient voltage dip caused a momentary loss of PDCI power which triggered its Remedial Action Scheme to properly automatically insert the 500 kV Fort Rock Series capacitors.

1409 PDCI 1000 kV DC Line appeared to block and restart. Significant voltage dip felt throughout western portion of SCE system. System frequency swung between 59.94 Hz and 60.06 Hz momentarily.

1411: PDCI 1000 kV DC Line appeared to block and restart again. Significant voltage dip felt throughout western portion of SCE system.

1413: Noted very erratic frequency swings and oscillations as well as MW and MVAR swings and oscillations of all major interties. LDWP advises they do not see these indications nor do they believe they are coming from Sylmar Converter Station.

Sequence of Events for HVDC System Oscillations Event on January 26, 2008

1415: San Onofre Nuclear Generating Station called and inquired about system conditions causing erratic readings on both Unit 2 and Unit 3.

1420: Notified CMRC and ISO shift manager and expressed concern about current system conditions being detrimental to SCE operations.

1427 to 1432: Swings and oscillations ceased while PDCI was ramping down 500 MW and started again when ramp was complete.

1440: DFR analysis indicates excessive harmonics causing oscillations and erratic PDCI power control causing swings. Requested CMRC and ISO to discuss removing PDCI from service with affected parties.

1455: CMRC advises they issued directive to remove PDCI from service.

1505: PDCI ramped to zero, WECC Transfer Path 65 unavailable. System frequency to 60.06 Hz momentarily and normal in five minutes. Oscillations and swings stopped.

Using Synchronized Phasor Measurement Technology (1)

BPA, LA DWP , CA ISO and WECC Could have monitored following using SPMT

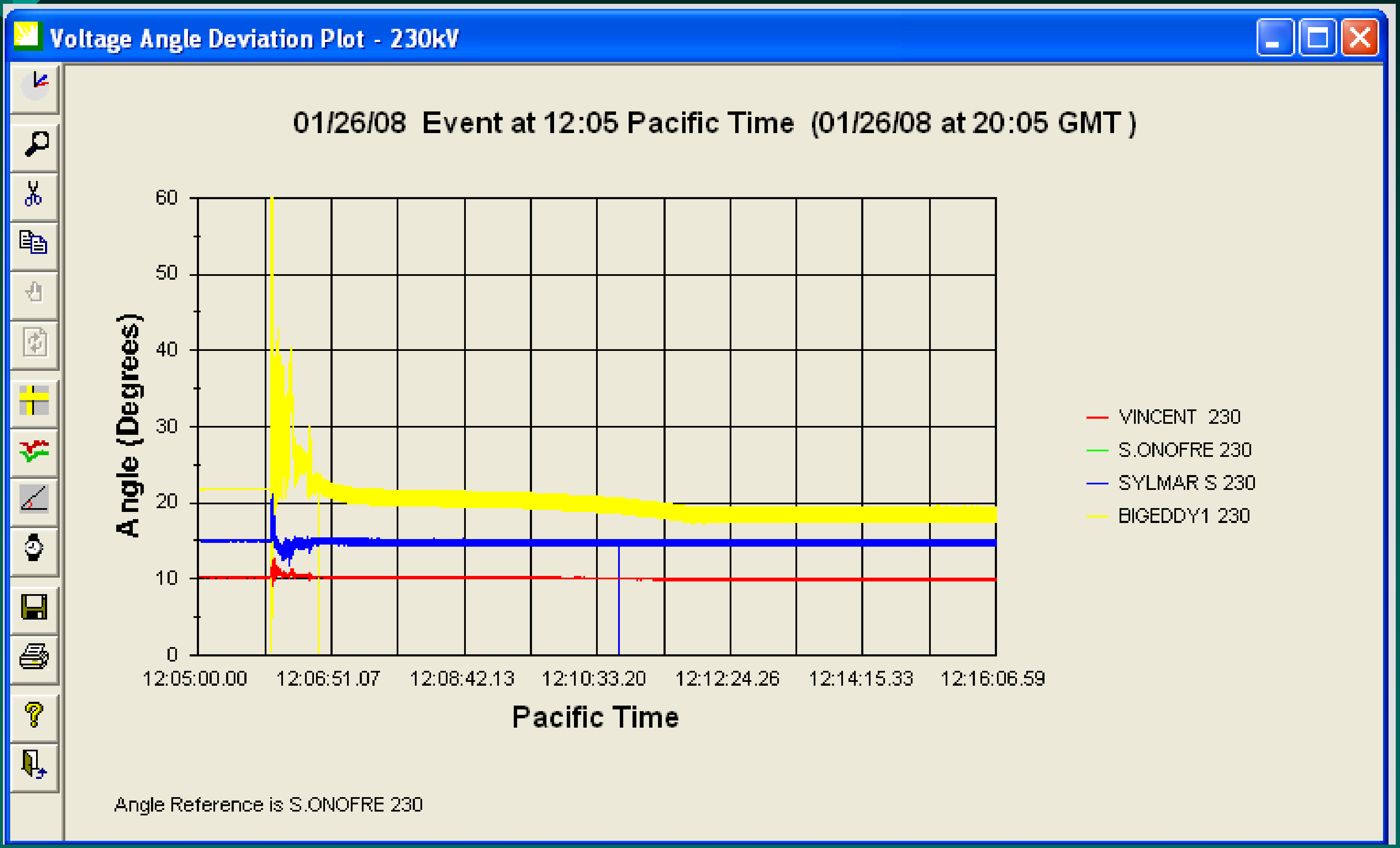
- Angle Differences
  - Celilo – Sylmar
- Power Flows
  - PDCI
  - SONGS Units
  - Palo Verde units
- Frequency
  - Celilo
  - Sylmar
  - Other locations

Using Synchronized Phasor Measurement Technology (2)

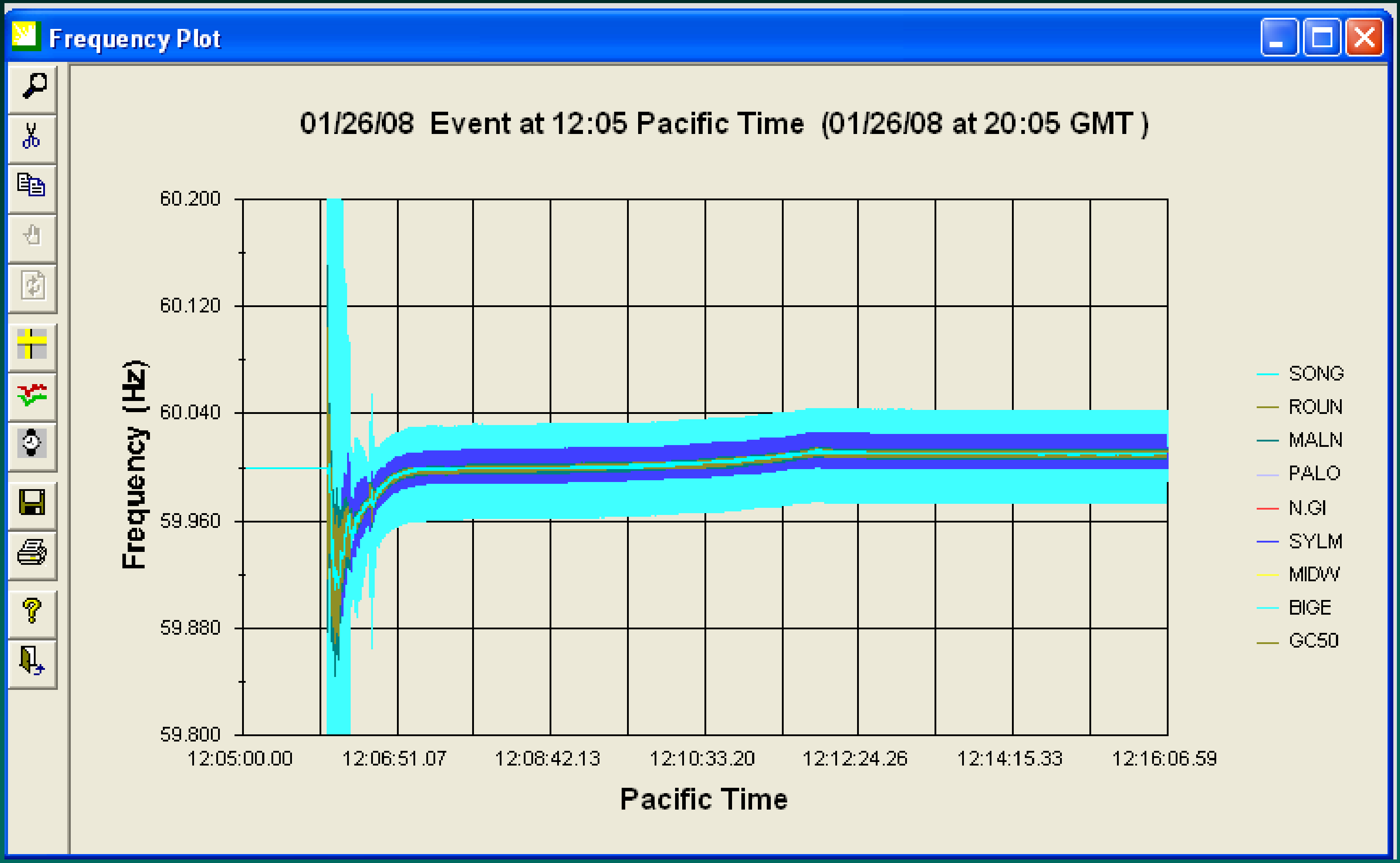
BPA & LA DWP CA ISO and WECC Could have monitored with SPMT

- Oscillations
  - PDCI
  - Pacific AC Inter-ties
  - Palo Verde units
  - SONGS units
- Voltages at
  - Big Eddy
  - Celilo / Sylmar
- Simulations conducted for ten minutes

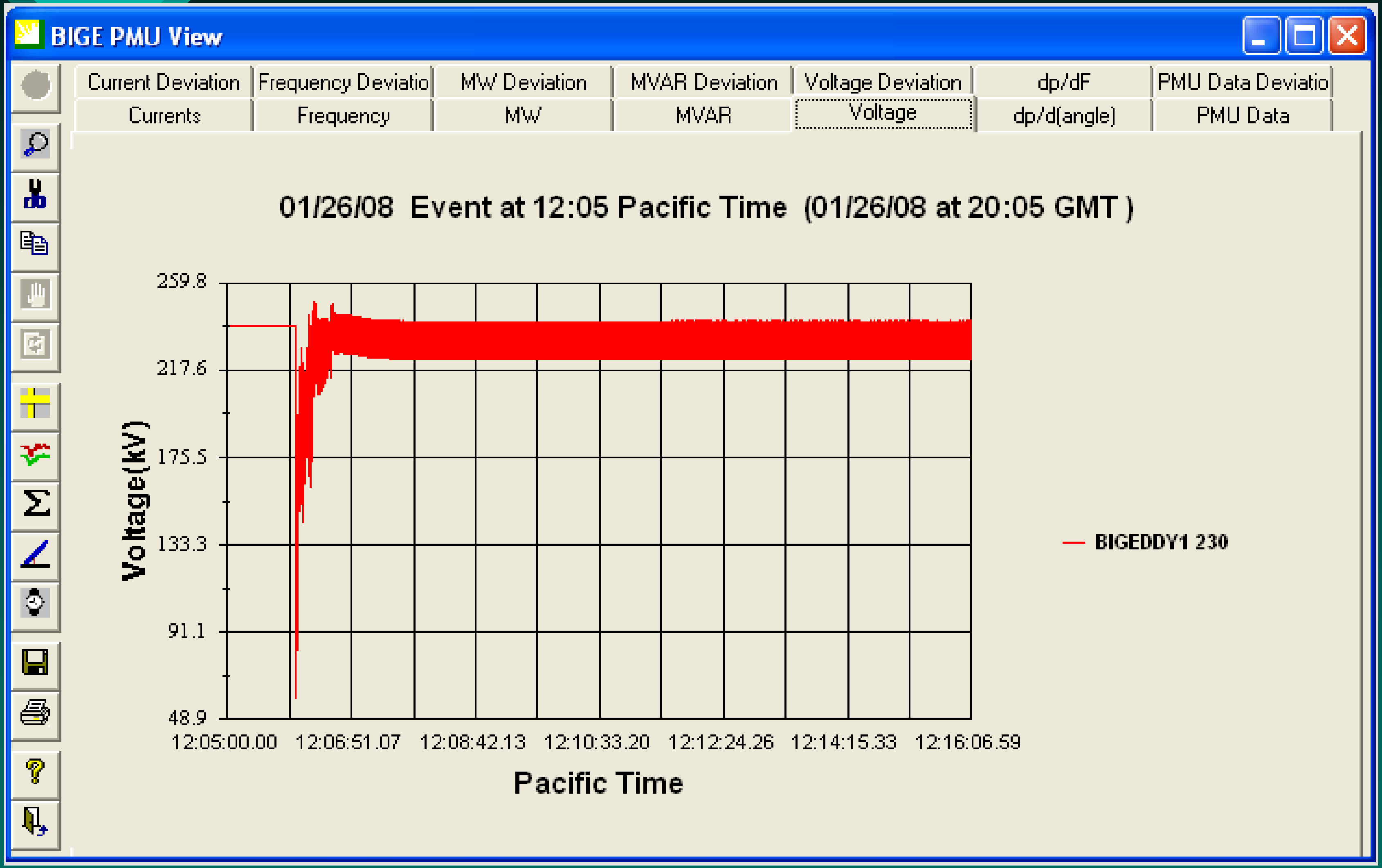
Angle Difference Big Eddy with respect to San Onofre



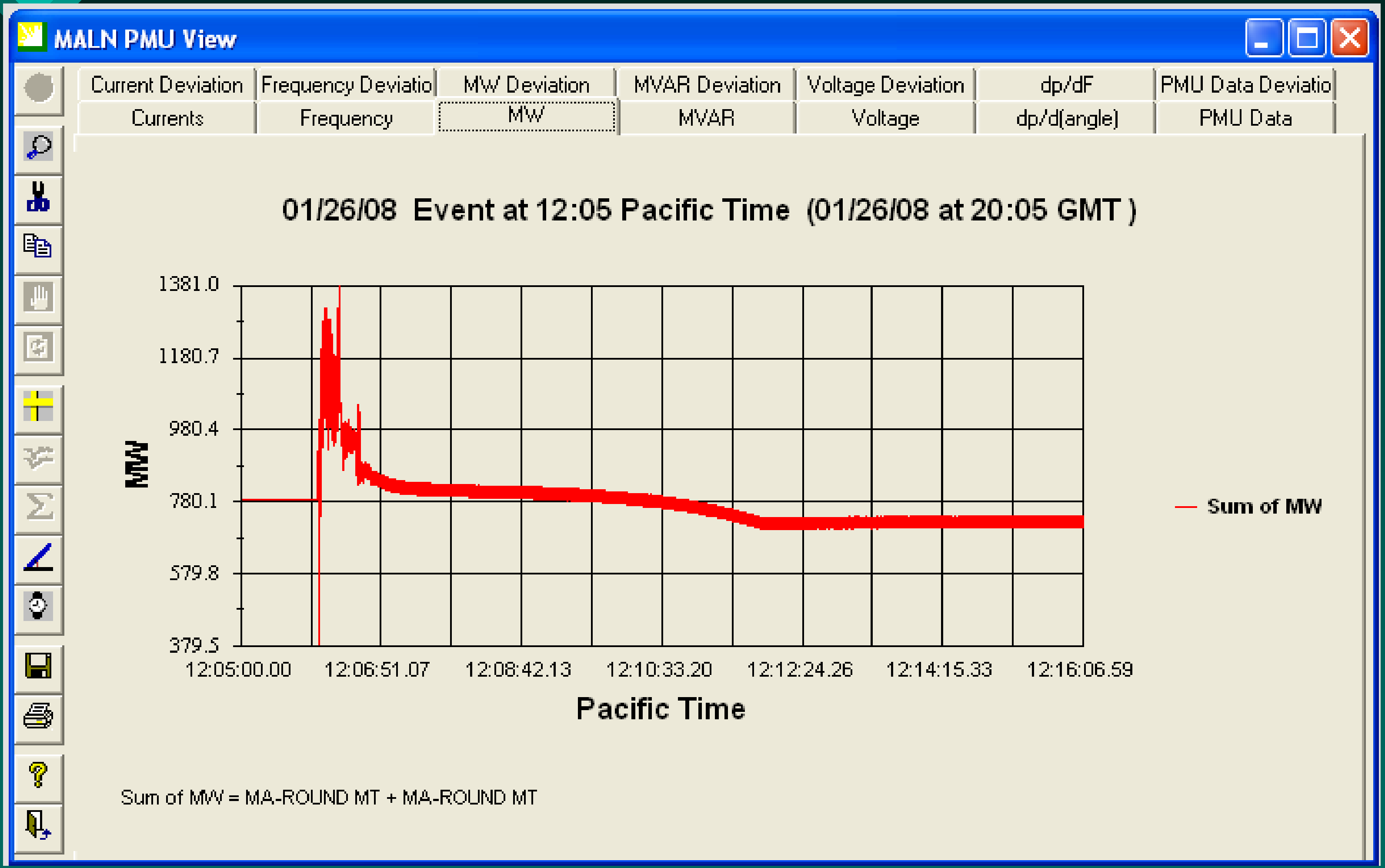
Frequency Deviations at Celilo and Sylmar Substations



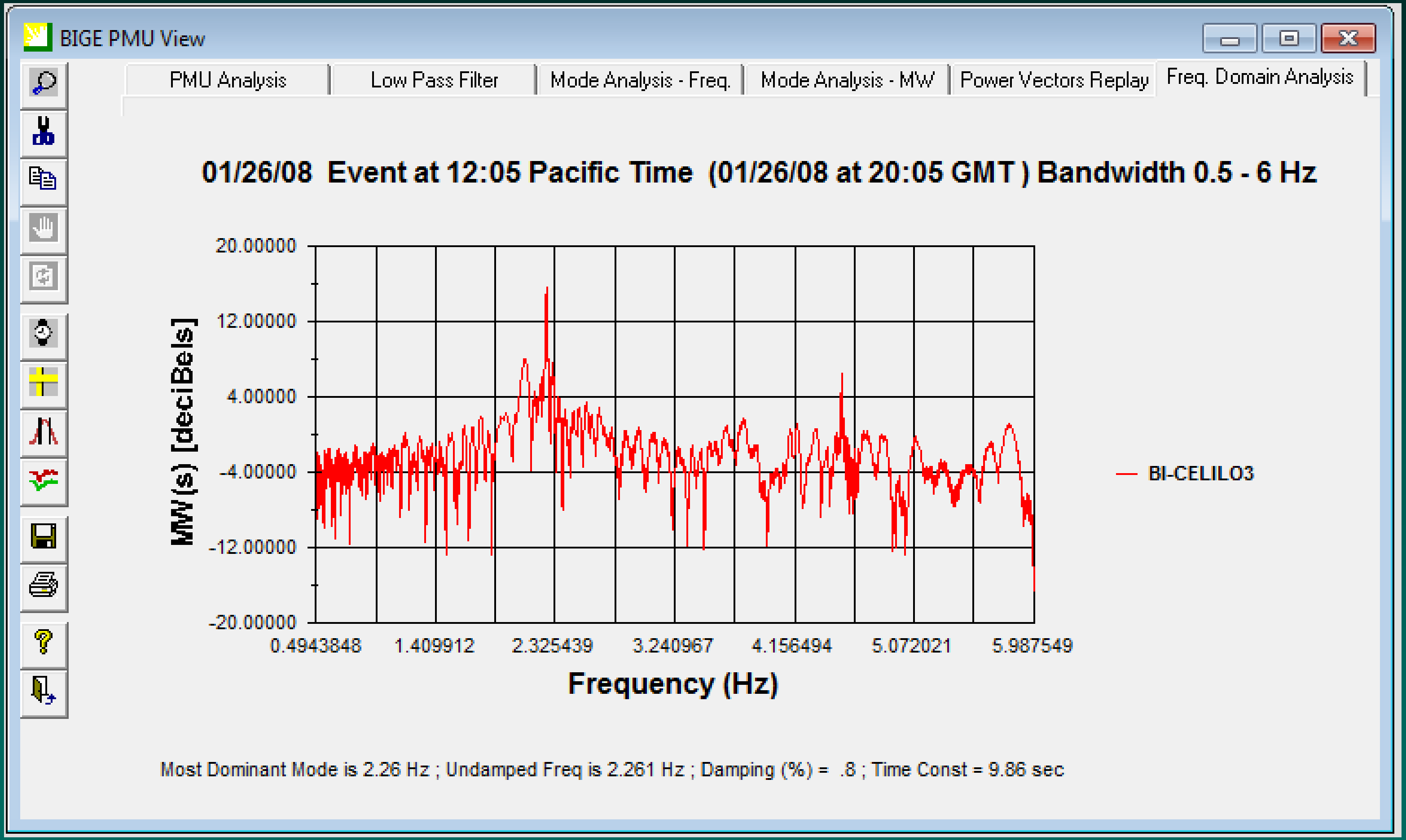
Voltage at Big Eddy 230 kV bus



Power Flow on Round Mountain-Malin 500 kV lines



FFT Analysis of Oscillations at Big Eddy Substation (Simulations)



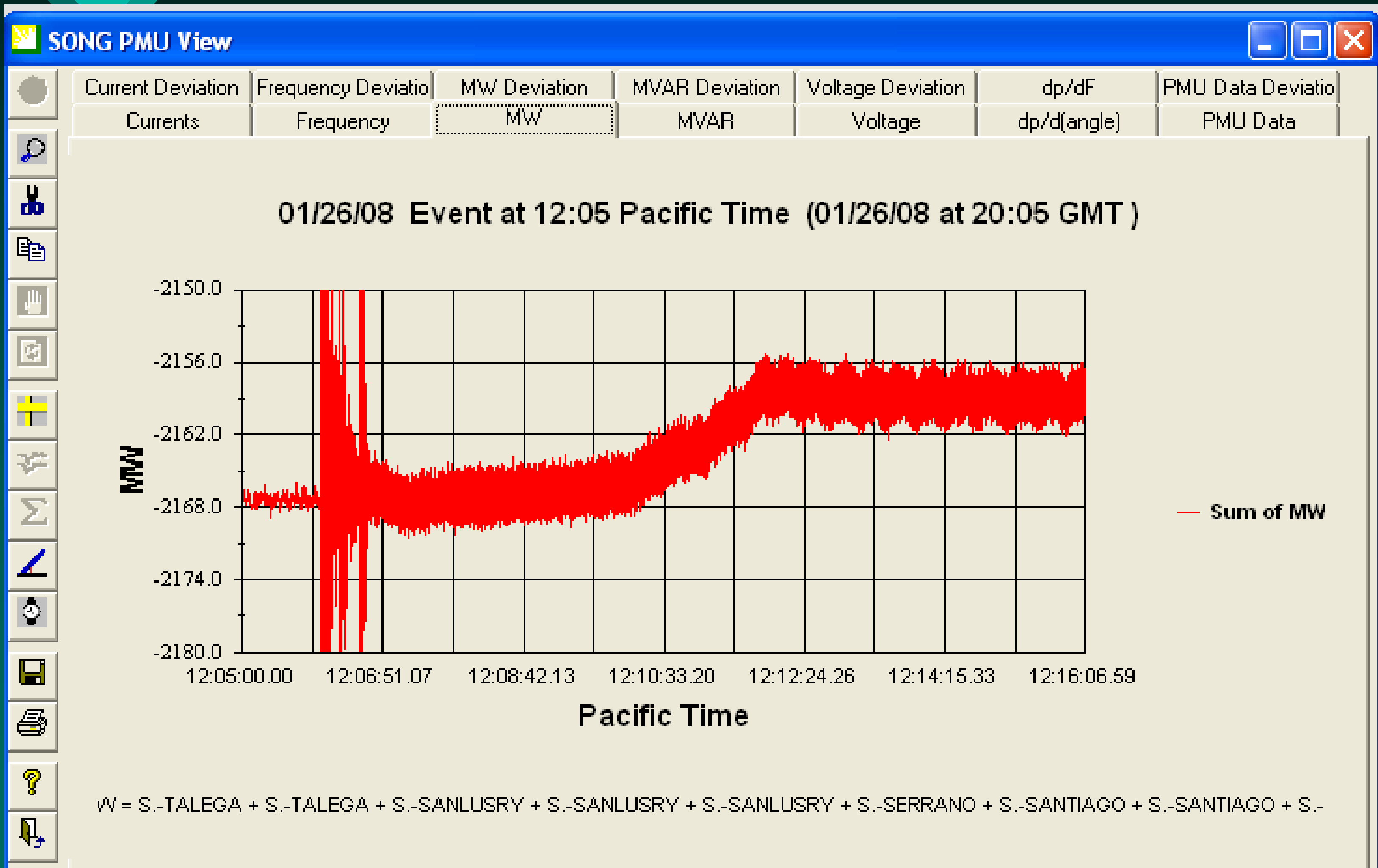
FFT Analysis of Oscillations at Big Eddy Substation

SCE - Power System Outlook

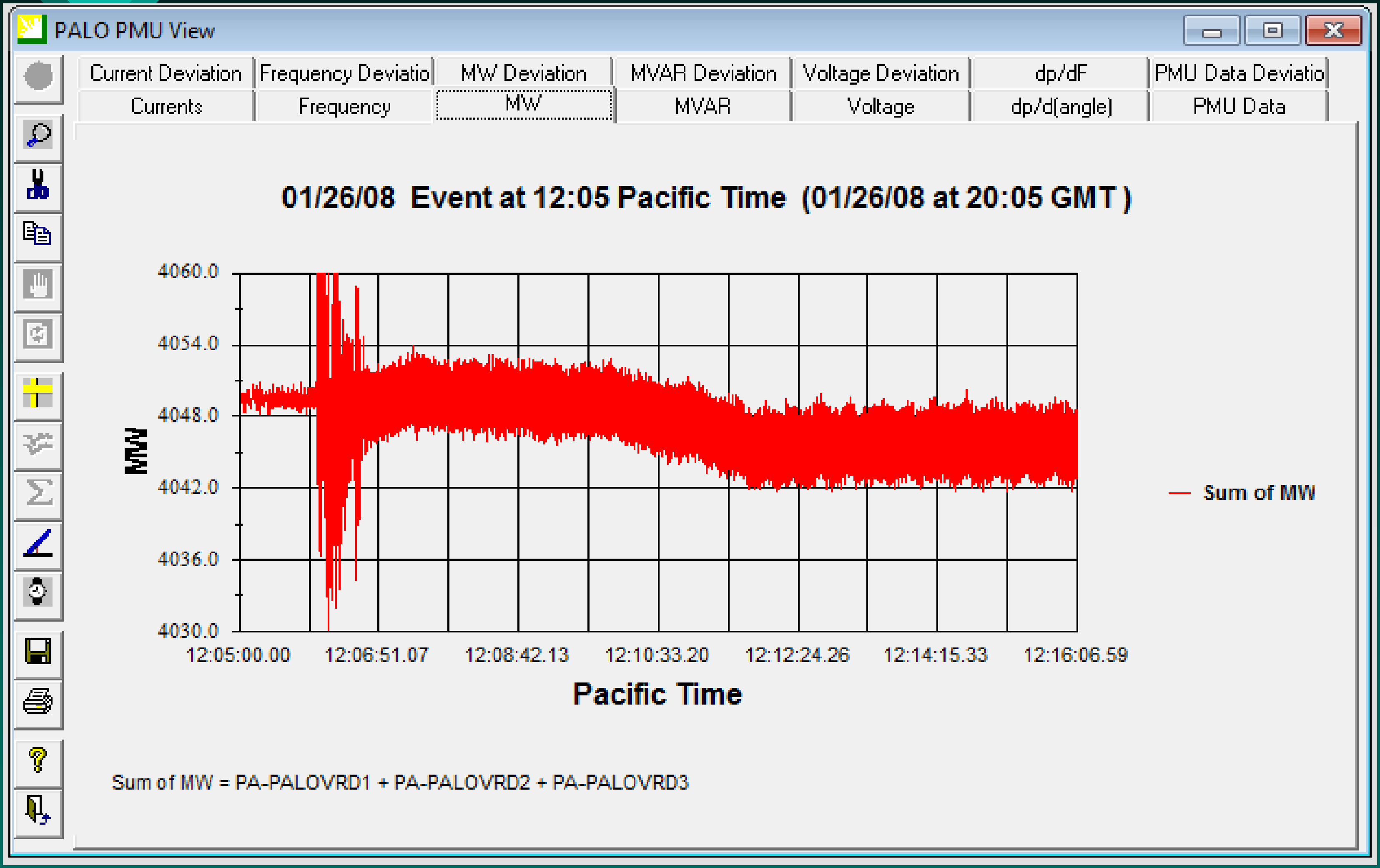
Dominant Modes:	1	2	3	4
Frequency (Hz):	2.26	4.52	0.103	0.14
Damping Ratio (%):	0.8	4.4	- -	17.8
Time Constant (sec):	9.86	0.81	2.75	6.46

OK

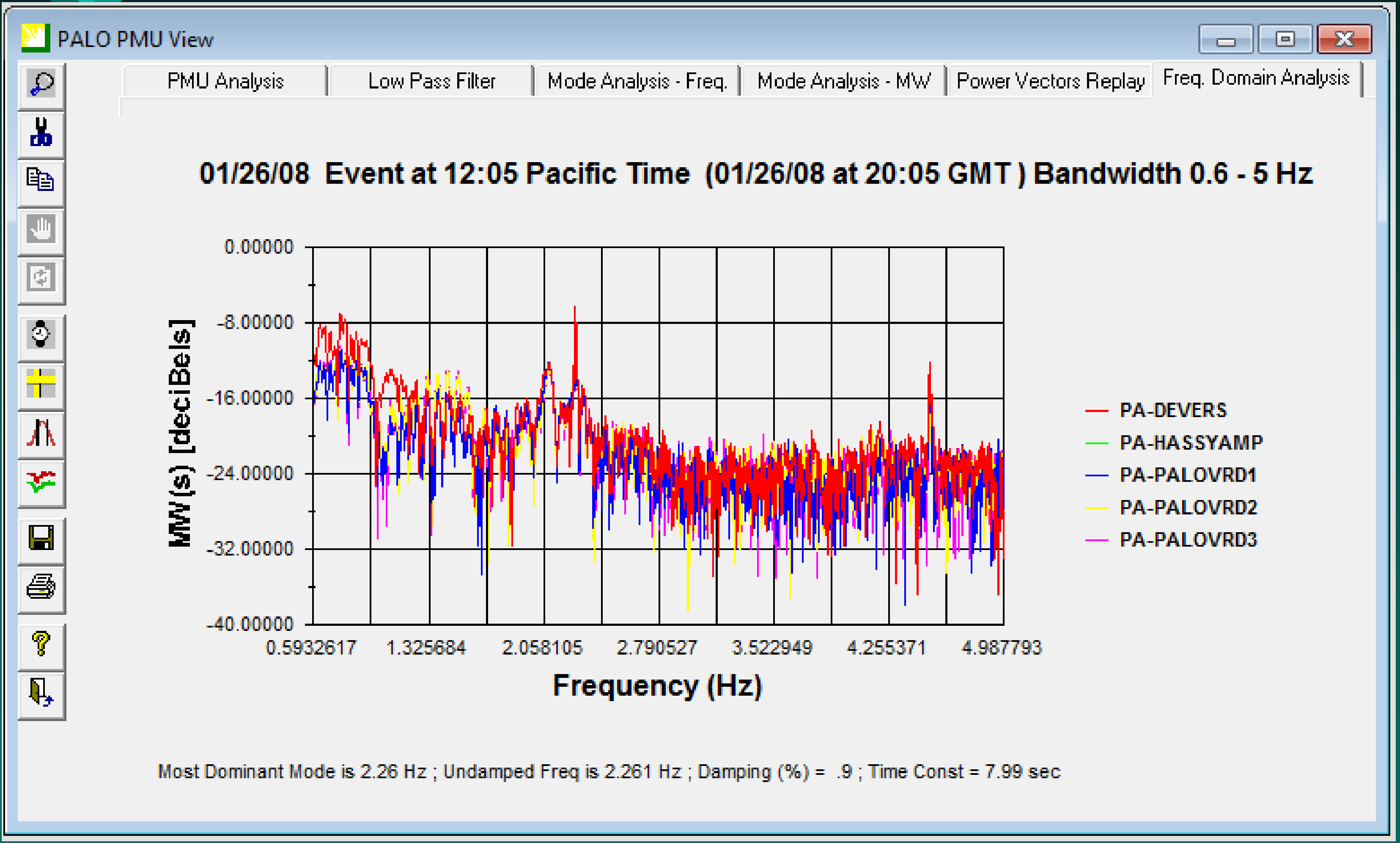
Power Flow on SONGS Machines



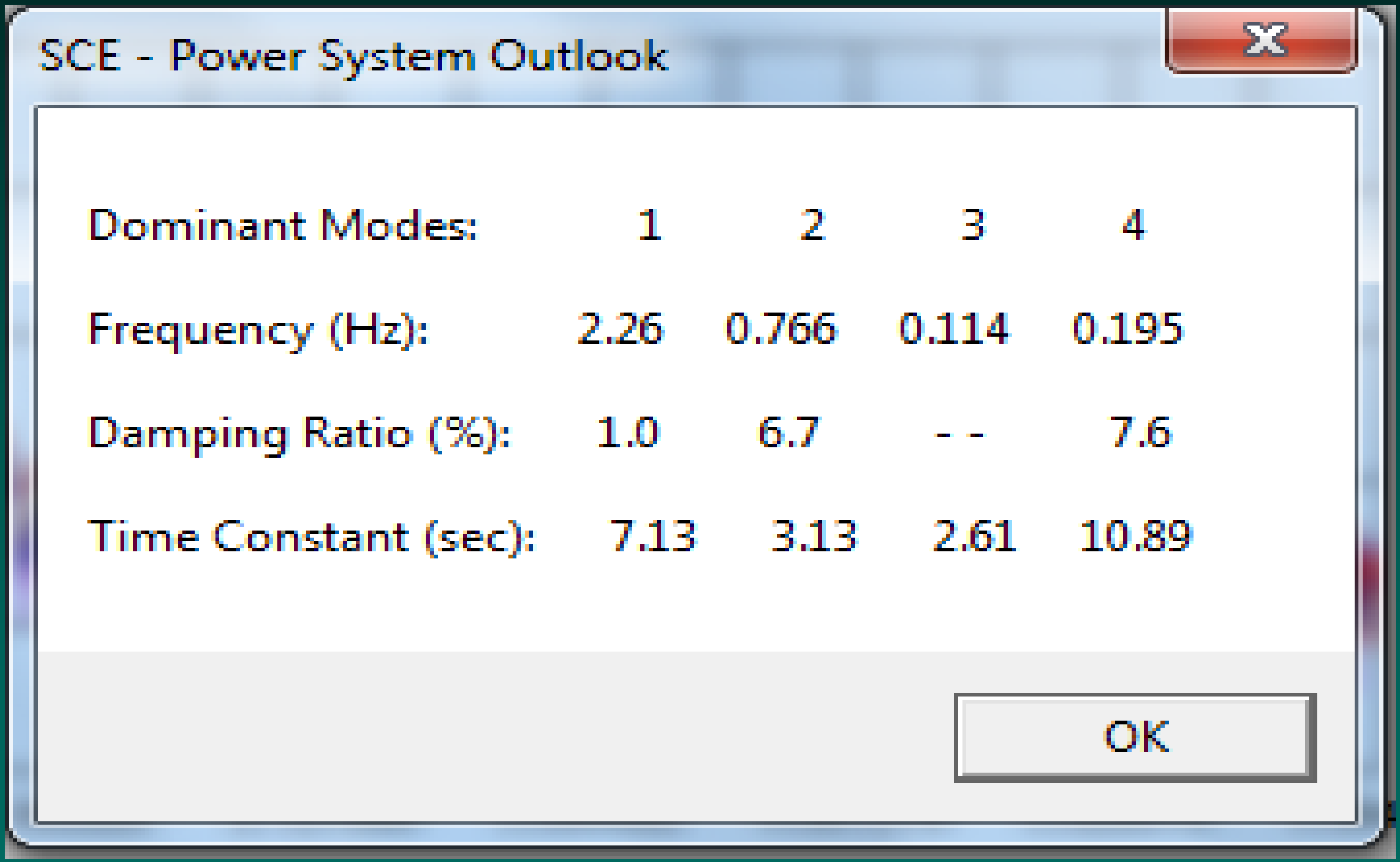
Power Flow on Palo Verde Machines



FFT of Power Flow on Palo Verde Machines



FFT Analysis at Palo Verde Generating Station

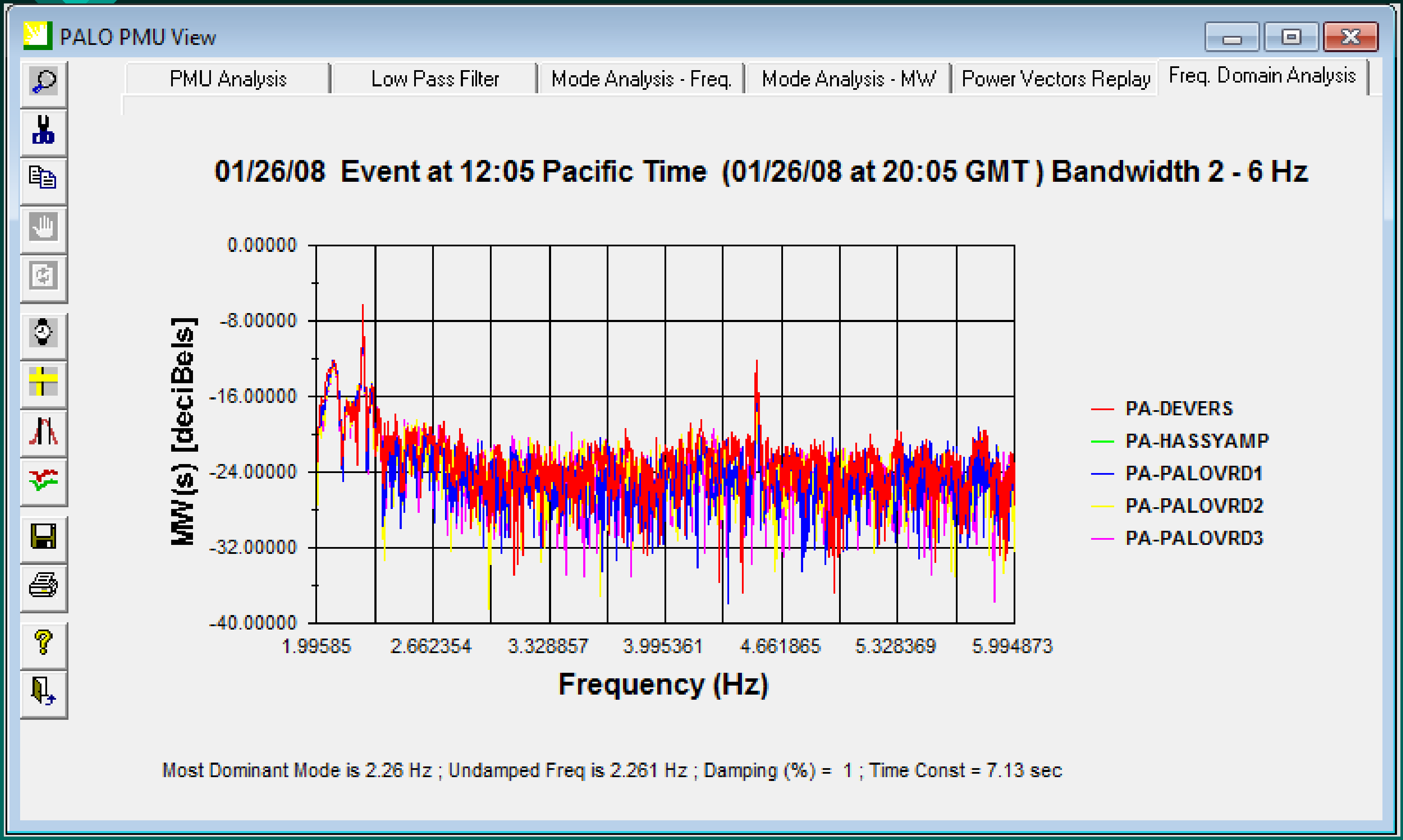


SCE - Power System Outlook

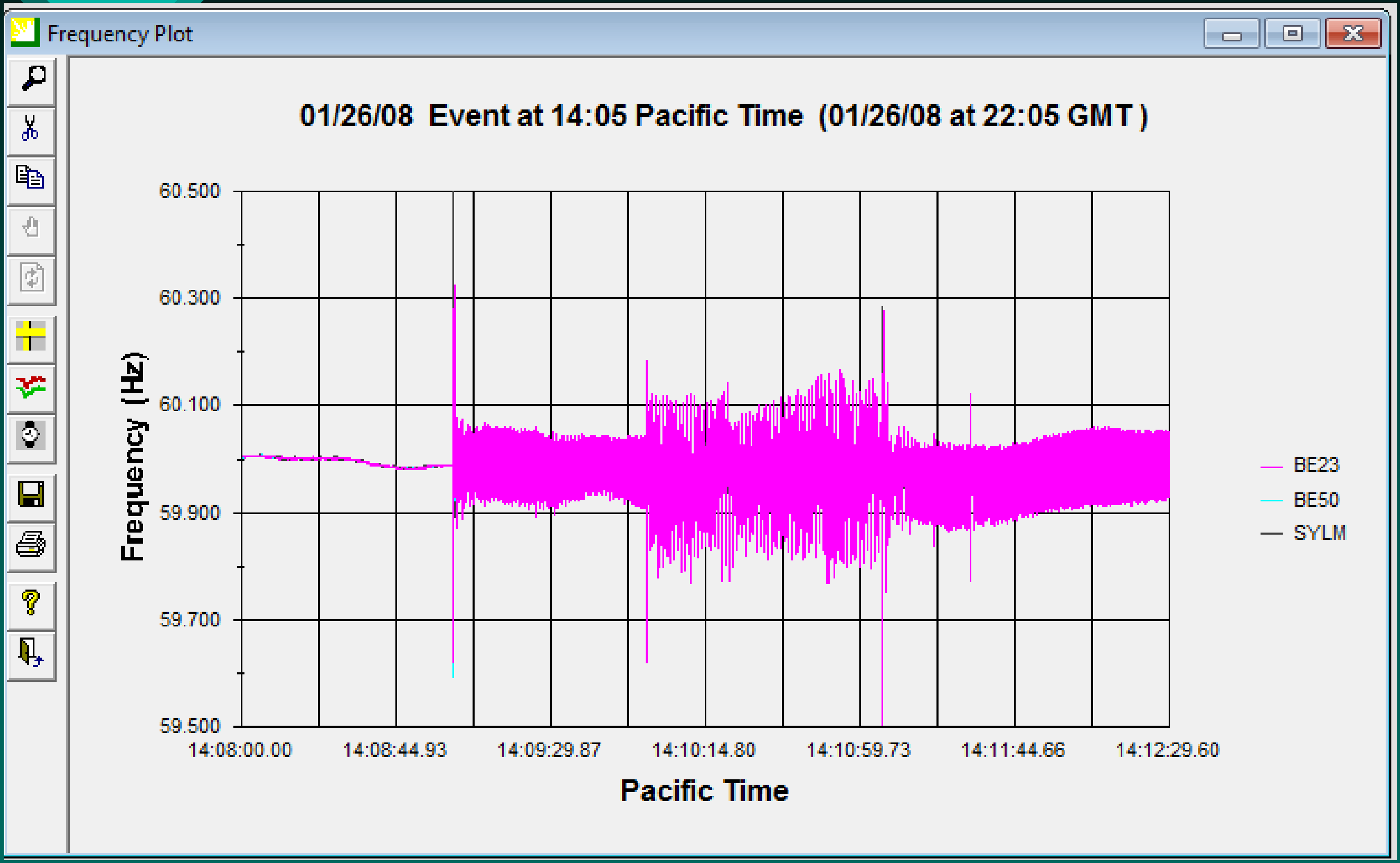
Dominant Modes:	1	2	3	4
Frequency (Hz):	2.26	0.766	0.114	0.195
Damping Ratio (%):	1.0	6.7	- -	7.6
Time Constant (sec):	7.13	3.13	2.61	10.89

OK

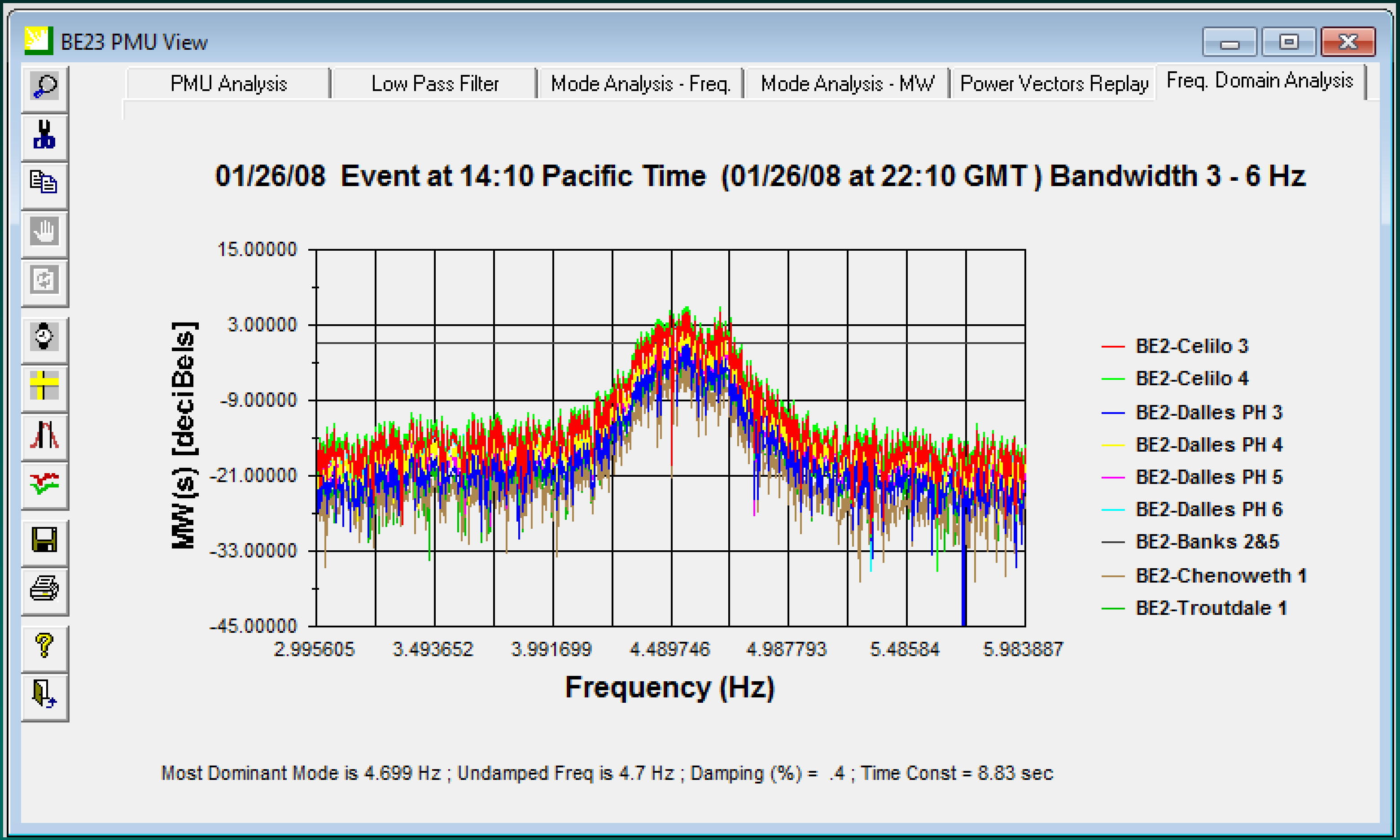
FFT Analysis of Oscillations at Palo Verde Generating Station (From Simulations)



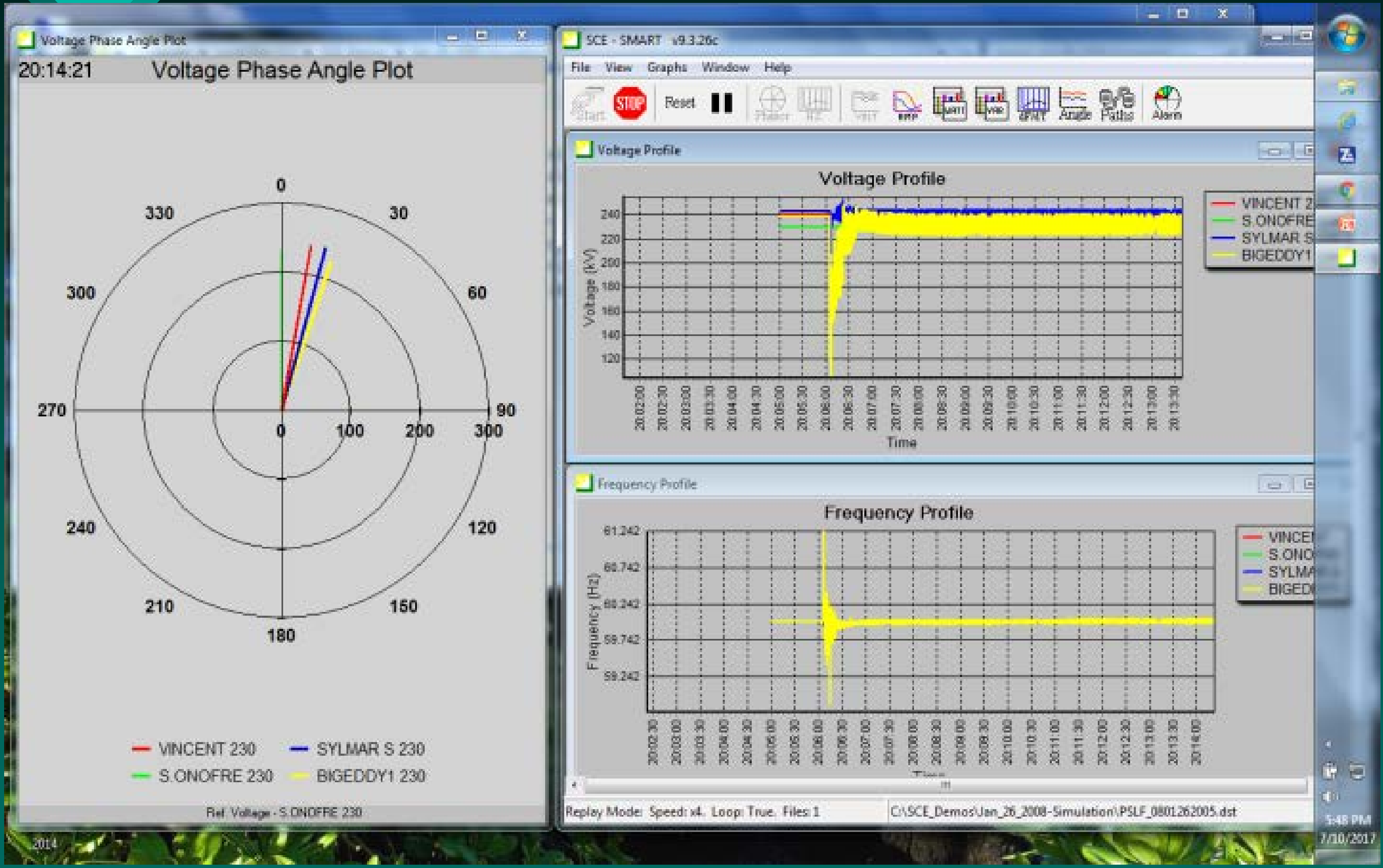
Frequency Oscillations at Big Eddy (From the event)



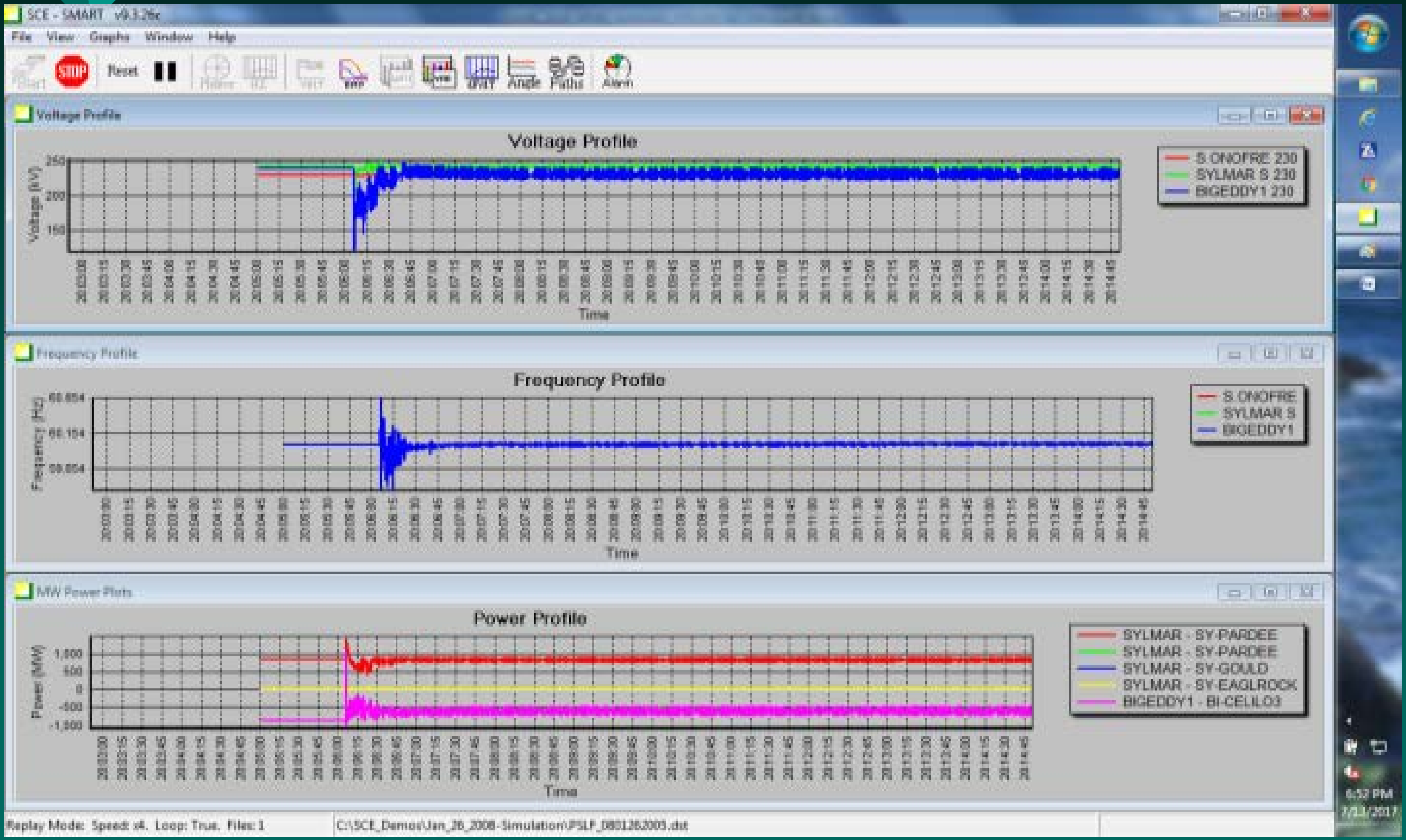
FFT Analysis of Oscillations at Big Eddy Substation (From Event)



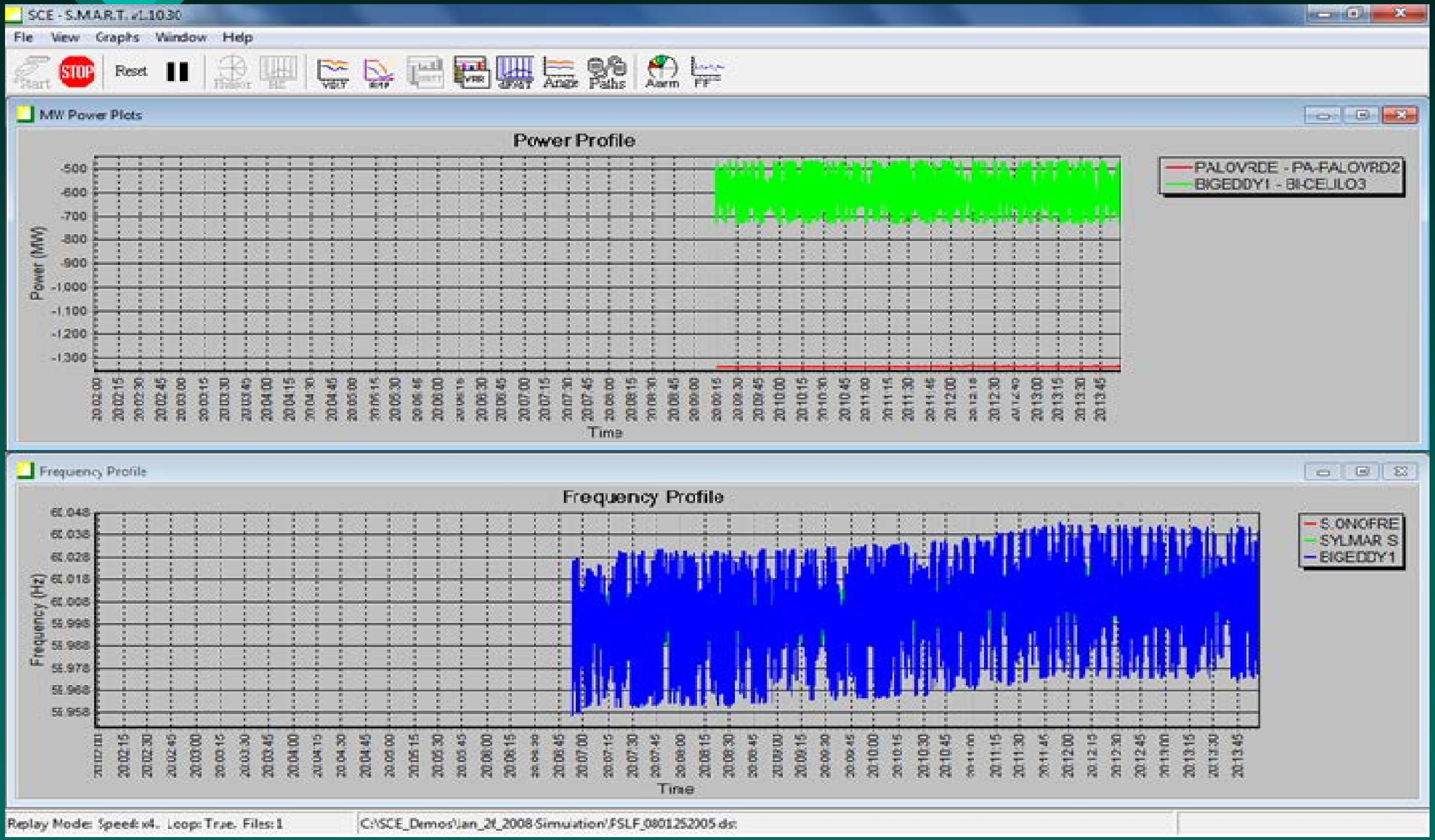
Phasor display, Voltage and Frequency plots at Celilo and Sylmar Substations (Simulations)



Voltage, Frequency and Power profile plots plots at Celilo and Sylmar Substations (Simulations)



Frequency and Power Profile at Celilo 230 kV buss



WECC System Event Simulation of January 26, 2008

Issues / Conclusions :

- Simulation is able to reproduce the high frequency oscillations that occurred on January 26, 2008
- The frequency of oscillations is lower (2.26 Hz) instead of 4.2-4.4 Hz in the actual event
- The simulation can be run on SPMT programs such as SMART and analyzed using PSO or similar programs
- SMART program can display high frequency oscillations in frequency, power and voltages at both HVDC terminals as well as on other transmission lines like PACI.
- High frequency oscillations were impacting generating units such as at SONGS and Palo Verde.
- The SCADA system is incapable of showing these sub-second events and SPMT technology is essential to capture these events.
- Operators would have been able to identify the cause of the problem was HVDC and shut it off.

Training Operators in Synchronized Phasor Measurement Technology

Issues / Questions:

- Synchronized Phasor Measurement Technology is fully developed and can help system operators to identify critical system situations and help them take preventive action timely.
- Operators need to be trained in using technology and in use of SPMT programs and analysis
- SPMT could have helped in preventing several system blackouts and cascading failures
- Simulations or replay of past recorded of significant events can be helpful in teaching operators in use of SPMT
- We need to analyze what happened and what caused and what we can learn from this event.
- The SCADA system is incapable of showing these sub-second events
- Real time monitoring systems can provide useful system dynamics related information quickly to the operators. Some such tools are under development
- The operators will benefit from better tools and training to deal with these kind of vulnerable situations

Training Operators in Synchronized Phasor Measurement Technology

Any Questions ?