NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Phase Angle Monitoring:

Industry Experience Following the 2011 Pacific Southwest Outage Recommendation 27

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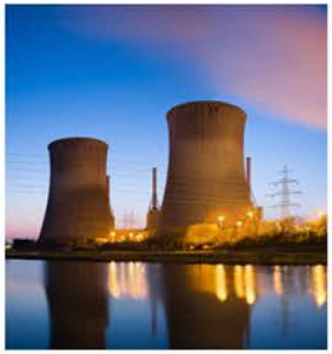
NASPI Work Group Meeting
October 2016

RELIABILITY | ACCOUNTABILITY

Background

- **Purpose:** Develop Technical Report on Phase Angle Monitoring and Alarming practices and experiences, and provide recommendations for future practices
  - In response to the 2011 Pacific Southwest Outage Recommendation #27
  - Was a NERC SAMS task but tabled until the NERC SMS kicked off
- **Topics:**
  - Phase Angle Fundamentals
  - Finding & Recommendation 27
  - Synchrocheck Relay Situational Awareness
  - EMS and PMU Application
  - Mitigation Strategies
  - Identifying Key Angle Differences & Correlating to System Conditions
  - Tying Phase Angles to Oscillations & System Studies
  - Phase Angle Monitoring Utility Practices in the West

Finding & Recommendation #27

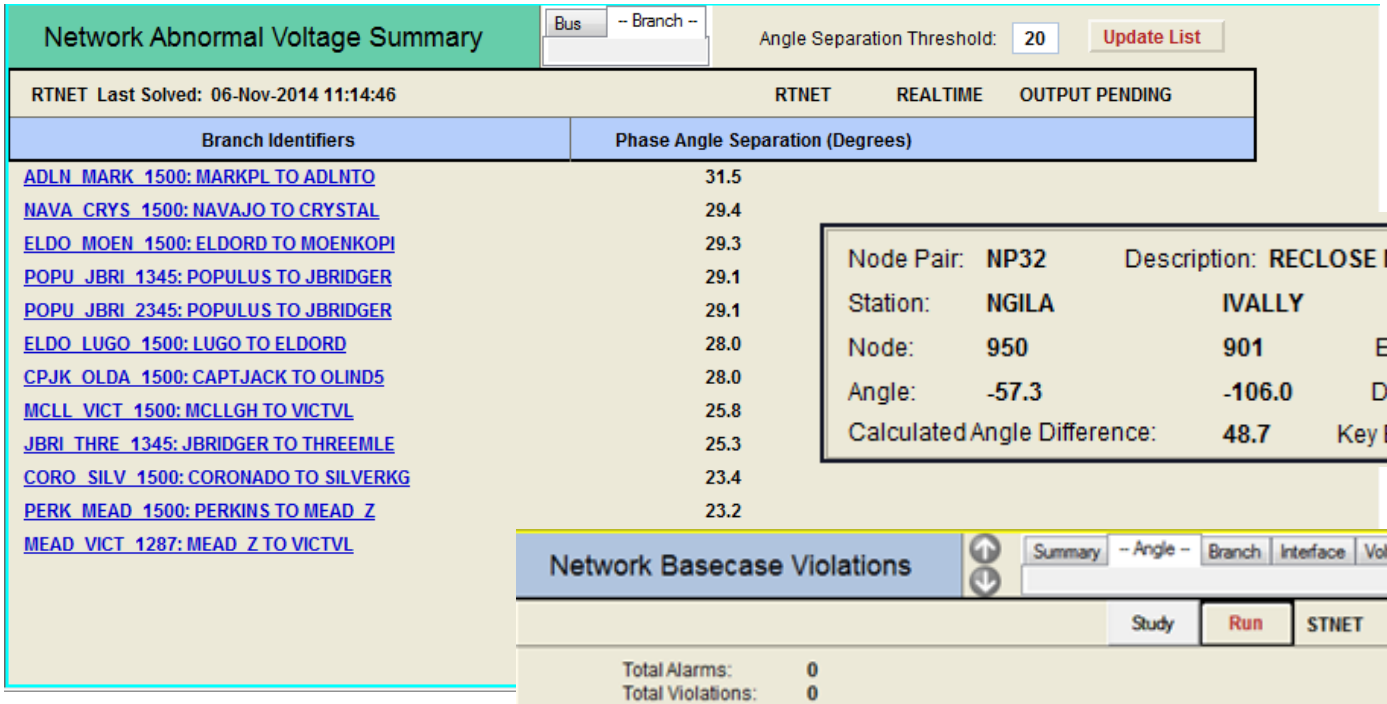
- Finding #27
  - *"Phase Angle Difference Following Loss of Transmission Line: "A TOP did not have tools in place to determine the phase angle difference between the two terminals of its 500 kV line after the line tripped. Yet, it informed the RC and another TOP that the line would be restored quickly, when, in fact, this could not have been accomplished."*

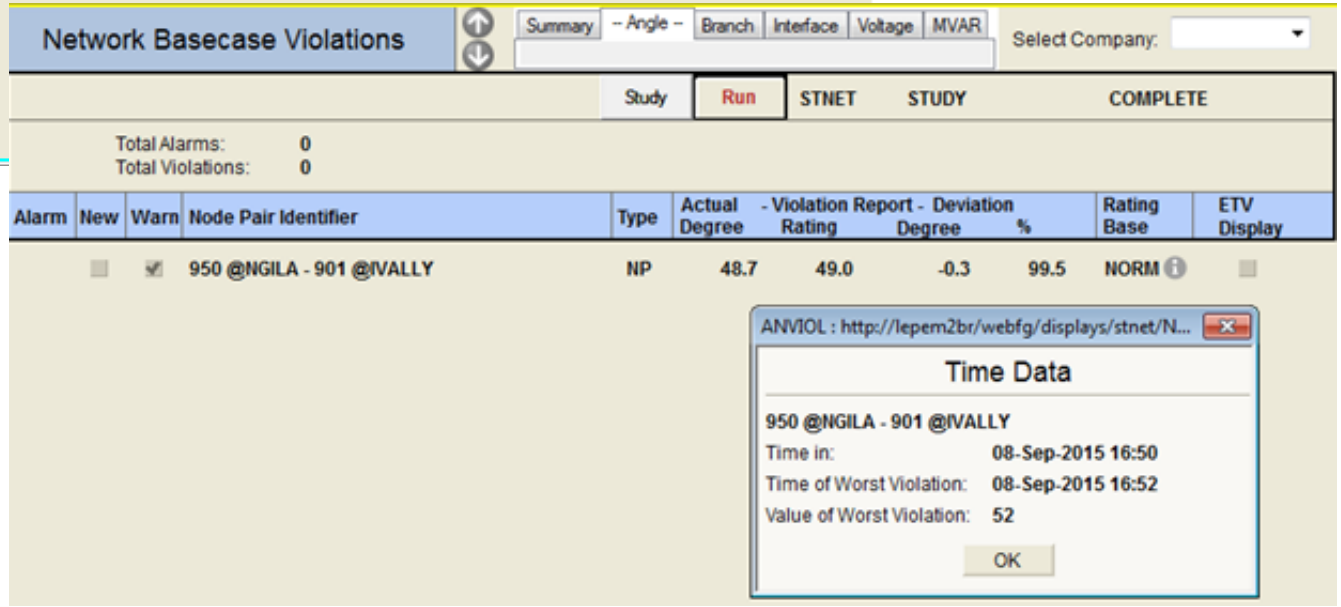
- Recommendation #27
  - *"TOPs should have: (1) the tools necessary to determine phase angle differences following the loss of lines; and (2) mitigation and operating plans for reclosing lines with large phase angle differences. TOPs should also train operators to effectively respond to phase angle differences. These plans should be developed based on the seasonal and next-day contingency analyses that address the angular differences across opened system elements."*

The Synchrocheck Relay & Line Outages

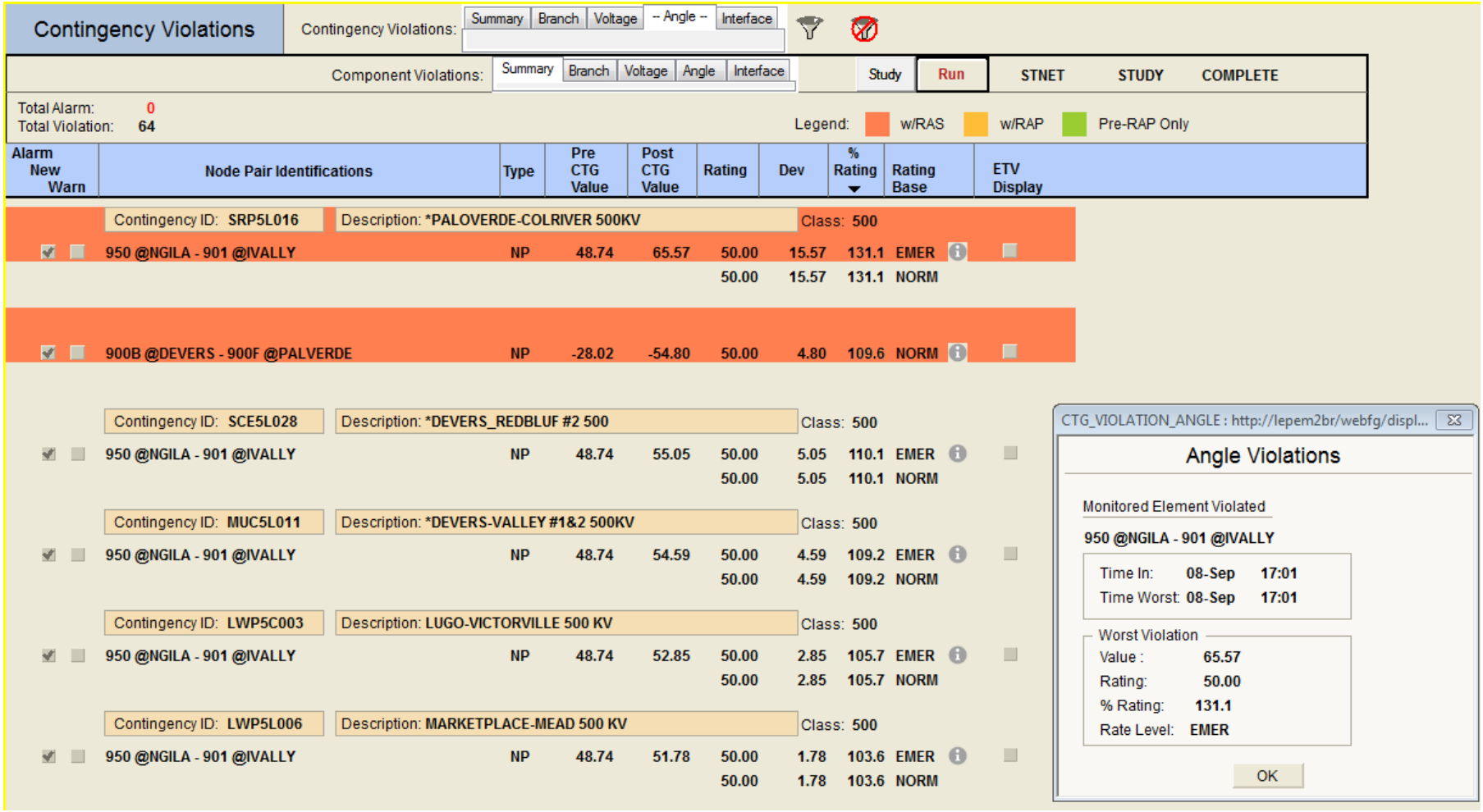
- Line O/S = phase angle increases (generally); impedance increases
  - Large phase angels can lead to system instability and loss of synchronism for generating resources
- Synchrocheck relays monitor phase angle difference across breaker terminals
  - Reclosing line near generator with substantially large angle difference results in large transient torque on shaft of machine – related to rotor being out of phase with BPS. Can cause instant damage or cumulative fatigue of shaft
  - Often used on transmission system as well
- Synchrocheck relays measure voltage magnitude difference, frequency slip, and phase angle difference between voltage
  - Supervises against pre-determined, programmed setting prior to restoring line to service.

Steady-State Monitoring & Alarming

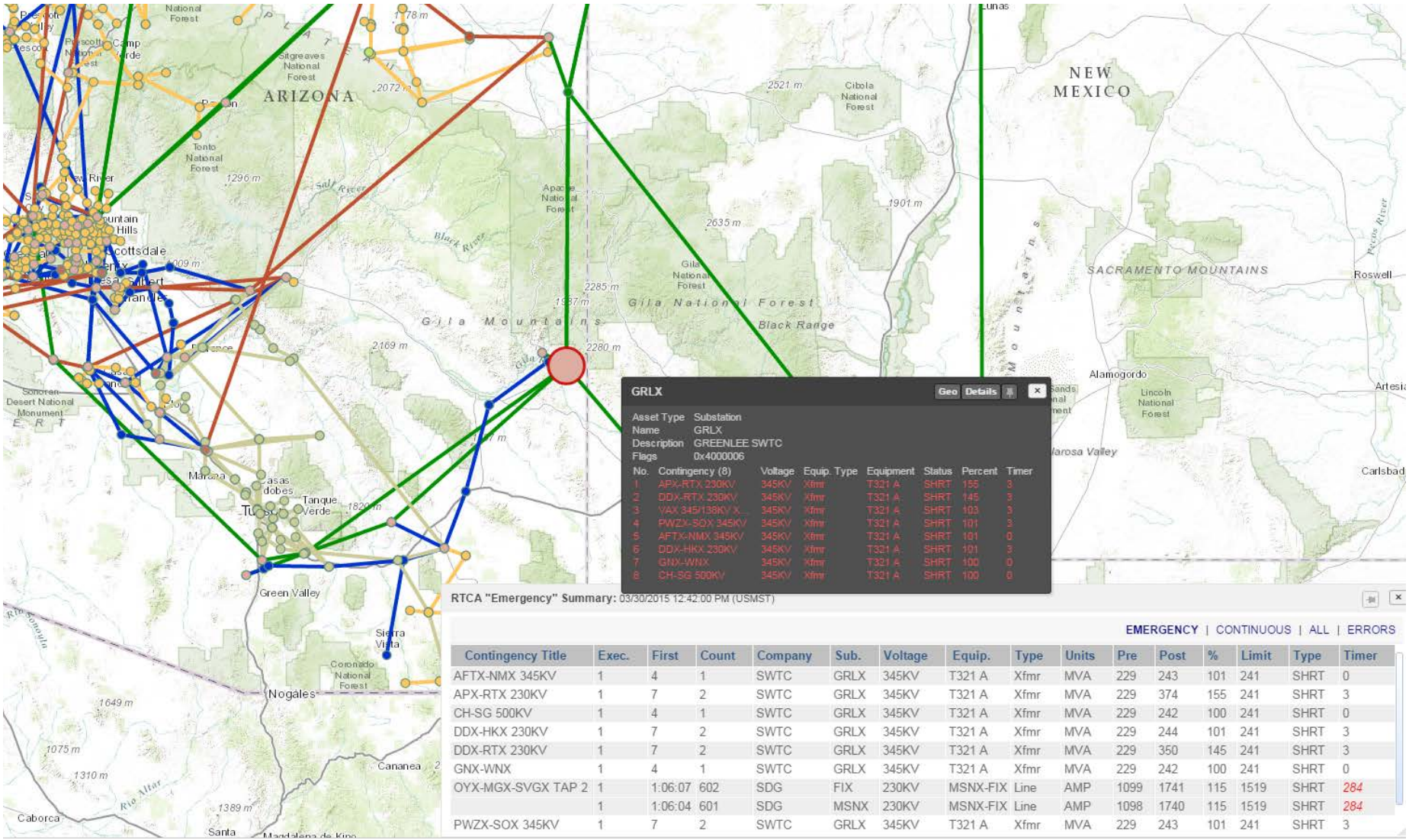




N-1 Angle Alarming in RTCA



Visualization of RTCA Results at APS



GRLX — Geo | Details

Asset Type	Substation
Name	GRLX
Description	GREENLEE SWTC
Flags	0x4000006

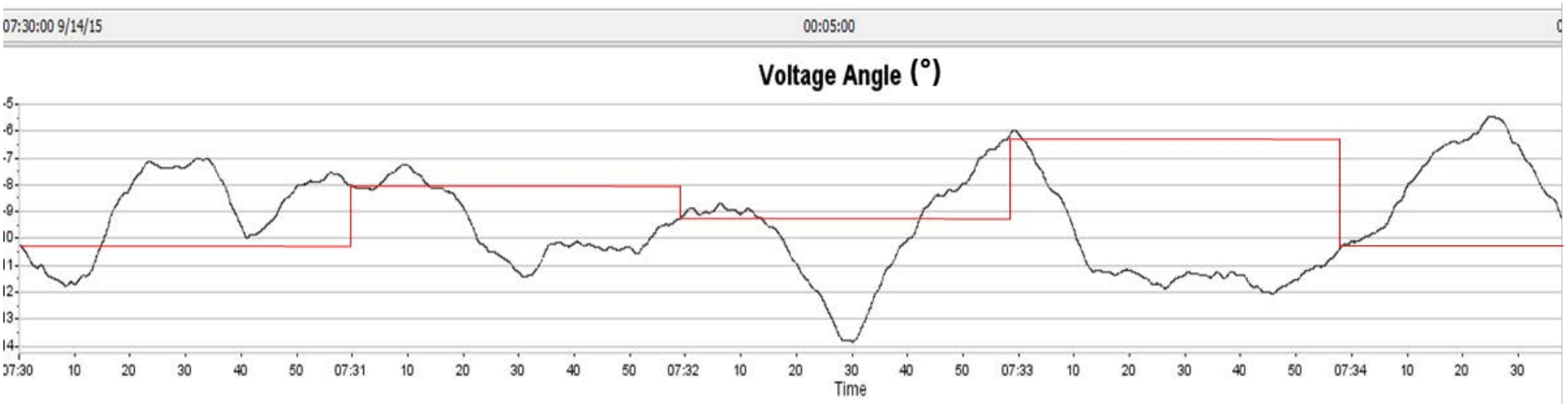
No.	Contingency (8)	Voltage	Equip. Type	Equipment	Status	Percent	Timer
1	APX-RTX 230KV	345KV	Xfmr	T321 A	SHRT	155	3
2	DDX-RTX 230KV	345KV	Xfmr	T321 A	SHRT	145	3
3	VAX 345/138KV X...	345KV	Xfmr	T321 A	SHRT	103	3
4	PWZX-SOX 345KV	345KV	Xfmr	T321 A	SHRT	101	3
5	AFTX-NMX 345KV	345KV	Xfmr	T321 A	SHRT	101	0
6	DDX-HKX 230KV	345KV	Xfmr	T321 A	SHRT	101	3
7	GNX-WNX	345KV	Xfmr	T321 A	SHRT	100	0
8	CH-SG 500KV	345KV	Xfmr	T321 A	SHRT	100	0

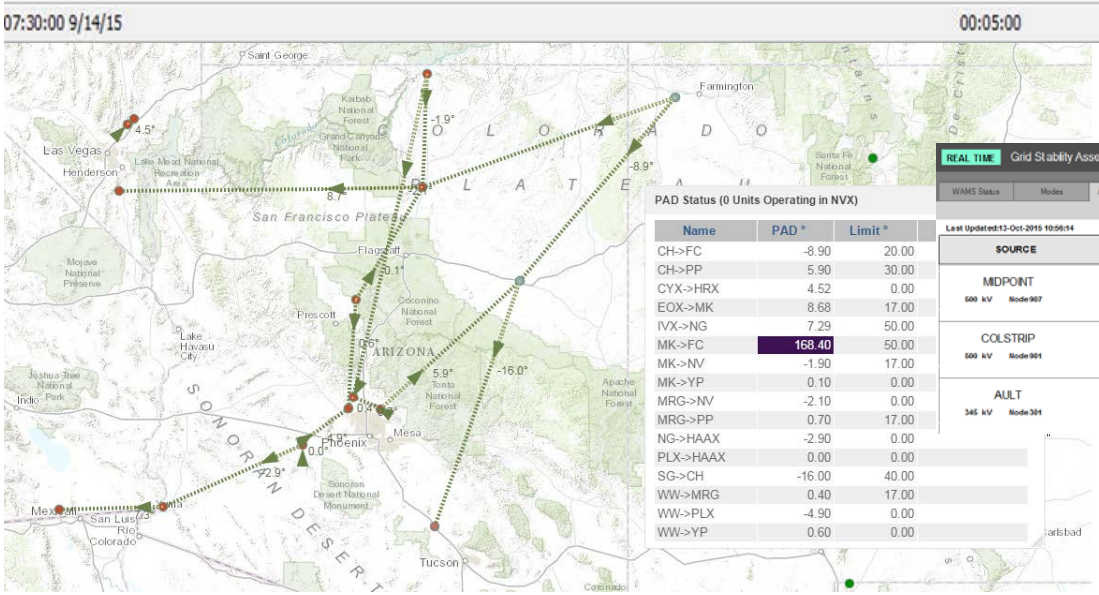
RTCA "Emergency" Summary: 03/30/2015 12:42:00 PM (USMST)

EMERGENCY | CONTINUOUS | ALL | ERRORS

Contingency Title	Exec.	First	Count	Company	Sub.	Voltage	Equip.	Type	Units	Pre	Post	%	Limit	Type	Timer
AFTX-NMX 345KV	1	4	1	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	243	101	241	SHRT	0
APX-RTX 230KV	1	7	2	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	374	155	241	SHRT	3
CH-SG 500KV	1	4	1	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	242	100	241	SHRT	0
DDX-HKX 230KV	1	7	2	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	244	101	241	SHRT	3
DDX-RTX 230KV	1	7	2	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	350	145	241	SHRT	3
GNX-WNX	1	4	1	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	242	100	241	SHRT	0
OYX-MGX-SVGX TAP 2	1	1:06:07	602	SDG	FIX	230KV	MSNX-FIX	Line	AMP	1099	1741	115	1519	SHRT	*284*
	1	1:06:04	601	SDG	MSNX	230KV	MSNX-FIX	Line	AMP	1098	1740	115	1519	SHRT	*284*
PWZX-SOX 345KV	1	7	2	SWTC	GRLX	345KV	T321 A	Xfmr	MVA	229	243	101	241	SHRT	3

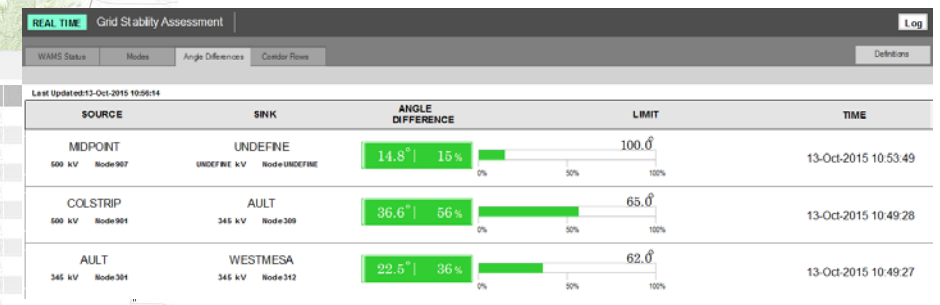
Synchrophasor-Based Tools





PAD Status (0 Units Operating in NVX)

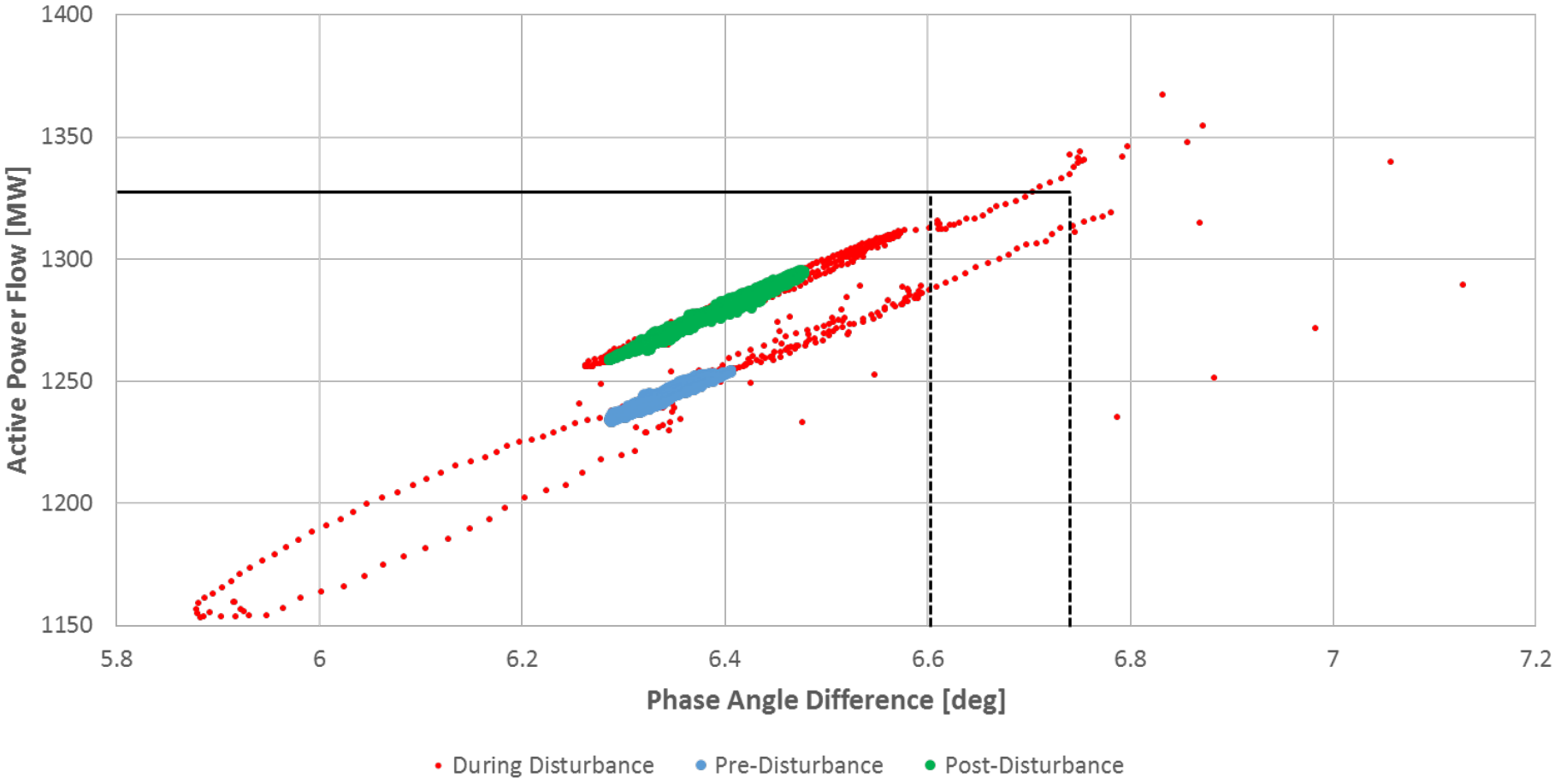
Name	PAD °	Limit °
CH->FC	-8.90	20.00
CH->PP	5.90	30.00
CYX->HRX	4.52	0.00
EOX->MK	8.68	17.00
IVX->NG	7.29	50.00
MK->FC	168.40	50.00
MK->NV	-1.90	17.00
MK->YP	0.10	0.00
MRG->NV	-2.10	0.00
MRG->PP	0.70	17.00
NG->HAAX	-2.90	0.00
PLX->HAAX	0.00	0.00
SG->CH	-16.00	40.00
WW->MRG	0.40	17.00
WW->PLX	-4.90	0.00
WW->YP	0.60	0.00



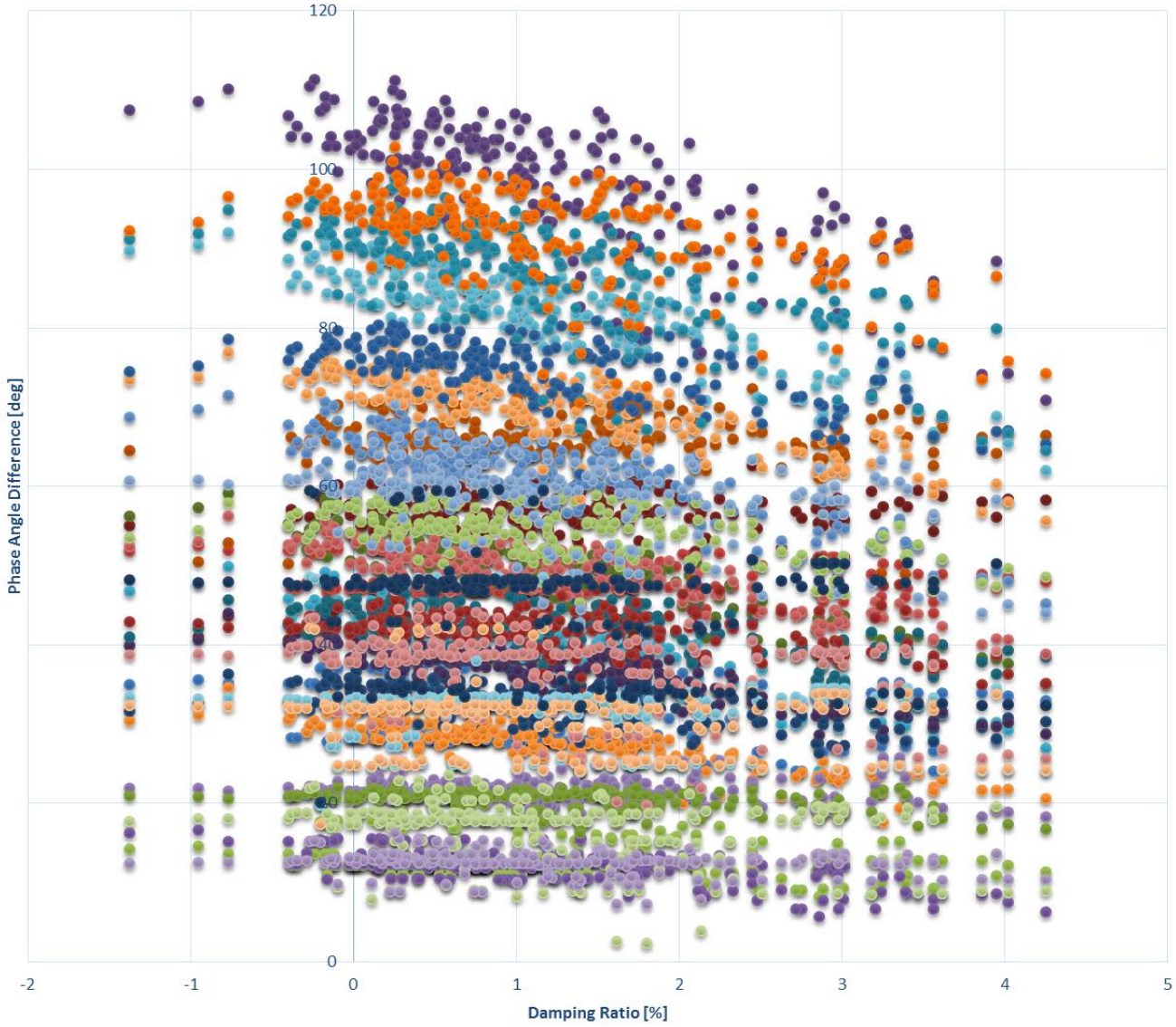
Mitigation Strategies

- Generation redispatch
  - Reducing generation on the sending end of the angle difference path
  - Increasing generation on the receiving end of the path
- Use of phase-shifting transformers to reduce power flow (if available)
- Reconfiguration of system topology to reduce power flow (if possible)
- Curtailment of interruptible load, if necessary
- Firm load shedding, if necessary
- Point-to-point transmission service curtailment
- Reconfiguration of in-series capacitors/reactors for compensation of transmission circuits

Angle Limit Philosophy



Angle Differences & Oscillation Damping Ratio



Recommendations

1. Contingency risk of interest is outage of the a transmission circuit and the phase angle difference across the terminals of that out-of-service circuit – exceeding synchrocheck relay limits
   - Post-contingency angle difference should be monitored in real-time.
   - PCs/RCs should identify key circuits for which monitoring is required.
   - Recommended that awareness of synchrocheck relay limit exceedances should be provided to system operator for EHV ≥ 345 kV.
2. Phase angle differences for potential contingency conditions should be monitored in real-time and compared against synchrocheck relay settings, if applicable, using RTCA tools.
   - Any N-1 or credible N-2 or N-1-1 exceedances of these limits should be provided to system operator for advanced notice of potential line restoration issues.

Recommendations

3. Wide-area angle difference monitoring provides additional layer of situational awareness for system operators.
   - Limits based on known risks such as transient stability, voltage stability, small signal stability, or overloads can effectively be developed based on operations studies or advanced online applications.
4. Line-based angle difference monitoring and comparison with known synchrocheck relay limits is not presently a universally adopted operating practice. NERC SMS and OC should explore wider adoption of these practices.
5. In the West, phase angle difference is correlated to oscillatory stability issues, particularly during high transfer conditions.
   - Tools such as Mode Meter, Oscillation Detection, and Phase Angle Difference (PAD) should continue to be pursued for increased situational awareness and defense in depth.

Questions and Answers