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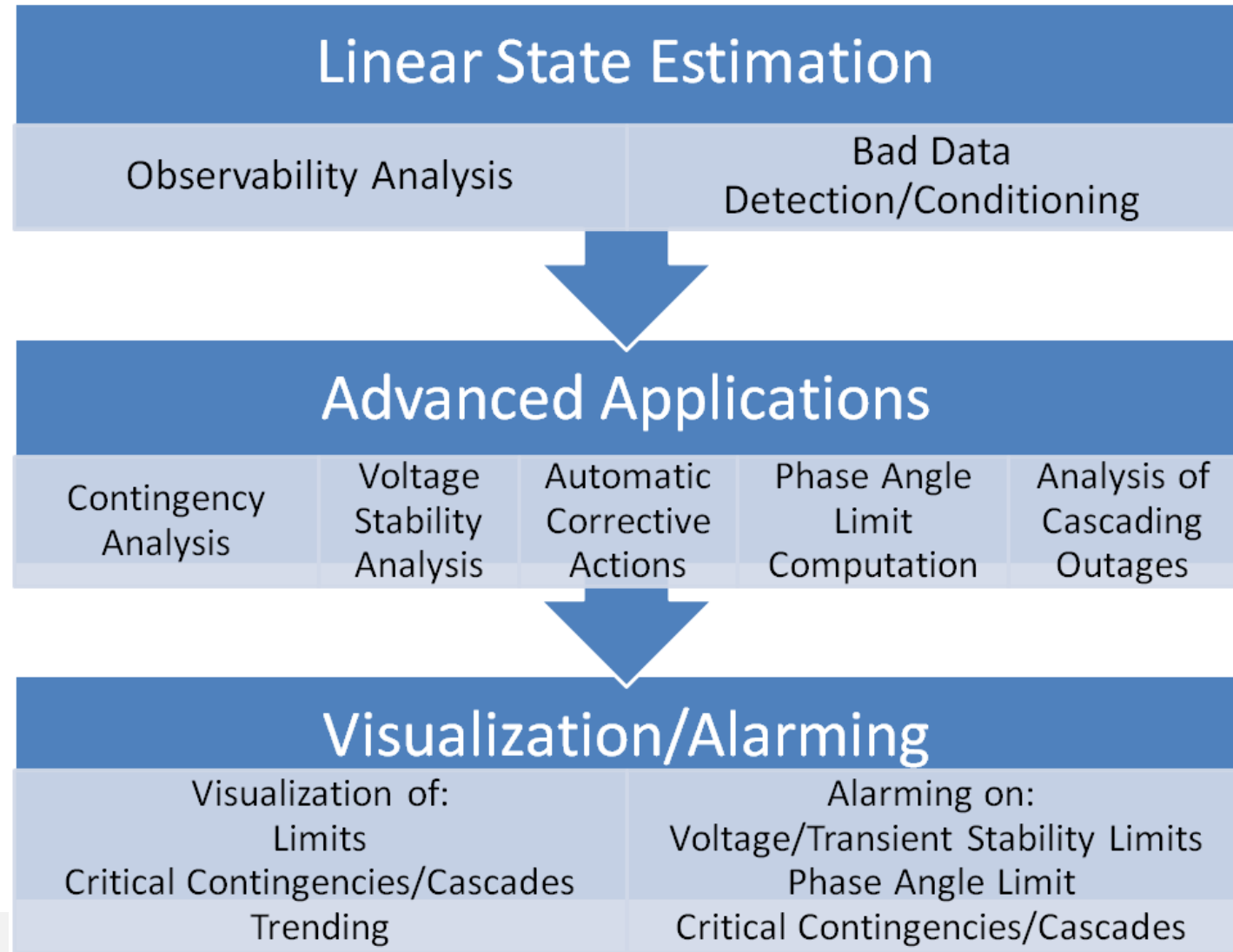
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PMU-based EMS and Power Network Analysis Applications

Robin Manuguid, SDG&E and Marianna Vaiman, V&R Energy
NASPI Work Group Meeting
Charlotte, NC • September 26 - 27, 2023

Linear State Estimation: Foundation for Measurement-Based Advanced Applications

- The framework was pioneered by V&R Energy during NASPI Voltage Stability Workshop on October 22, 2014:
 - Introduced the concept of a “PMU-based State Estimator Case” or “LSE Case”
 - Prior to this, “standard” output of LSE was conditioned and expanded PMU stream
- Only the use of LSE produced accurate results



2014 NASPI Voltage Stability Case 1



- Correct results announced by NASPI at the Workshop

Voltage Stability Case 1

First Time of Unacceptable Operating Conditions	303.4 sec
Shunt Cap Switching Time	247.8 sec
Pre-Switching Real Power Margin	343.75 MW
Post-Switching Real Power Margin	400.00 MW
Real Power Margin @ 0 sec	618.75 MW
Real Power Margin @ 150 sec	506.25 MW
Real Power Margin @ 305 sec	112.50 MW
Real Power Margin @ 445 sec	400.00 MW
Description of Method	PV Analysis



- Results submitted by vendors one week before the Workshop

VOLTAGE STABILITY CASE 1
RESULTS AND COMMENT SHEET

	Electric Power Group	RPI	V&R	Alstom Grid	ABB
First Time of Unacceptable Operating Conditions	170	None	303.5	None	None
Shunt Cap Switching Time	247	247.8	245	247.8	248
Pre-Switching Real Power Margin	23.53 kV/100 MW	411	335	29	92
Post-Switching Real Power Margin	7.5 kV/100 MW	461	391	86	92
Real Power Margin @ 0 sec	0.38 kV/100 MW	645	617	Not Available	196
Real Power Margin @ 150 sec	3.1 kV/100 MW	520	515	76	193
Real Power Margin @ 305 sec	6 kV/100 MW	190	111	46	32
Real Power Margin @ 445 sec	2.9 kV/100 MW	388	385	69	107
Description of Method	Voltage Sensitivity to Change in Real Power	AQ Bus Method	Linear State Estimation, PV/QV Analysis	RVII – local voltage instability detector	Equivalencing, PV analysis

2014 NASPI Voltage Stability Case 2



- Correct results announced by NASPI at the Workshop →



VOLTAGE STABILITY CASE 2 RESULTS AND COMMENT SHEET

	Alstom Grid	V&R Energy
First Time of Insecure (N-1) Operating Condition	2410	1312
Reason(s) for Insecurity	Line L02	Contingency L02 Contingency L11
First Time of Unacceptable N-0 Operating Condition	4064	None
Reason for Unacceptable Condition	Voltage Violation @ Bus 113	N/A
Time of Instability	4070	4012
Security Margin (Transfer into Zone 10) @ 1500 sec	730	40
Stability Margin (Transfer into Zone 10) @ 1500 sec	760	250
Security Margin (Transfer into Zone 10) @ 4000 sec	170	Negative
Stability Margin (Transfer into Zone 10) @ 4000 sec	200	Negative
Assumptions Used	-Total generation is the sum of three branches: • Bus 151 to Bus 156 CKT 1 • Bus 151 to Bus 156 CKT 2 • Bus 136 to Bus 130 CKT 1 -Upper bound voltage limit criteria was relaxed -Bus 136 generator Pmax increased from 1000MW to 1070MW for transfer analysis	Ignored 500kV equivalents & their voltages
Noticeable System Changes	At t=502s, line 130-115 circuit 1 tripped and reconnected at t=800s At t=2246s, first shunt cap (100 MVAR at bus 112) gets switched in at load in zone 10=912MW At t=2868s, Second shunt cap (125 MVAR at bus 120) gets switched in at load in zone 10=1152MW	Event 1 - 502 s. Switching off line 130-115 "1". Event 2 - 802 s. Line 130-115 "1" switched back. Event 3 - 1302 s. Switching off FACTS at bus 122. Event 4 - 1602 s. Switching in FACTS at bus 122. Event 5 - 2462 s. Shunt cap switching at bus 112. Event 6 - 2868 s. ("non-switching"). Increase in transformer 116-117 flow. FACTS reaches reactive limit, loses control of bus 116 voltage. Event 7 - 4012 s. Contingency 116-120 which causes system collapse at 4012 s. There is no State Estimator solution after this N-1 contingency occurs.
Description of Method	PV Analysis	Linear State Estimation, AC Contingency Analysis, VS assessment (PV/QV, Sensitivity)

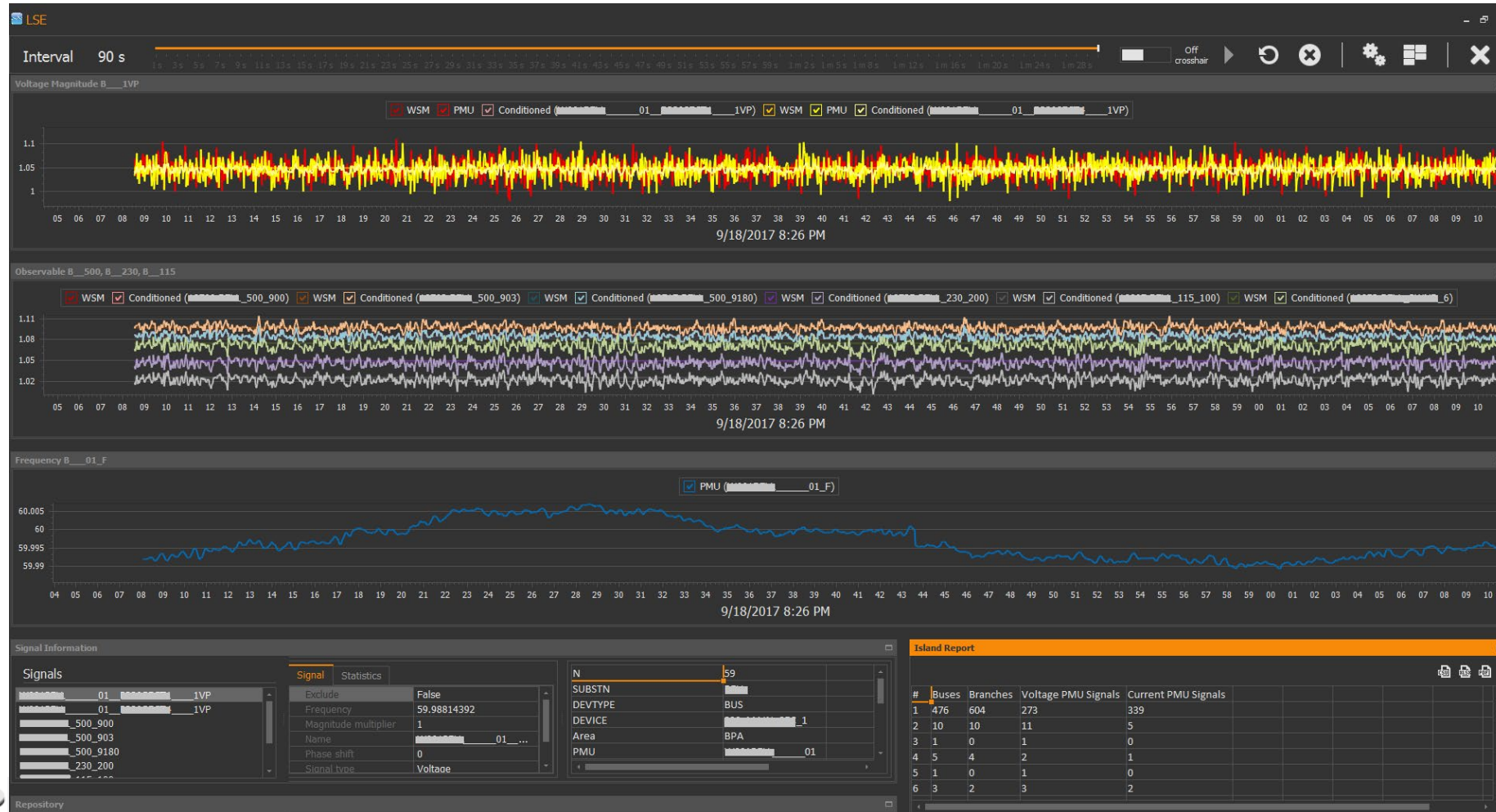
Voltage Stability Case 2

First Time of Insecure (N-1) Operating Condition	1312 seconds
Reason(s) for Insecurity	Voltage Violation in Zone 10 – N-1 Outages
First Time of Unacceptable N-0 Operating Condition	None
Reason for Unacceptable Condition	N/A
Time of Instability	4012 seconds
Security Margin (Transfer into Zone 10) @ 1500 sec	50.0 MW
Stability Margin (Transfer into Zone 10) @ 1500 sec	250.0 MW
Security Margin (Transfer into Zone 10) @ 4000 sec	0.0 (-) – Insecure
Stability Margin (Transfer into Zone 10) @ 4000 sec	0.0 (-) – N-1 Unstable
Assumptions Used	50/50 Pickup
Noticeable System Changes	1. Line 115-130 Trips 2. Line 115-130 Returned to Service 3. Bus 122 STATCOM Trips 4. Bus 122 STATCOM Switched Back In 5. Bus 112 Shunt Cap Switches In 6. Line 116-120 Trips - Unstable
Description of Method	PV, Contingency Analysis

Results submitted by vendors one week before the Workshop

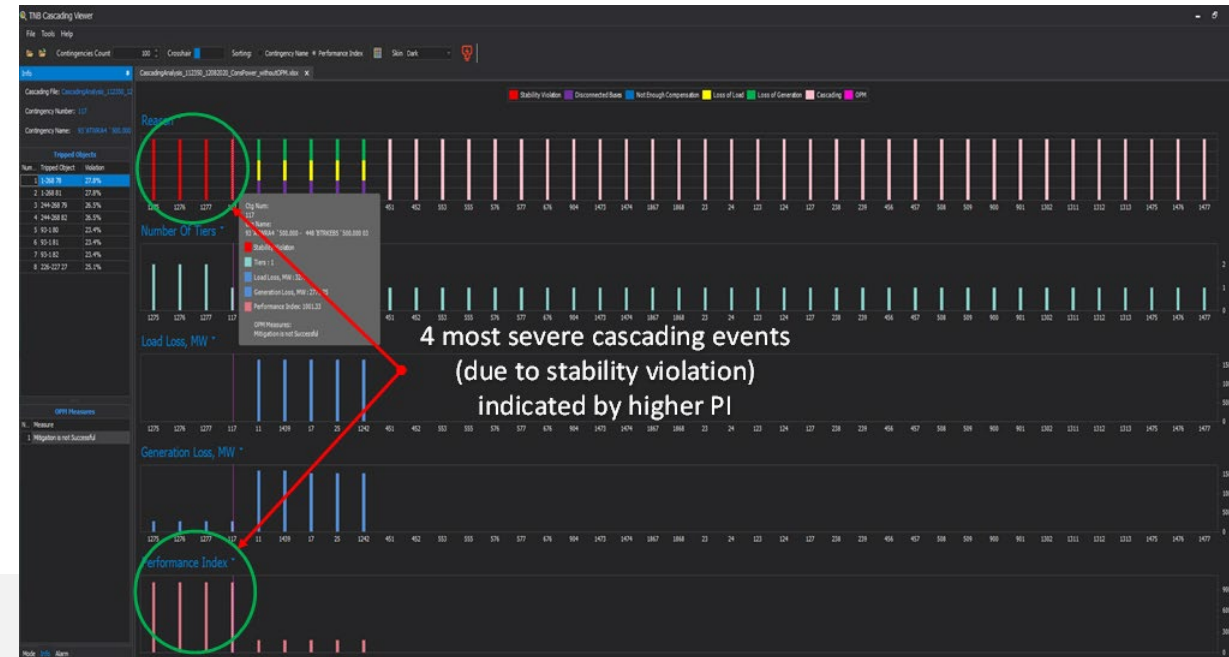
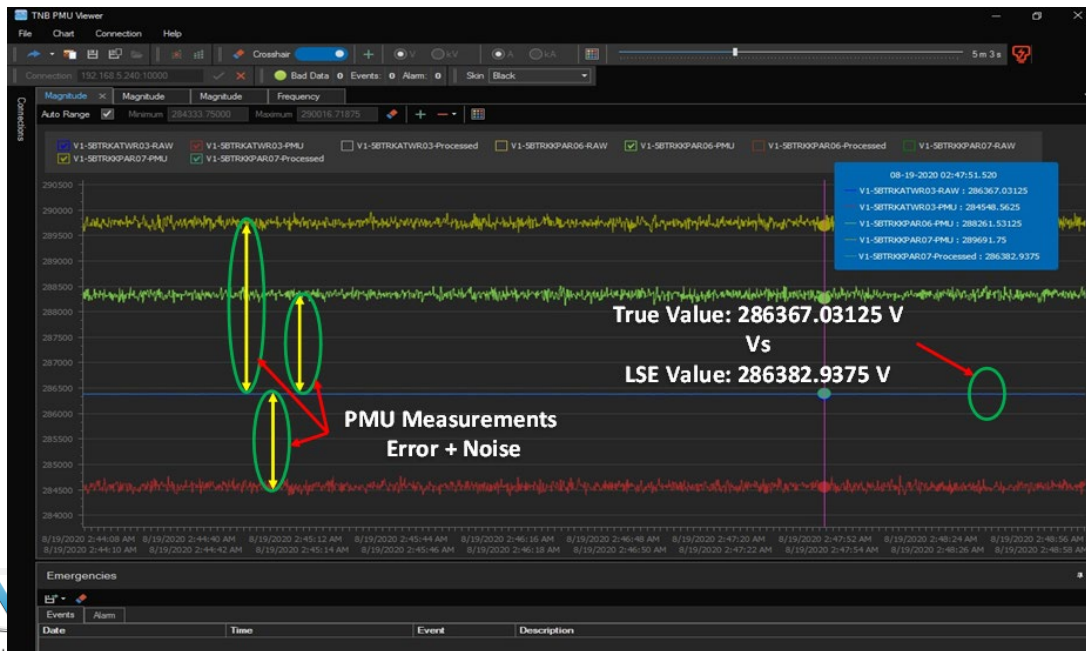
PMU-ROSE LSE at Peak RC

- Provides the mechanism for selecting, viewing, and analyzing the input data and LSE result



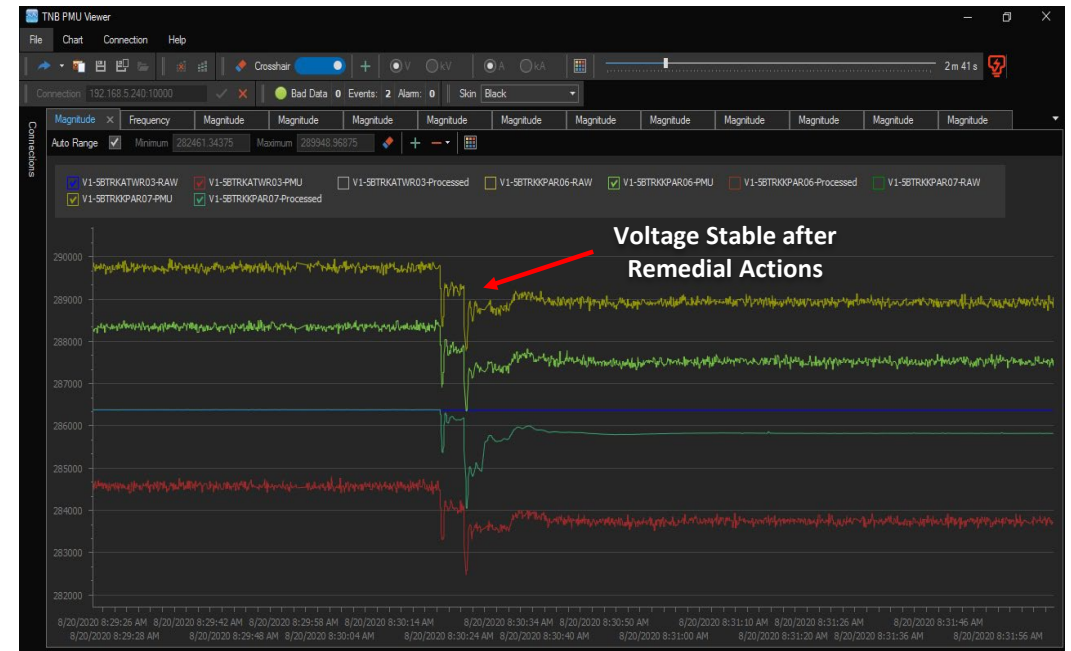
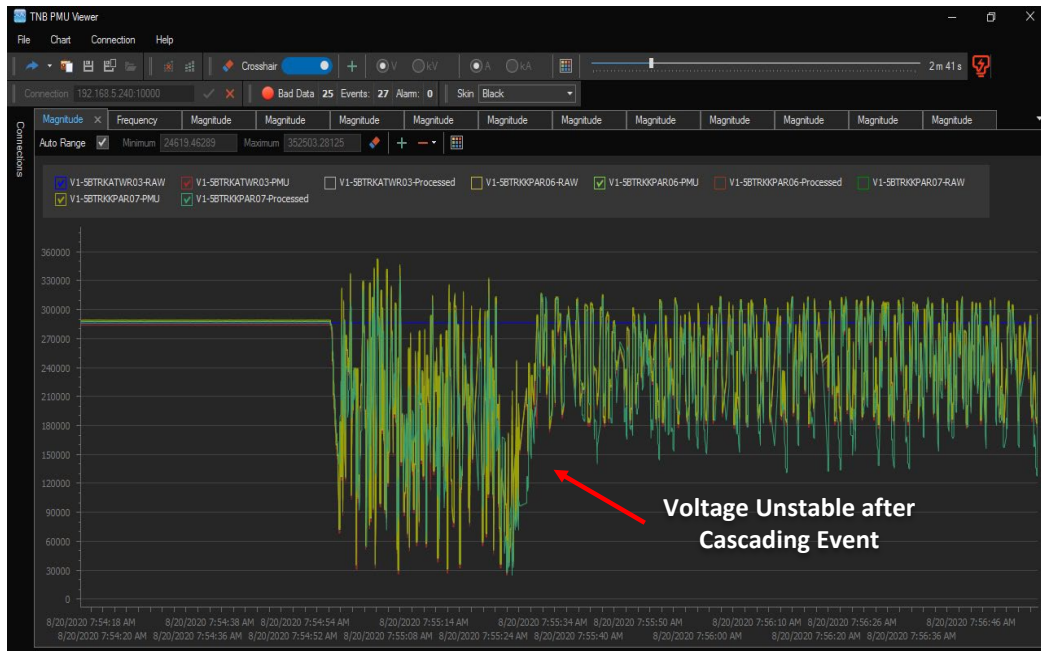
PMU ROSE at TNB: Estimating Values Using LSE and Cascading Analysis

- LSE results:
 - LSE (dark green line) successfully suppresses the error and estimates voltage with a difference of less than 0.01% compared to the true value
 - Substation with multiple PMU measurements with random errors and noise denoted by yellow, light green and red lines
 - The true value is blue line
- Cascading results:
 - Cascading Viewer visualizes results of online cascading analysis
 - 1877 N-1 initiating events are analyzed in one run
 - 41 critical cascading events were identified and ranked based on severity measured using the Performance Index (PI)



PMU ROSE at TNB: Effect of Remedial Actions

- A critical Initiating event results in stability violation
- The initiating event was tripping a transformer which leads to overload on other branches
- Optimal mitigation measures are identified to alleviate this stability violation
- The effect of these measures can be seen in the PMU Viewer





PMU-Based Linear State Estimator at SDG&E[®]:

Implementation and Drivers

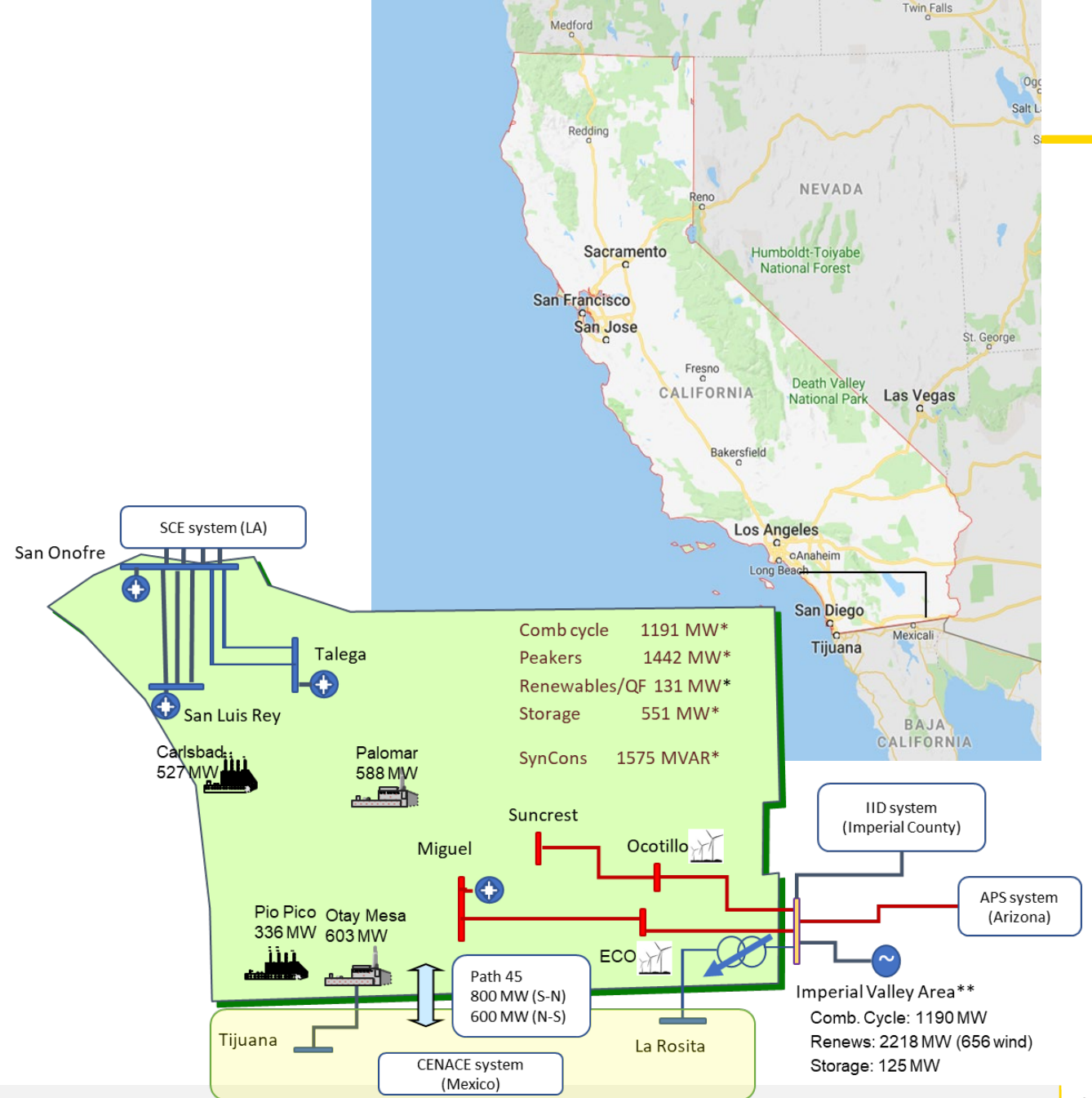
Robin Manuguid

September 26-27, 2023



About SDG&E®

- SDG&E is a regulated public utility in southern California, U.S.A.
- Serves San Diego & Southern Orange Counties: 1.46 million electric and 892,000 gas meters
- System Peak = 4,890 MW (9/16/14)
- Service area span 4,100 square miles.
- NERC-Registered: TO/P, GO/P, TP, LSE
- Within the CAISO BA area boundary in the RC West footprint; Coordinated Functional Registration (CFR) with the CAISO for TOP Reliability Standards



Importance of Linear State Estimator



- **Linear State Estimator (LSE) is based on PMU measurements of voltage and current:**
 - Voltage and current vectors are considered as the state variable
- **Advantages of LSE:**
 - Improves real-time resilience:
 - A backup to the conventional SE solution if it fails to solve or SCADA data is not available
 - Improves real-time reliability:
 - A check/validation for the quality of conventional state estimator
 - High speed of state estimation due to using a direct non-iterative solution
 - Solves at PMU sample rate (30 times/sec)

SDG&E Real-Time Operations Tools

- Conventional SE/RTCA
- EMS (GE) network
model

CA Contingency Case Report - Case 0: CASE CONTAINS CONVERGED SOLUTION

File Actions Navigation CA Case

Page 1 of 7 Total Records: 505

ALL LIMIT VIOLATIONS

MDB #	Contingency Name	# Viola...	Acknowledg...	Case Solution...	Composite ...	SI Orde...	Composite ...	SI Com...	Solution
520	TL20012-TL20074	1	Acknowledge	Full Solution	0.0	1	31.6	2	Harmless in CA
504	TL20050-TL20051 NC	1	Acknowledge	Full Solution	0.0	2	393.6	1	Harmless in CA
500	TL20012-TL20050 NC	1	Acknowledge	Full Solution	0.0	3	12.5	4	Harmful by CA,
78	TL20012-TL20054 B	1	Acknowledge	Full Solution	0.0	4	94.7	3	Harmless in CA
575	TL20012-TL20050	1	Acknowledge	Full Solution	0.0	5	0.0	5	Harmless in CA
540	TL20004-TL20000 C	1	Acknowledge	Full Solution	0.0	6	0.0	6	Harmless in CA

BC Limit Violations - Case 0: CASE CONTAINS CONVERGED SOLUTION

File Actions Navigation Base Case

Page 1 of 1 Total Records: 2

Limit ...	Viol...	Unit	Limit ...	Split Bus	Actual...	L1/Lo...	L2/Hig...	L3 Limit	% of L...	% of L...	% of L...	Island #	Netwo...
Line F...	HI F	MVA	A		76.332	58.00	64.00	70.00	131.62	119.28	109.06	1	Off
Line F...	HI F	MVA	N			132.00	145.00	160.00	106.66	97.10	88.00	1	Off

SDG&E Real-Time Operations Tools

- Conventional SE/RTCA
- EMS (GE) network
model

Study Case : 0 02/23/21 10:51:20.045 PST: RTNA: SE: time execution

Notes:

Status: CASE CONTAINS NON-CONVERGENT SOLUTION

192	0.5360E+04	VOL	0.001	3	179	7
		ANG	-0.19	3	166	16
		VOL	0.001	3	179	10
193	0.5360E+04	ANG	-0.09	3	166	30
		VOL	0.002	3	179	20
194	0.5361E+04	ANG	0.44	3	166	150 *
		VOL	0.012	3	179	122
195	0.5364E+04	ANG	0.36	3	166	3
		VOL	0.001	3	179	1
196	0.5361E+04	ANG	0.27	3	166	2
		VOL	0.001	3	179	7
197	0.5360E+04	ANG	0.19	3	166	9
		VOL	0.001	3	179	10
198	0.5360E+04	ANG	0.11	3	166	17
		VOL	0.002	3	179	15
199	0.5361E+04	ANG	-0.46	3	166	153 *
		VOL	-0.022	3	179	119
200	0.5364E+04	ANG	-0.37	3	166	10
		VOL	0.001	3	179	1

STATE ESTIMATOR CONVERGENCE SUMMARY - FULL SYSTEM

ACTIVATED OPTIONS: 2 14 16 21 35 55

NUMBER OF ITERATIONS : 200

PERFORMANCE INDEX : 0.53638E+04

ISLAND NO.	NO. OF BUSES	PERFORMANCE INDEX	CONVERGENCE STATUS
1	748		STATE ESTIMATOR NOT SOLVED - State estimator not converged in maximum number of iterations.

SE Bad Measurement Summary - Case 0: CASE CONTAINS CONVERGED SOLUTION

File Actions Navigation Base Case

Page 1 of 1

Case Number: 0 04/23/22 08:56:20.047 PDT: RTNA: SE: time execution

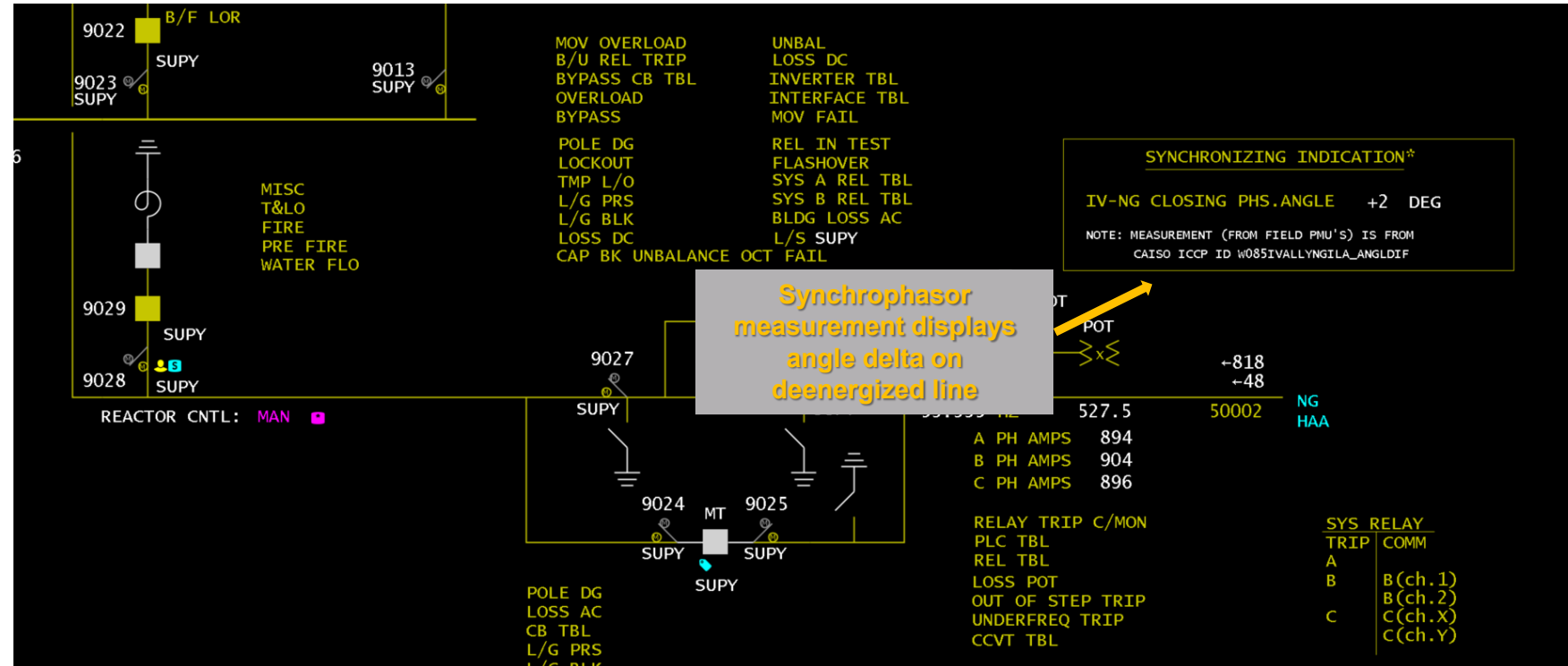
Notes:

Status: CASE CONTAINS CONVERGED SOLUTION

Device Name	Bus Name	Bad Data Type	Measured	Estimate	Weighted Residual at Convergence
	0	LINE-T-Q	26.50	-4.55	6.86
	30	GENR-Q	-0.30	-34.17	6.31
	30	GENR-Q	9.80	-34.17	8.33
	30	GENR-Q	-10.40	-34.17	4.29
	30	GENR-Q	0.60	-34.17	6.49
	30	XFMR-F-Q	22.50	-68.35	28.74
	30	XFMR-F-Q	-22.10	-68.35	13.87
		GENR-Q	15.28	26.08	-3.59
		GENR-Q	-3.96	9.10	-4.35
		XFMR-T-Q	10.62	35.18	-8.17
		XFMR-F-Q	15.09	-12.56	9.52
		XFMR-F-Q	96.00	117.62	-7.99
		LINE-F-Q	-14.20	11.28	-9.46
		XFMR-TAP	-16.00	1.00	-17.00
		GENR-P	308.60	618.15	-81.98
		XFMR-F-Q	95.80	82.12	16.16
		LINE-F-Q	-99.10	-59.47	-46.96
		LINE-F-P	1077.80	852.48	184.71
		LINE-T-P	-244.40	-248.91	6.94
		LINE-F-P	245.00	249.93	-7.19
		XFMR-F-Q	-44.39	-10.44	-7.17
		XFMR-F-Q	-44.39	-10.83	-7.11

SDG&E Real-Time Operations Tools

- **EMS Display with PMU data**



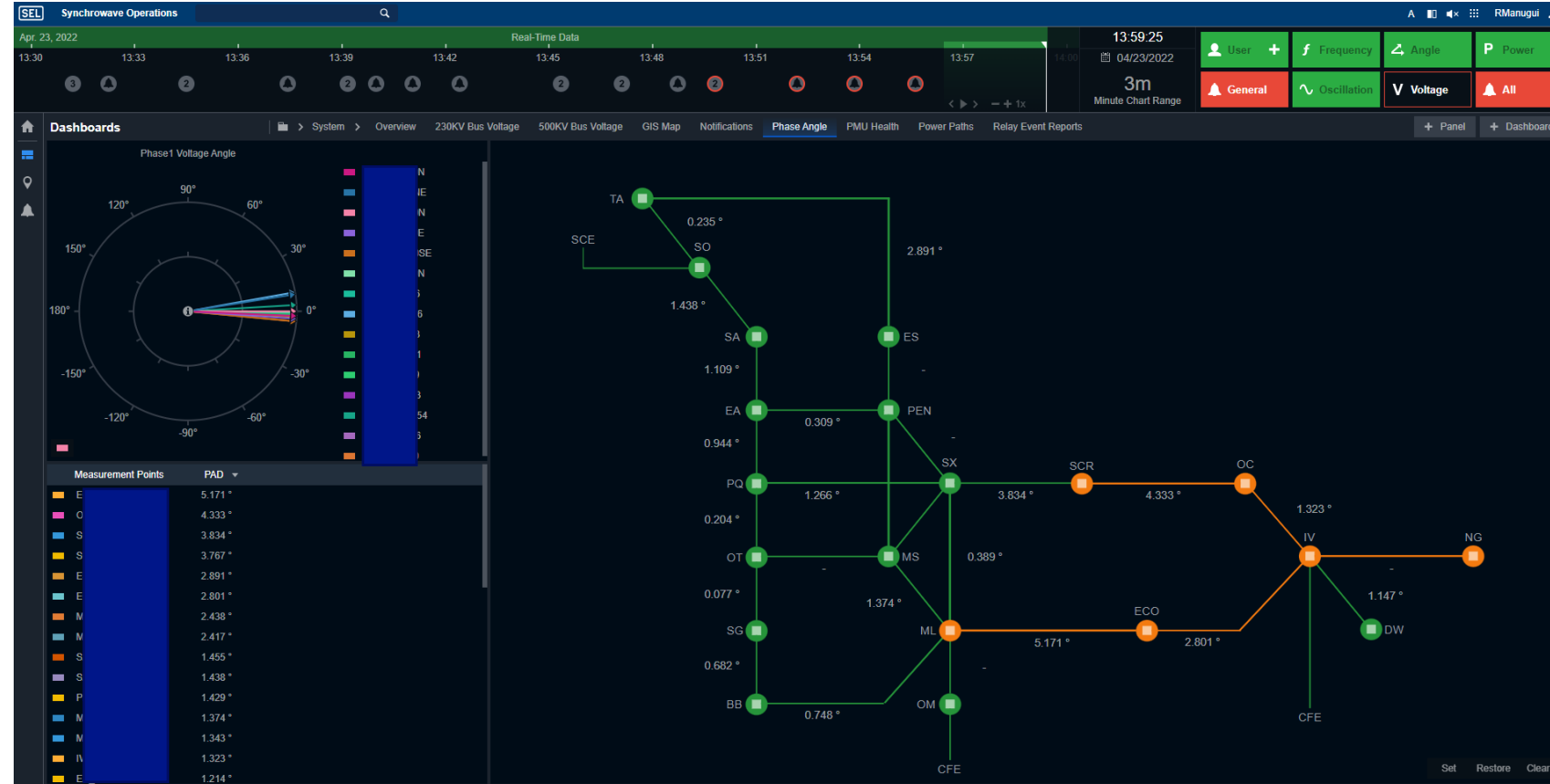
SDG&E Real-Time Operations Tools

- **Voltage Stability – use RC West’s EMS model export in CIM15 loaded in V&R’s ROSE**



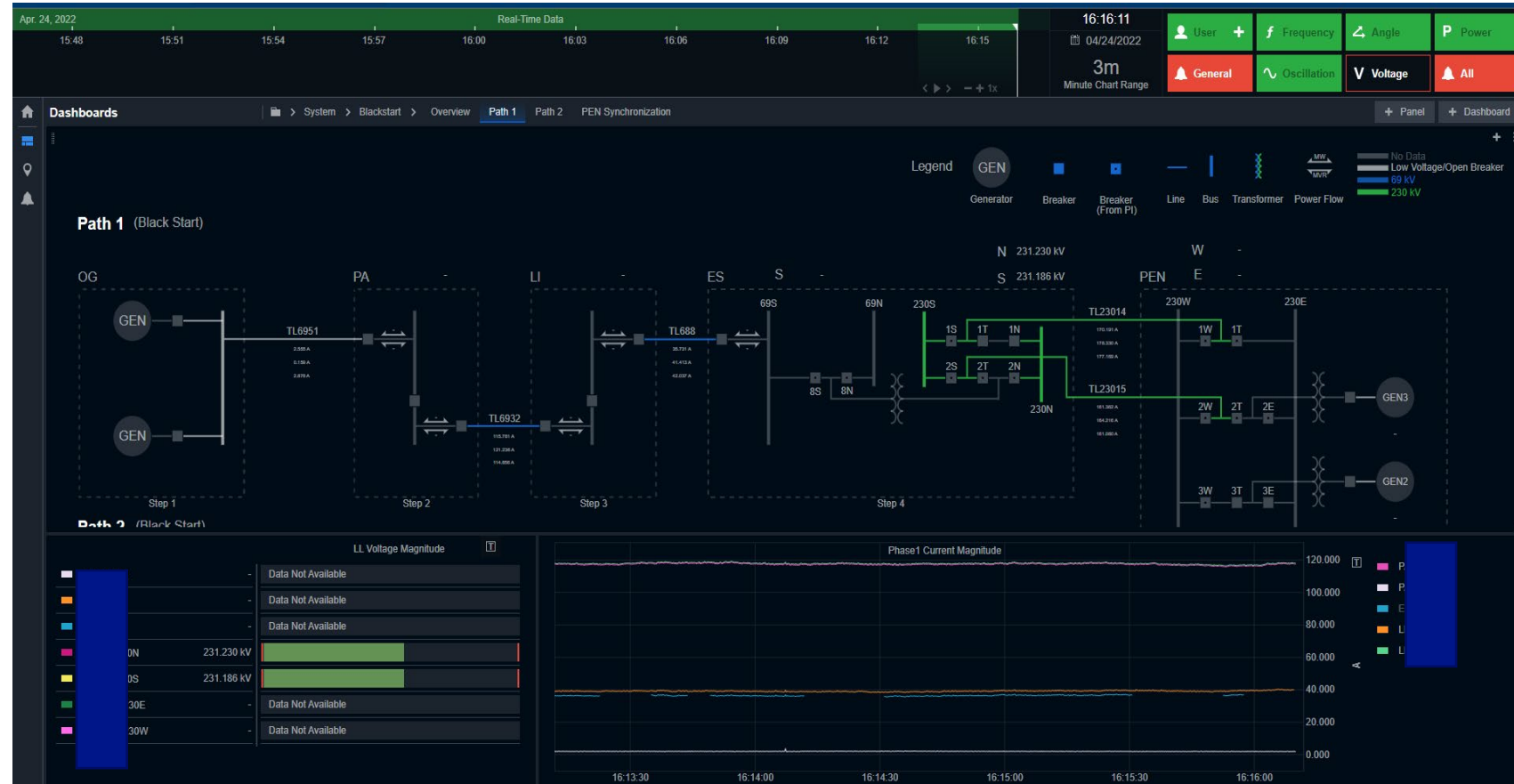
SDG&E Real-Time Operations Tools

- **Synchrowave Operations System – (SEL)** power system monitoring and visualization, oscillation detection, notification



SDG&E Real-Time Operations Tools

- Synchrowave Operations System – (SEL) power system detection, notification, visualization



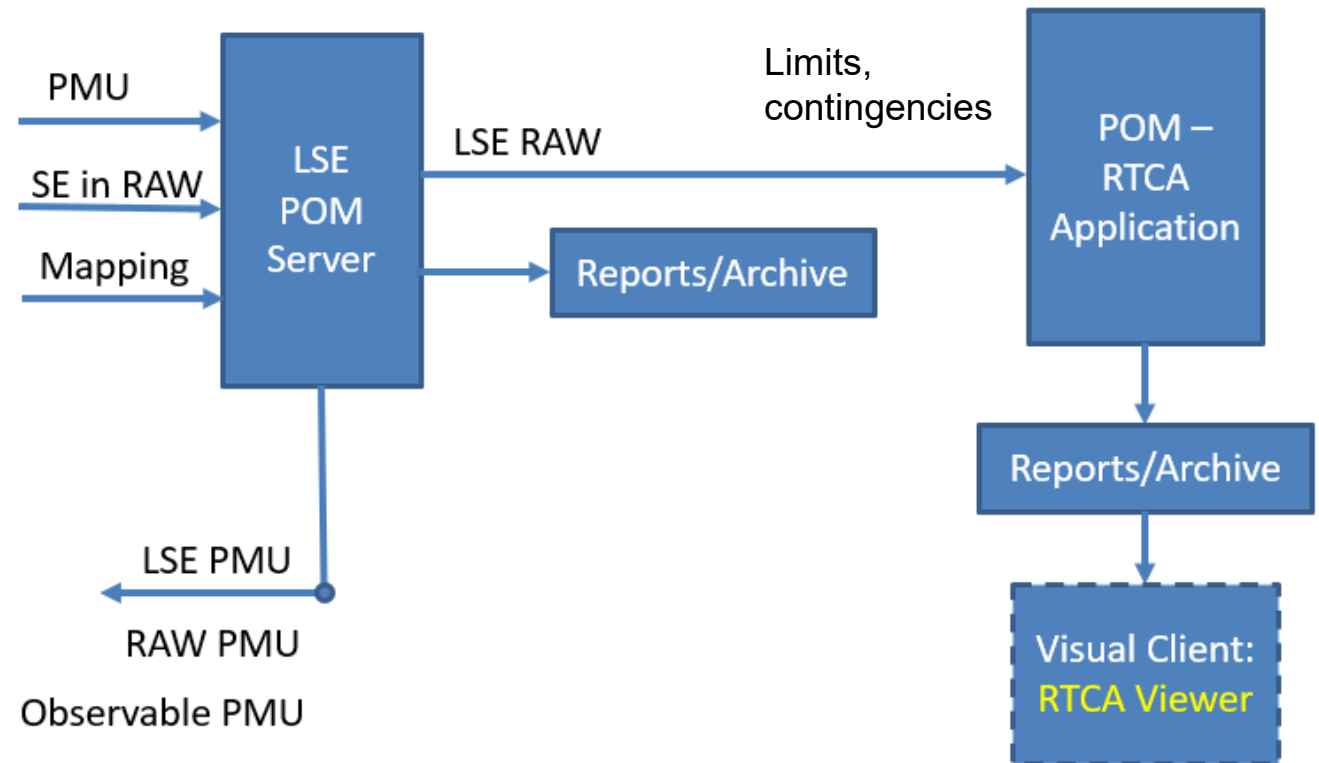
SDG&E PMU ROSE Architecture



Abbreviations:

- LSE PMU - LSE result at PMU locations
- LSE RAW - PMU-based State Estimator cases in Siemens PSS/E .raw data format
- Observable PMU - LSE result at locations observable with existing PMUs
- RAW PMU - Voltage magnitude and phase and current amplitude and phase from conventional State Estimator cases, converted to IEEE standard C37.118
- RTCA - Real-Time Contingency Analysis
- SE in RAW - Power flow cases (e.g., conventional State Estimator cases) in Siemens PSS/E .raw data format
- POM - Physical and Operational Margins applications (POM Core)

3 apps: LSE POM Server, POM-RTCA, RTCA Viewer



SDG&E PMU-Based LSE



LSE is performed 30 fps and includes:

- Bad data detection and conditioning
- Observability analysis
- Creation of conditioned and expanded PMU data streams
- Creation of PMU-based state estimator case (e.g., LSE Case) for the use by RTCA

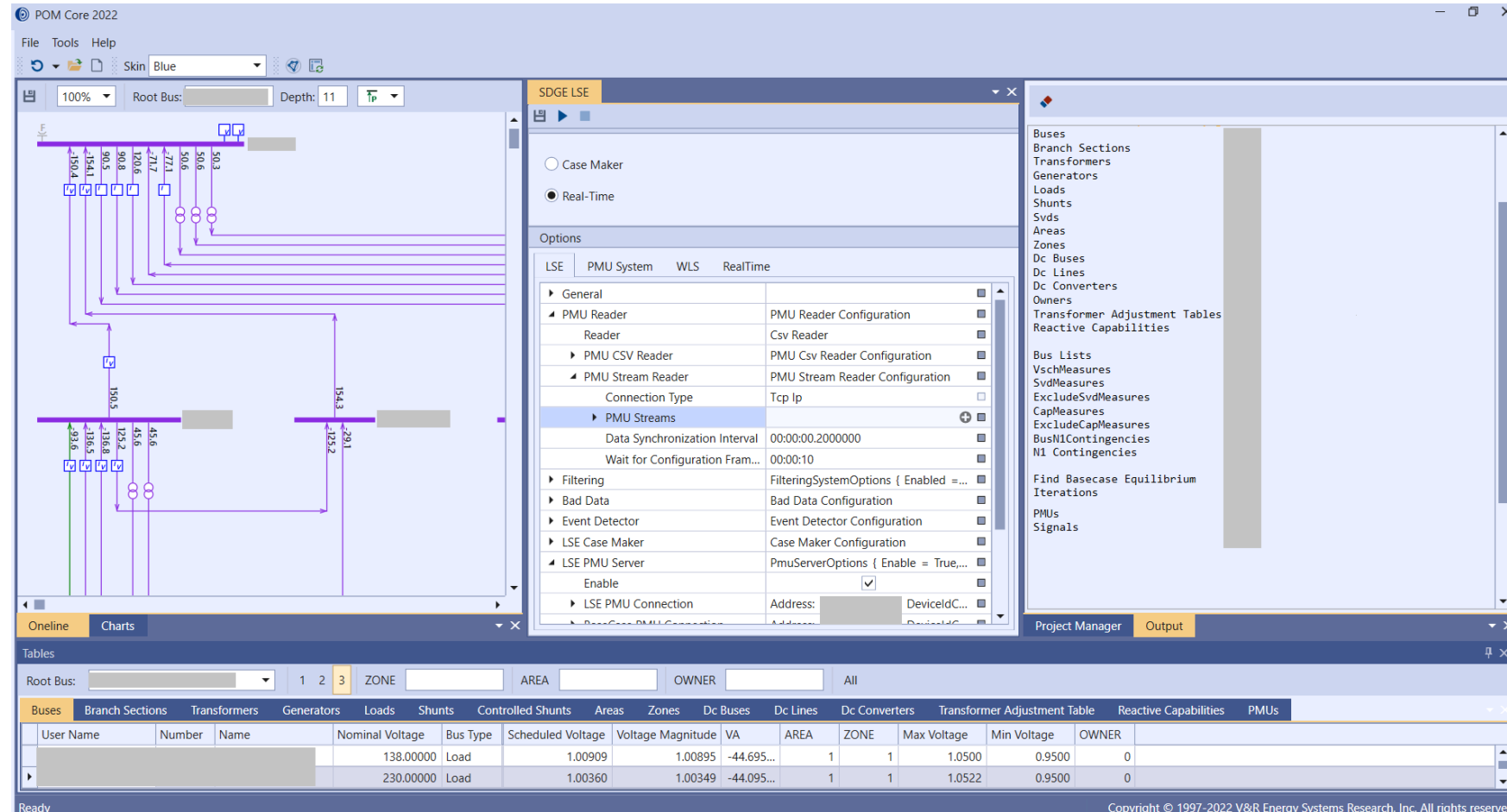
Scalable System

- More PMU measurements available
- More distributed PMUs across the system
- More accurate LSE/Base Case

Drivers:

- Backup of conventional SE
- Faster analysis
- Improve PMU data quality
- Increase system observability

SDGE PMU ROSE: LSE



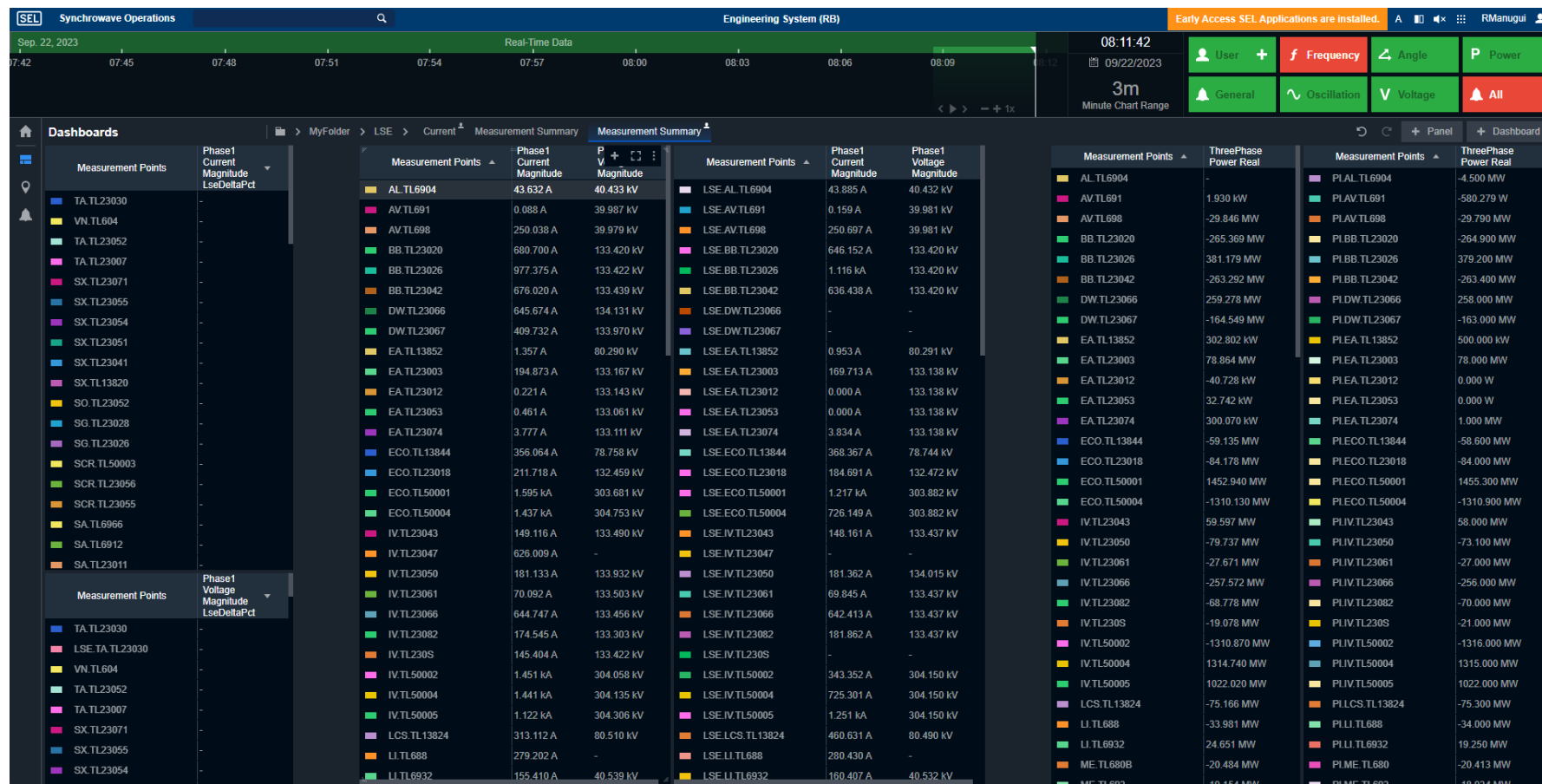
SDG&E PMU-Based LSE: Conditioned streams

LSE is performed 30 fps and includes:

- Bad data detection and conditioning
- Observability analysis
- Creation of conditioned and expanded PMU data streams

Options	
LSE	PMU System WLS RealTime
LSE PMU Server PMU Server Configuration	
Enable	☒
LSE PMU Connection Address: 127.0.0.1:10500 DeviceIdCode: 1000	
Address	127.0.0.1:10500
Device Id Code	1000
LSE PMU Power Connection Address: 127.0.0.1:10600 DeviceIdCode: 1000	
Address	127.0.0.1:10600
Device Id Code	1000
BaseCase PMU Connection Address: 127.0.0.1:10501 DeviceIdCode: 1000	
Address	127.0.0.1:10501
Device Id Code	1000
BaseCase PMU Power Connection Address: 127.0.0.1:10601 DeviceIdCode: 1000	
Address	127.0.0.1:10601
Device Id Code	1000
Observable PMU Connection Address: 127.0.0.1:10502 DeviceIdCode: 1000	
Address	127.0.0.1:10502
Device Id Code	1000
Observable PMU Power Connection Address: 127.0.0.1:10602 DeviceIdCode: 1000	
Address	127.0.0.1:10602
Device Id Code	1000
Frame Rate	30
Use PMU Time	☒
Maximum Number Of Clients	0

WASA Dashboard: LSE PMU, SE SCADA, SCADA



SDG&E PMU-Based LSE: RTCA



- Internal SE model produced by SDGE EMS is used
- LSE (e.g., PMU-based State Estimator) cases are sent by the LSE to RTCA application
- AC contingency analysis is performed using contingency list from EMS
- Output is archived and visualized using RTCA Viewer application
- Can be connected with automated remedial actions program, voltage stability, cascading analysis

Drivers:

Compare SE-based and LSE-based RTCA results

SDGE PMU ROSE: RTCA

The screenshot shows the POM Core 2022 SDGE RTCA application. The main window displays a tree view on the left with categories like Buses, Branch Sections, Transformers, Generators, Loads, Shunts, Svds, Areas, Zones, Dc Buses, Dc Lines, Dc Converters, Owners, Transformer Adjustment Tables, Reactive Capabilities, and N1 Contingencies. The central panel contains settings for SDGE RTCA, including Off-Line and Real-Time modes, Critical Contingencies Calculation, Solve Arguments, Output Directory, Real Time Options, and RTCA Server Options. The bottom table displays data for various components.

Root Bus:	1	2	3	ZONE	AREA	OWNER	All						
Bus	Branch Sections	Transformers	Generators	Loads	Shunts	Controlled Shunts	Areas	Zones	Dc Buses	Dc Lines	Dc Converters	Transformer Adjustment Table	Reactive Capabilities
User Name	Number	Name	Nominal Voltage	Bus Type	Scheduled Voltage	Voltage Magnitude	VA	AREA	ZONE	Max Voltage	Min Voltage	OWNER	
			69.00000	Load	1.02008	1.02009	-51.271...	1	1	1.0507	0.9493	0	
			69.00000	Load	1.01724	1.01725	-49.892...	1	1	1.0507	0.9493	0	
			69.00000	Load	1.02129	1.02129	-50.963...	1	1	1.0507	0.9493	0	

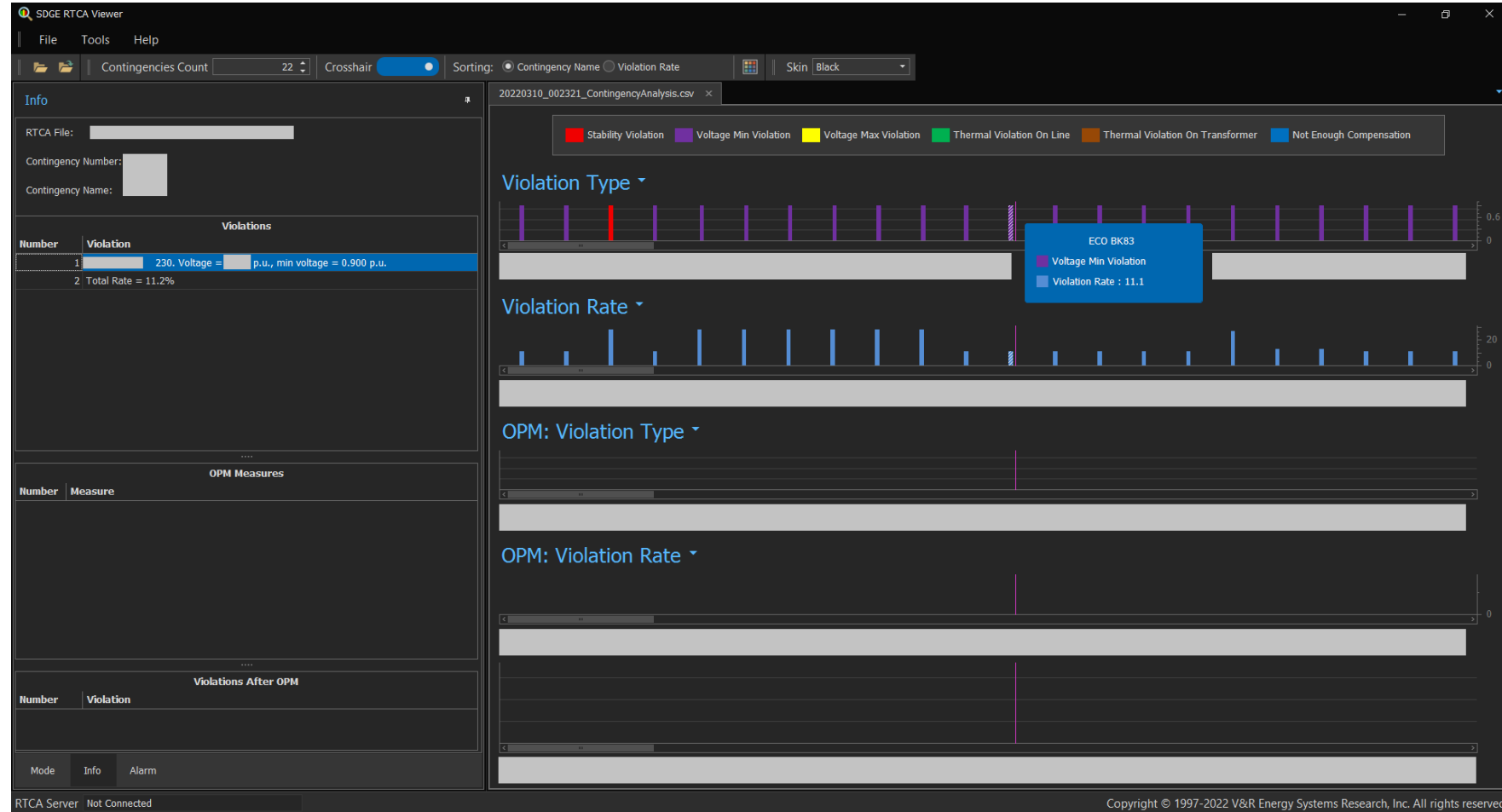
SDG&E PMU-Based LSE: RTCA



- 522 Contingencies in SE/RTCA
- So far 146 valid contingencies

Six Violation types:

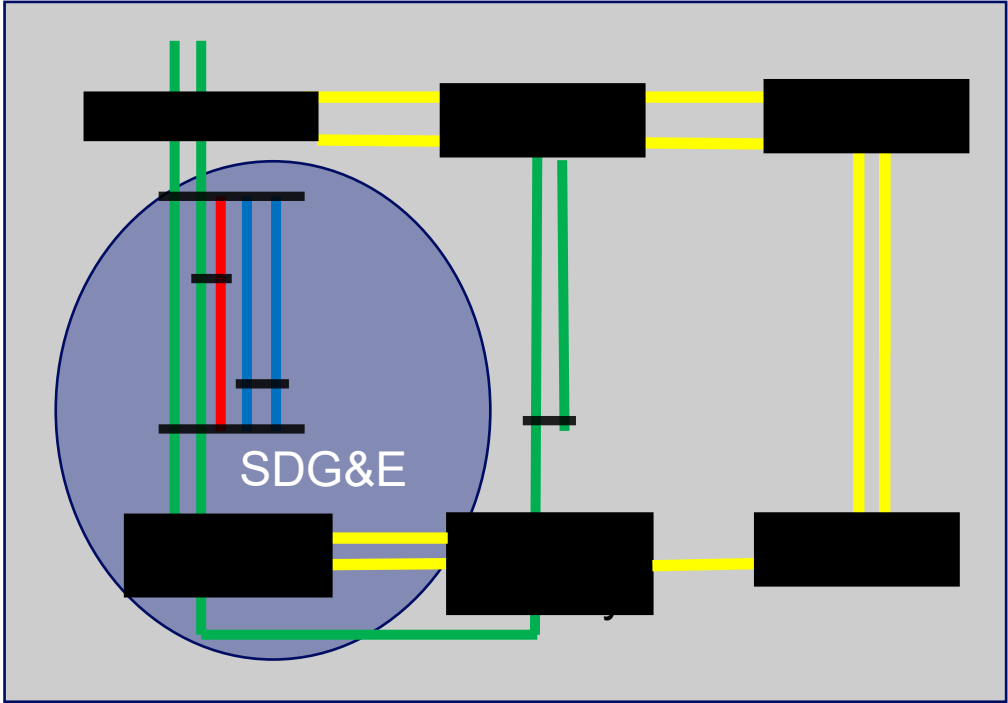
- Stability Violation;
- Voltage Min Violations;
- Voltage Max Violations;
- Thermal Violations on Line;
- Thermal Violations on Transformer;
- Not Enough Compensation.
- Angle diffs (not included)



SDG&E PMU-Based LSE: RTCA

Bus (SDG&E-owned)	Count	SCADA Coverage	PMU Coverage
500kV	5	5/5	100%
230kV	22	100%	100%
138kV	31	30/31	6/26
69kV	88	85/88	11/88 *

Observability	Initial (before bad data detection)	Stages				LSE Case
		1	2	3	4	
buses	44	106	118	119	119	109
branches	89	192	212	212	213	157



Pacific Southwest Major Corridors (Pacific Southwest Blackout in 2011 took about 11 minutes)

* Optimal PMU placement to identify additional PMU locations to achieve full SDG&E network observability has been conducted.

Conclusions

- SDGE PMU ROSE is installed at SDG&E for LSE and RTCA.
- “Bad data” and modelling/mapping errors are being investigated
- Multiple PMUs in one location does not help expand observability.
- Engaging vendor, IT, and EMS support early will help identify and resolve problems faster.
- More PMUs are being installed and existing stand-alone PMUs to be relocated, which will increase system observability, and the size of LSE case (in terms of number of buses, lines, etc.)

Thank you

Question?

Robin Manuguid

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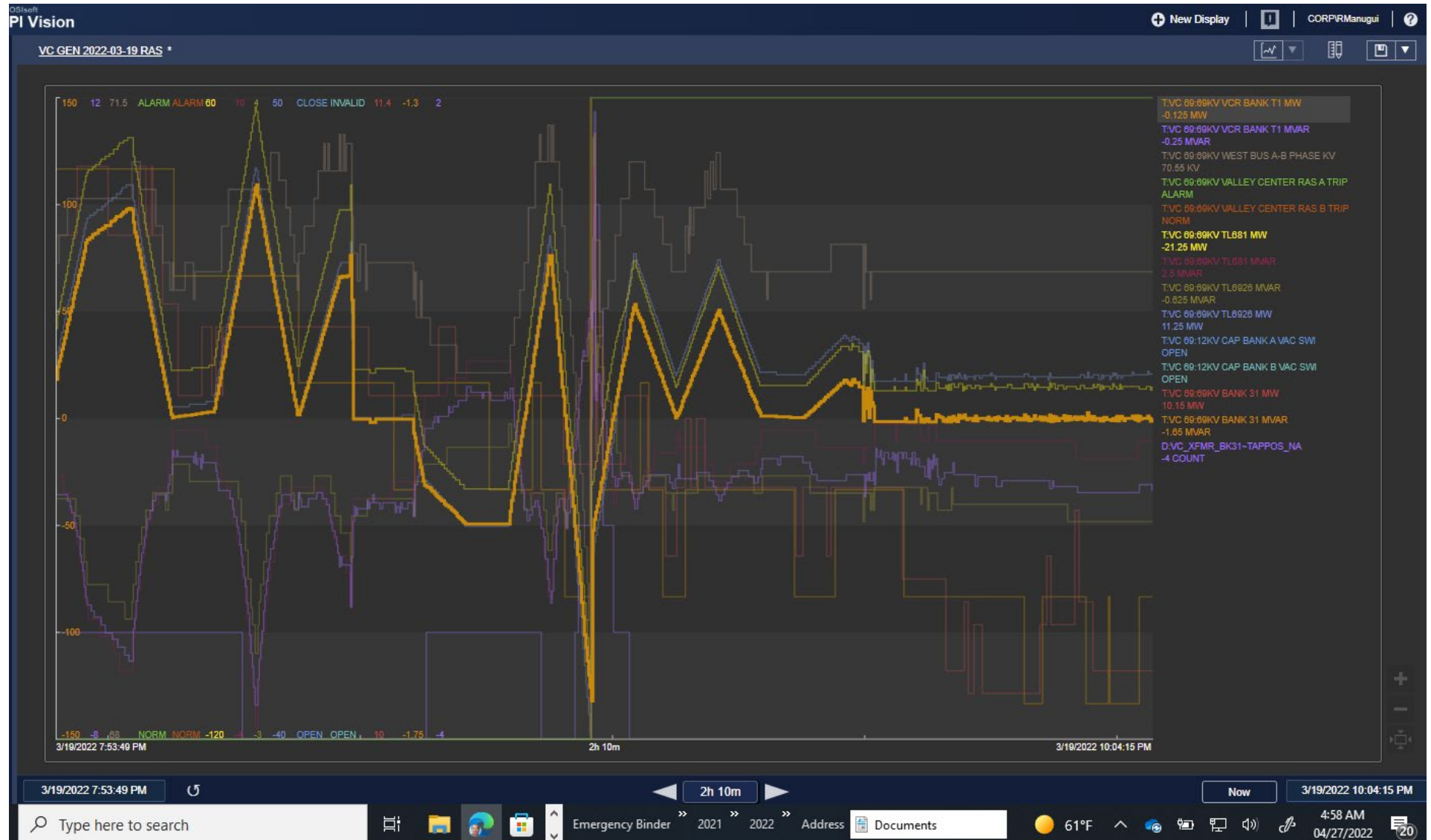


Robin Manuguid



Robin is a staff engineer in Grid Operations and leads the long-term outage coordination studies to sequence multi-phase transmission projects and successful completion of major projects. He provides real-time support for real-time tools (i.e., SE, RTCA, and near-RTVSA) and conducts next-day studies. He reviews and updates operating procedures which are often triggered by operating studies. Robin joined SDG&E in 1992 after earning his BSEE from Cal Poly, San Luis Obispo. Since joining the Electric Grid Operations in 2004, he's been engaging with WECC activities, coordinating with SDG&E SMEs on various NATF programs. He is a Principal Engineer with SDG&E. He is an IEEE member.

Back up slide



LSE Project Alignment with the ERO RRP

The Five Risks:

1. Grid Transformation
 - Batteries on weak grid
2. Security Risks
 - Batteries on weak grid
 - Network model accuracy.
3. Resilience to extreme events
 - Loss of comm paths
4. Critical Infrastructure Interdependencies
 - Polled SCADA data vs streams
5. Energy Policy

