PMU-based EMS and Power Network Analysis Applications

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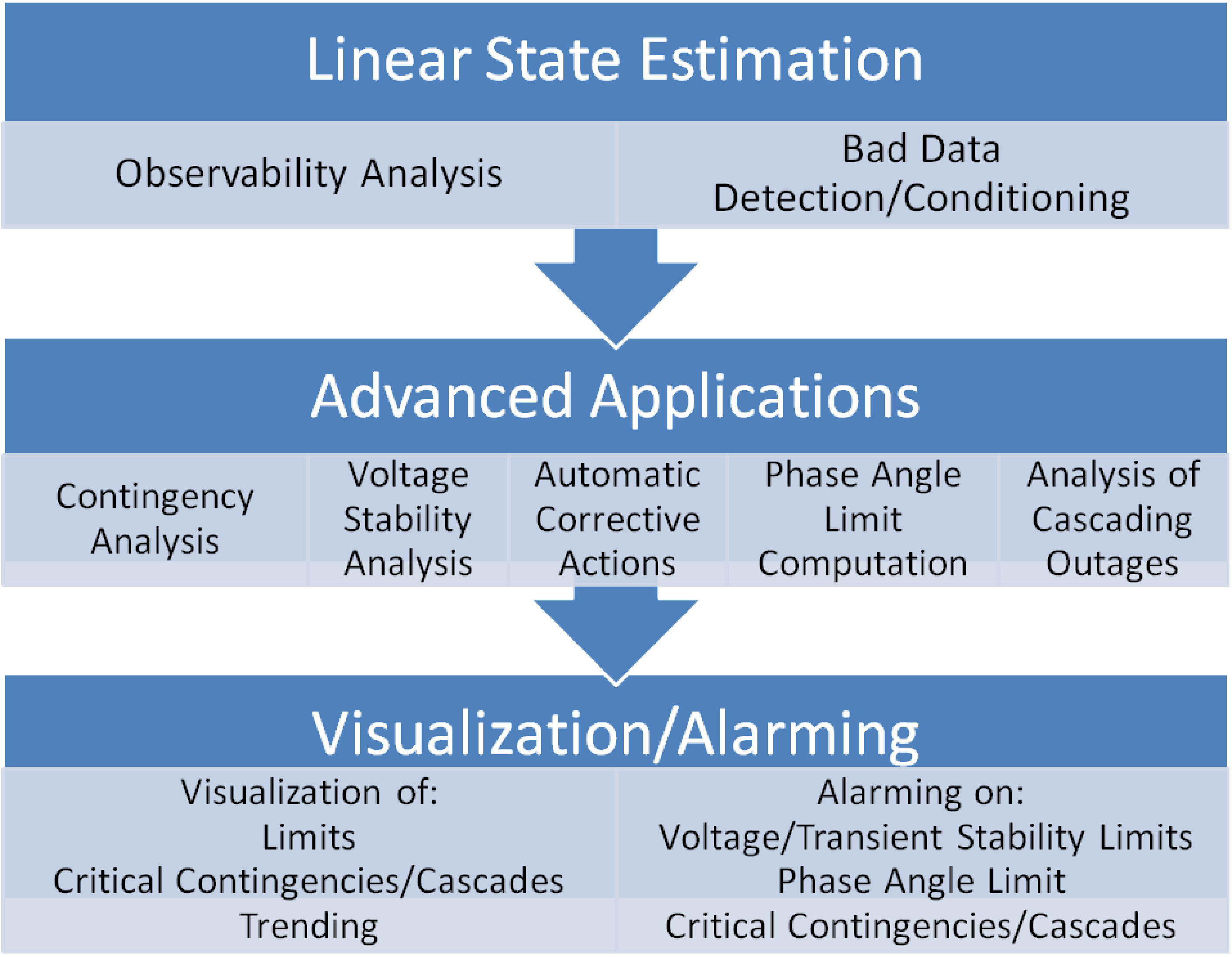
NASPI Work Group Meeting

Salt Lake City • April 16 - 17, 2024

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:
  - Invented 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

NASPI North American SynchroPhasor Initiative

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 Work-shop

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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

V&R ENERGY

2014 NASPI Voltage Stability Case 2

- Correct results announced by NASPI at the Workshop →

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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

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VOLTAGE STABILITY CASE 2
RESULTS AND COMMENT SHEET

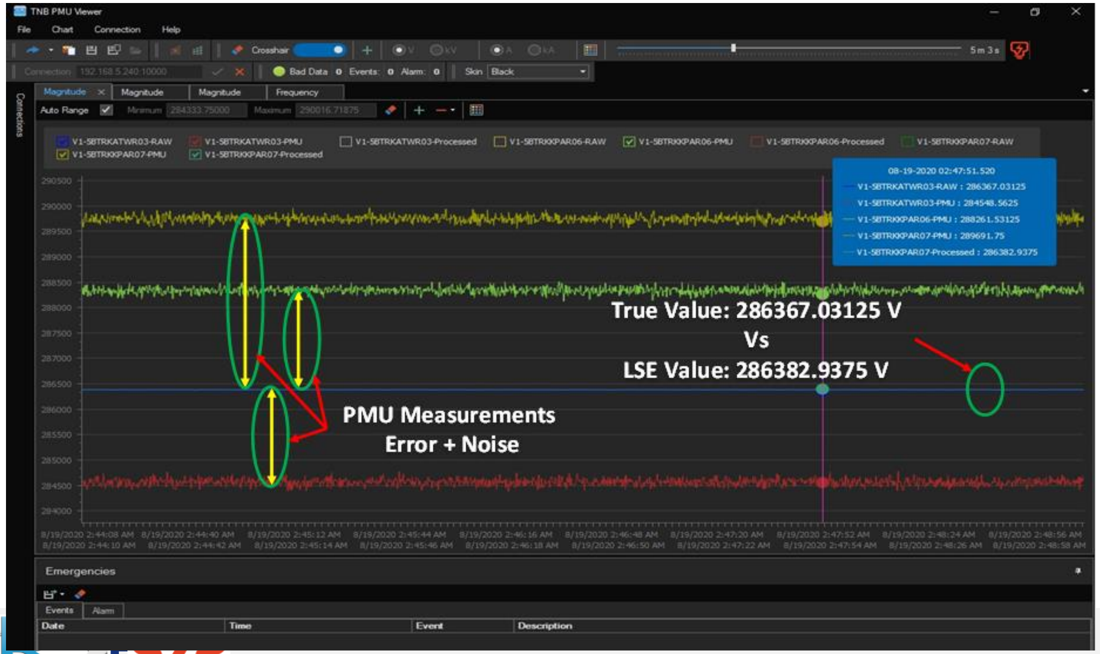
	Alstom Grid	V&R Energy
First Time of Insecure (N-1) Operating Condition	2410	1312
Reason(s) for Insecurity	Line L02	Contingency L02 Contingency L11
First Time of Unacceptable N-0 Operating Condition	4064	None
Reason for Unacceptable Condition	Voltage Violation @ Bus 113	N/A
Time of Instability	4070	4012
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)

- ← Results submitted by vendors one week before the Workshop

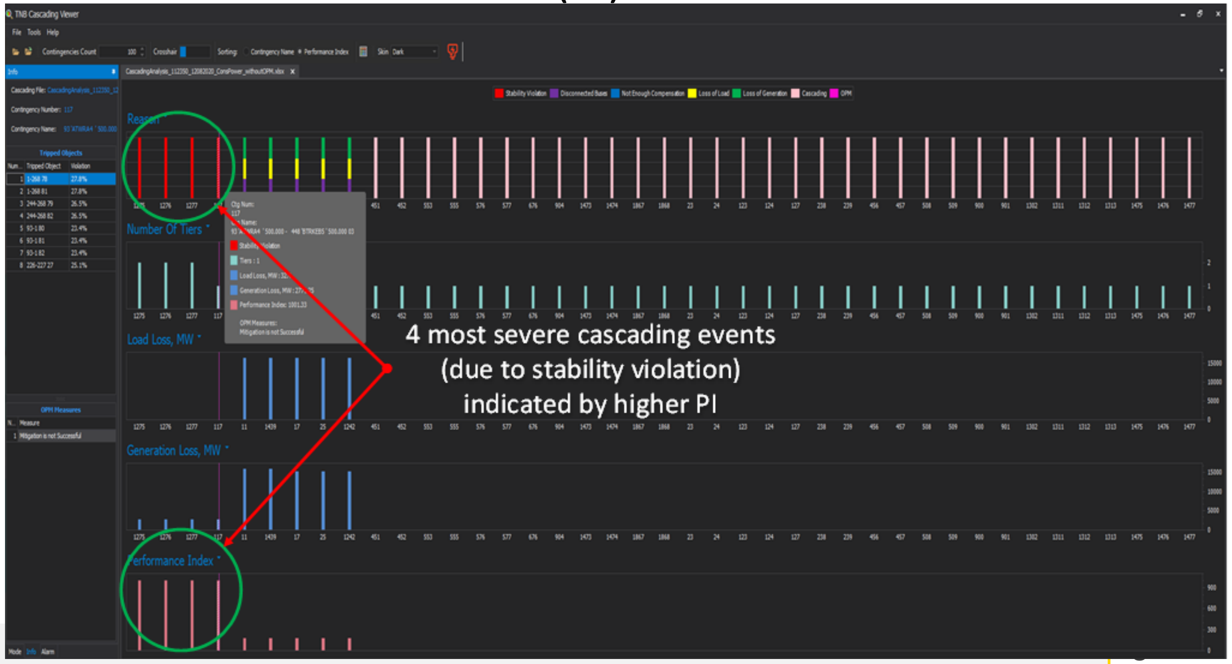
V&R ENERGY

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



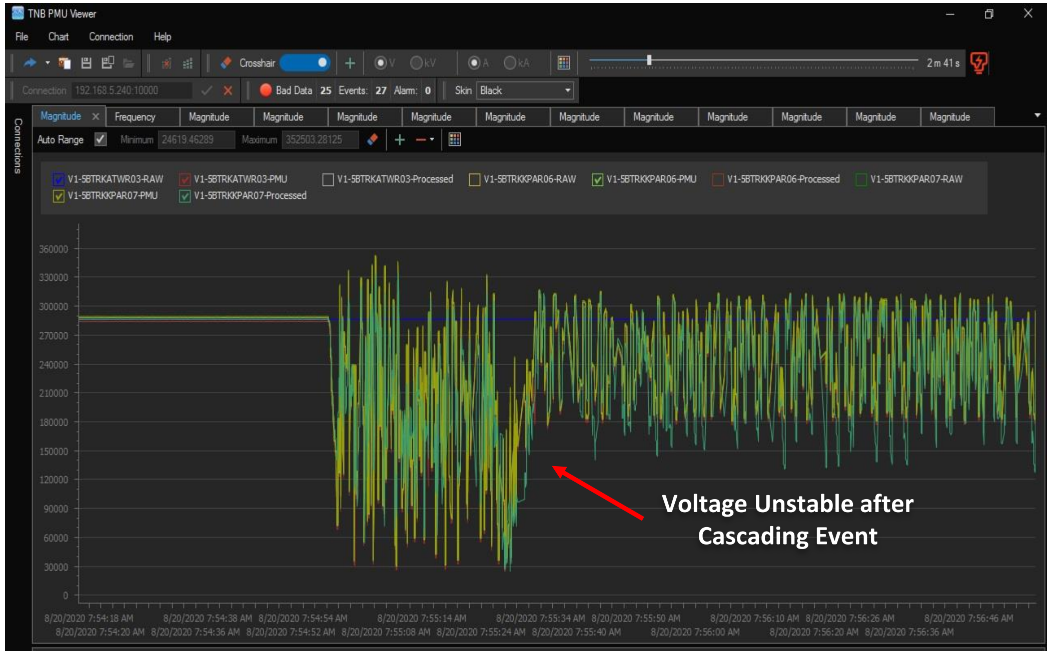
- Cascading results:
  - Cascading Viewer visualizes results of online cascading analysis
  - 1877 N-1 initiating events are analyzed in one run
  - 41 critical cascading events were identified and ranked based on severity measured using the Performance Index (PI)

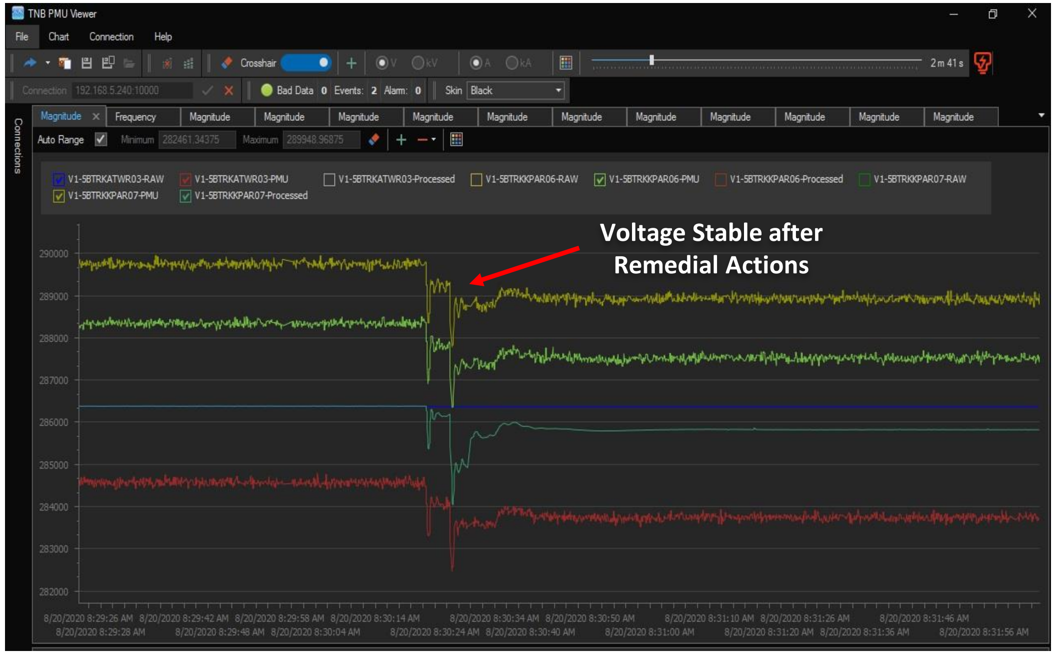


TNB PMU ROSE: Alleviating Voltage Stability Violation

- 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



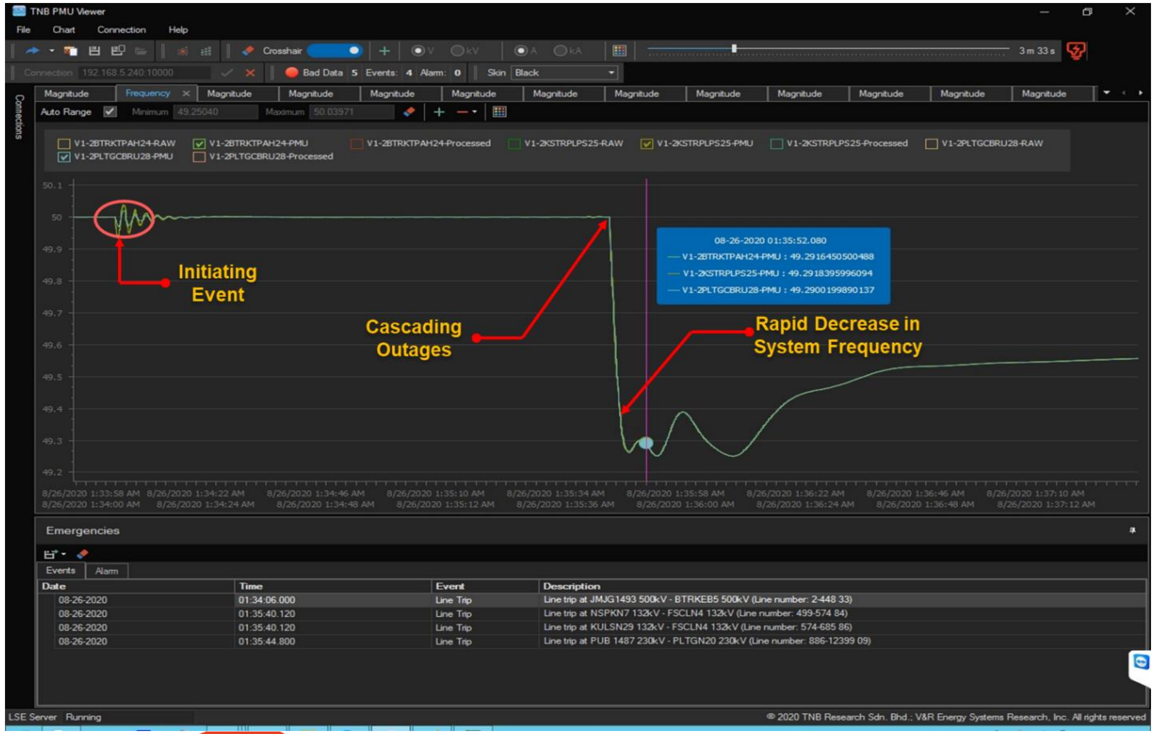


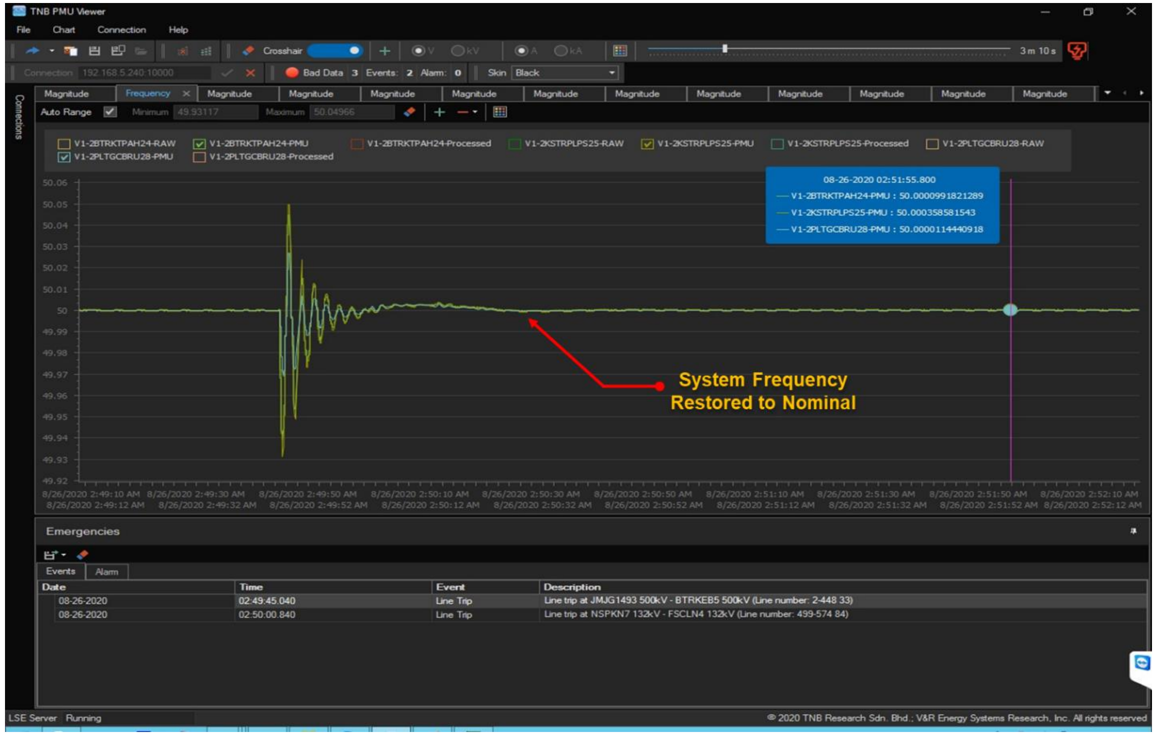
- LSE calculation accurately represents transient event

TNB PMU ROSE: Alleviating Frequence Violation

- A significant decrease in system frequency following the occurrence of critical cascading events
- These events were triggered by the tripping of a 500kV transmission line

- Optimal mitigation measures are identified to alleviate frequency violation
- The effect of these measures can be seen in the PMU Viewer





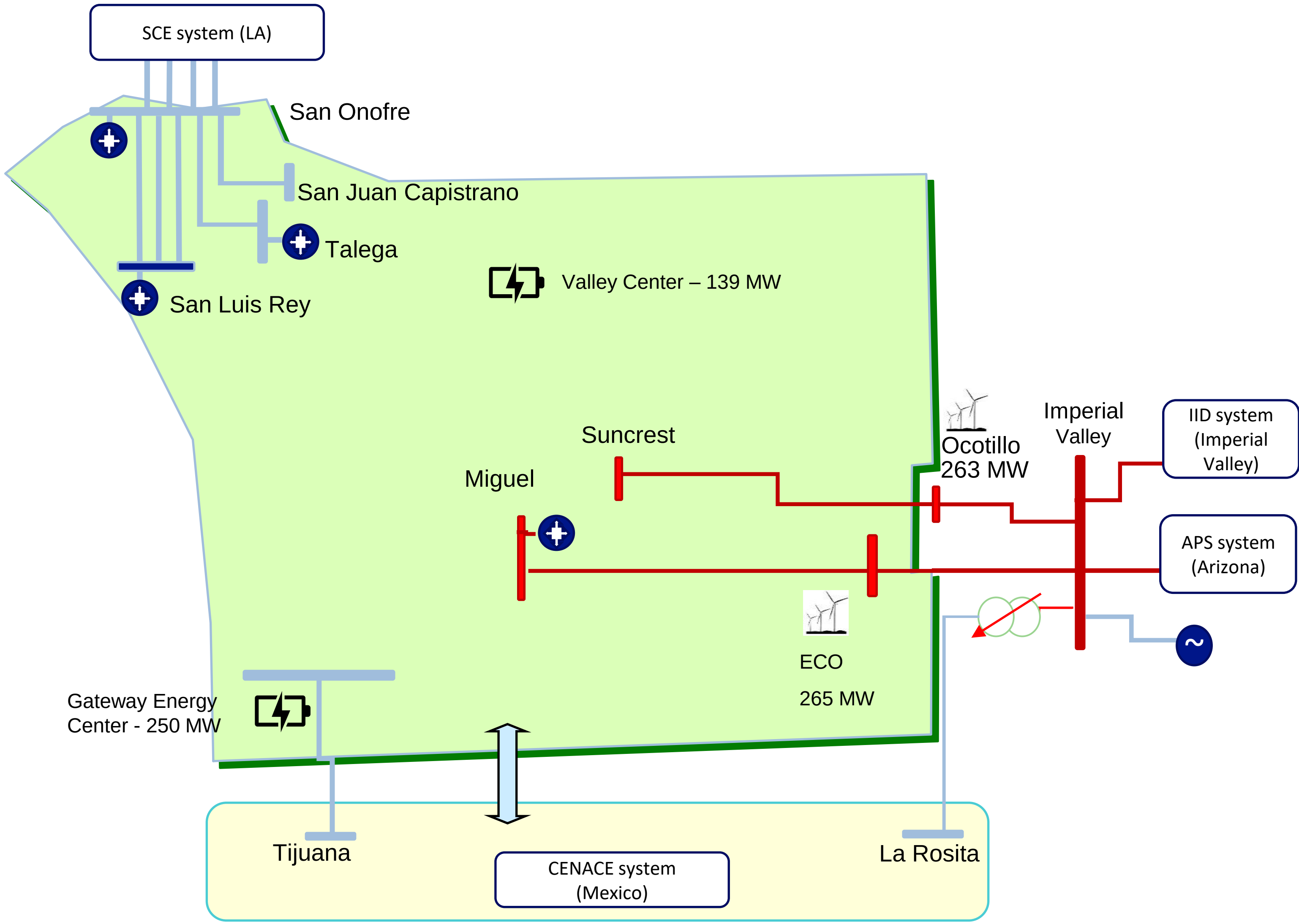
PMU-Based Linear State Estimator at SDG&E®

Robin Manuguid, PE

April 16-17, 2024

About SDG&E®

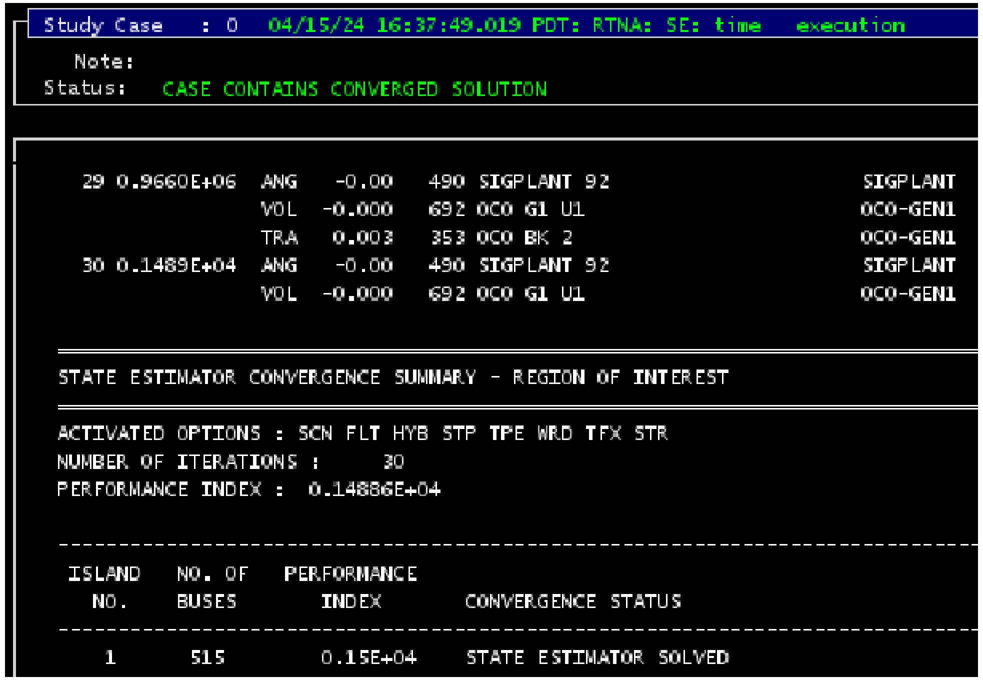
- SDG&E is a regulated public utility in southern California.
- Serves San Diego & Southern Orange Counties: 1.46 million electric meters
- System Peak = 4,890 MW (9/16/14)
- Service area span 4,100 square miles.
- NERC-Registered: TO/P, GO/P, TP, LSE
- Within the CAISO BA area boundary in the RC West footprint



Presentation Outline

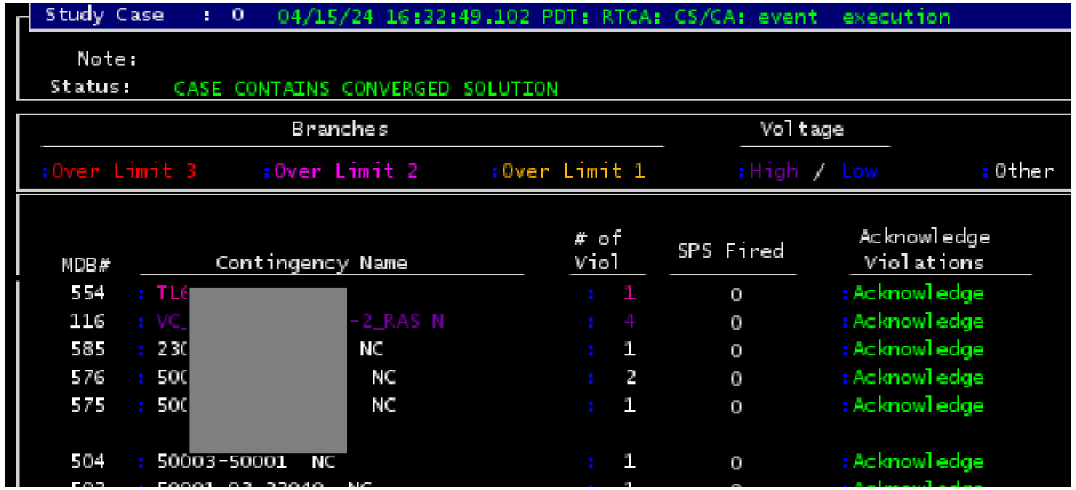
- About SDG&E.
- Existing Real-Time Tools
  - State Estimator / RTCA
  - Phase angle difference
  - Voltage Stability Analysis
  - SEL Synchrowave Operations
- Linear State Estimator
  - PMU additions
  - Observability Analysis Update
  - LSE Case Update
- Conclusions

Real-Time Tools – State Estimator and RTCA



SE Convergence Report

Always a good thing when SE is converging. Calls are made by the System Operator to the Operating Engineer and EMS support when not solving.

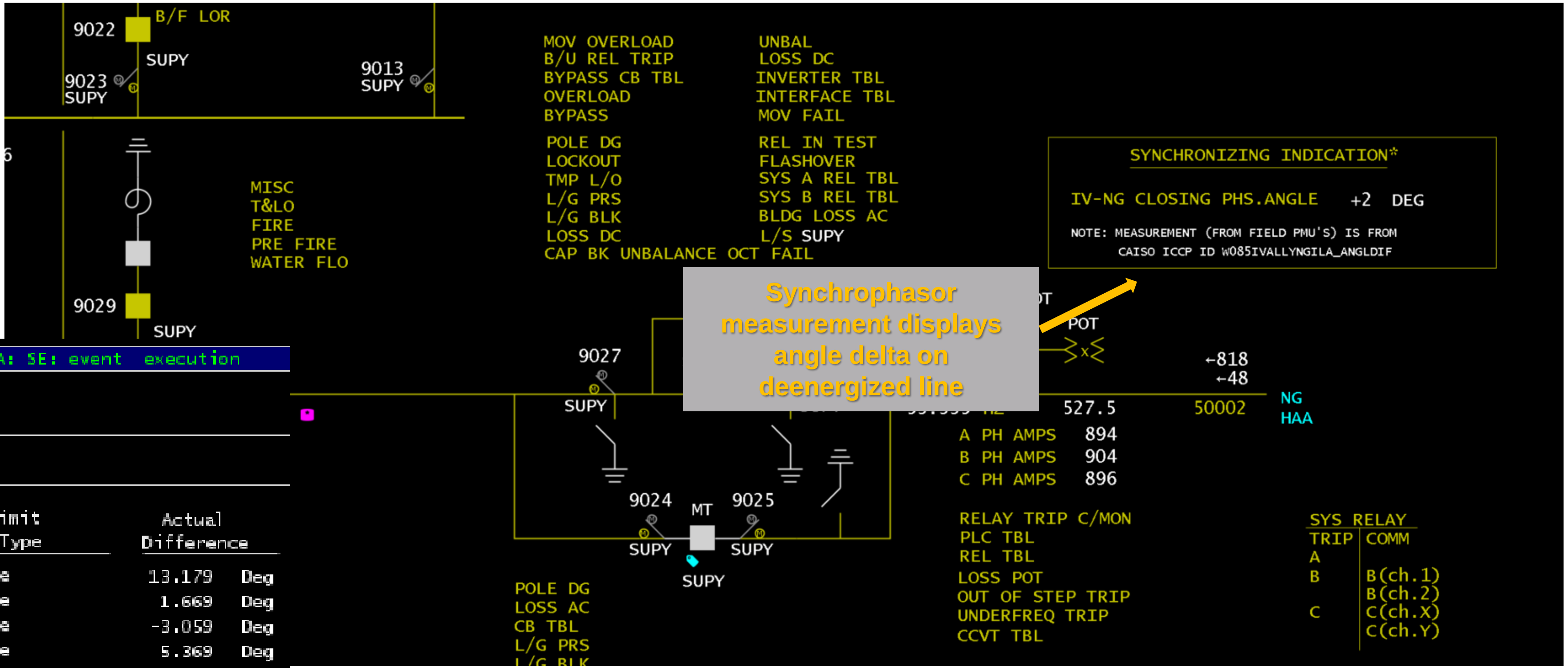


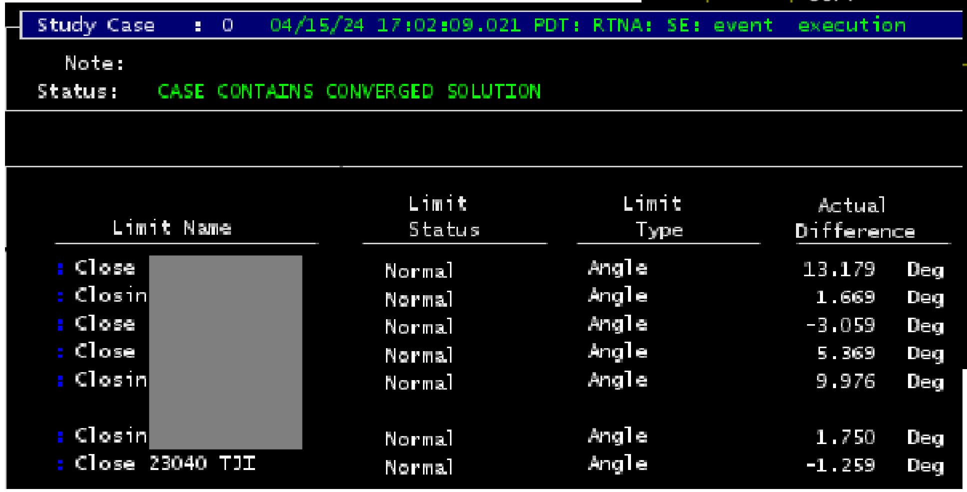
Real-Time Contingency Analysis Report

Always a good thing when no contingencies are showing limit exceedance. Calls are made to the CAISO when issues show up. Operating Engineer assists in providing operating plan to mitigate issues.

Real-Time Tools – Phase Angle Difference

EMS Display with PMU data to calculate phase angle difference for transmission line with closing angle limit.





Study Case : 0 04/15/24 17:02:09.021 PDT: RTNA: SE: event execution

Note:

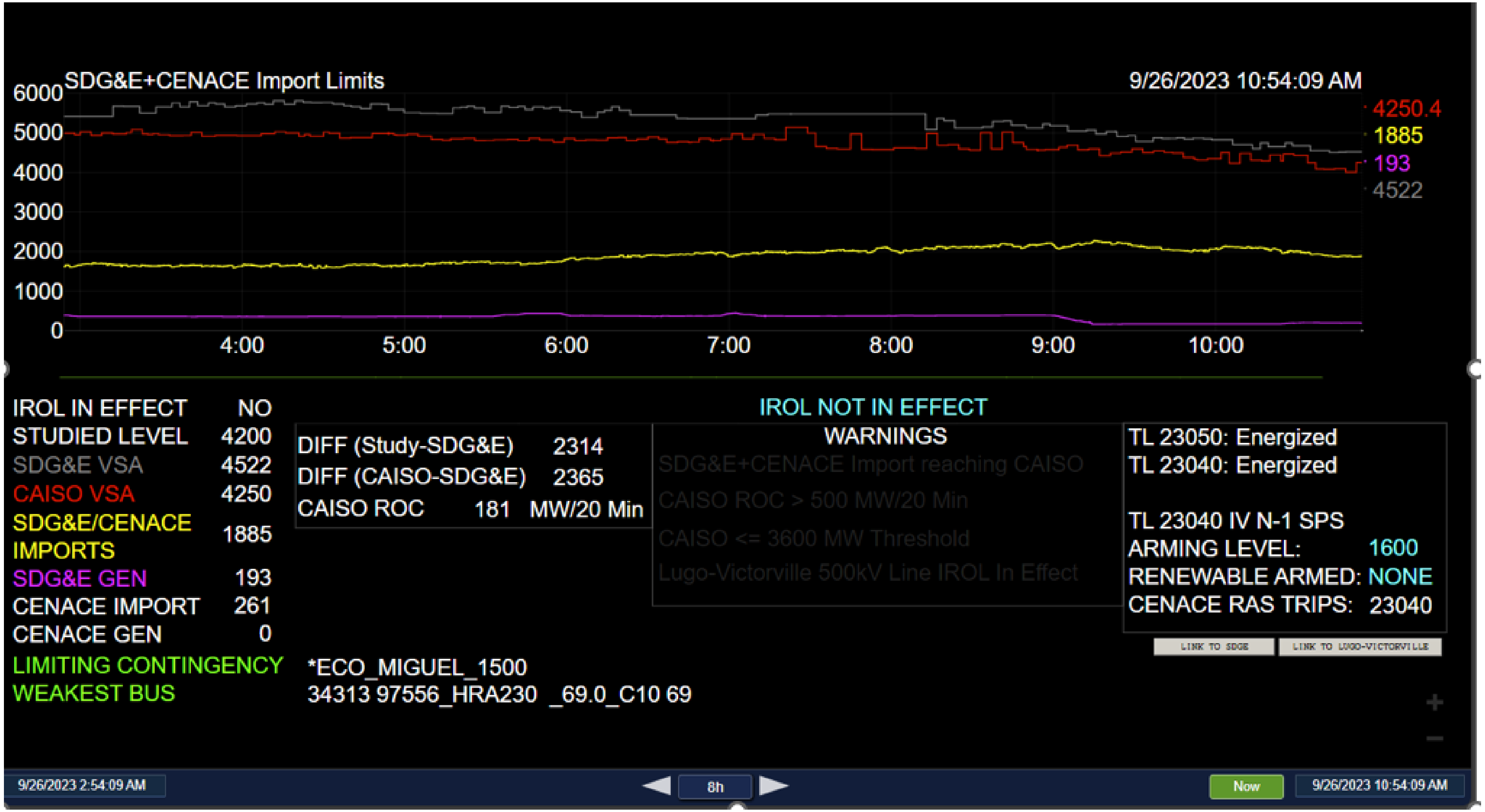
Status: CASE CONTAINS CONVERGED SOLUTION

Limit Name	Limit Status	Limit Type	Actual Difference	
Close [redacted]	Normal	Angle	13.179	Deg
Closin [redacted]	Normal	Angle	1.669	Deg
Close [redacted]	Normal	Angle	-3.059	Deg
Close [redacted]	Normal	Angle	5.369	Deg
Closin [redacted]	Normal	Angle	9.976	Deg
Closin [redacted]	Normal	Angle	1.750	Deg
Close 23040 TJI	Normal	Angle	-1.259	Deg

SDGE™

Real-Time Tools – Voltage Stability Analysis

utilizing RC West's export of EMS model in CIM15 and loaded in V&R's ROSE



Real-Time Tools – SEL Synchrowave Operations

power system visualization, oscillation detection and notification

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/communication is not available
  - Improves real-time reliability:
    - A check/validation for the quality of conventional state estimator
  - High speed state estimation due to using a direct non-iterative solution
    - Solves at PMU sample rate (30 times/sec)
    - Buses with no PMUs could become observable.

SDG&E PMU ROSE Architecture

LSE POM Server

Inputs:

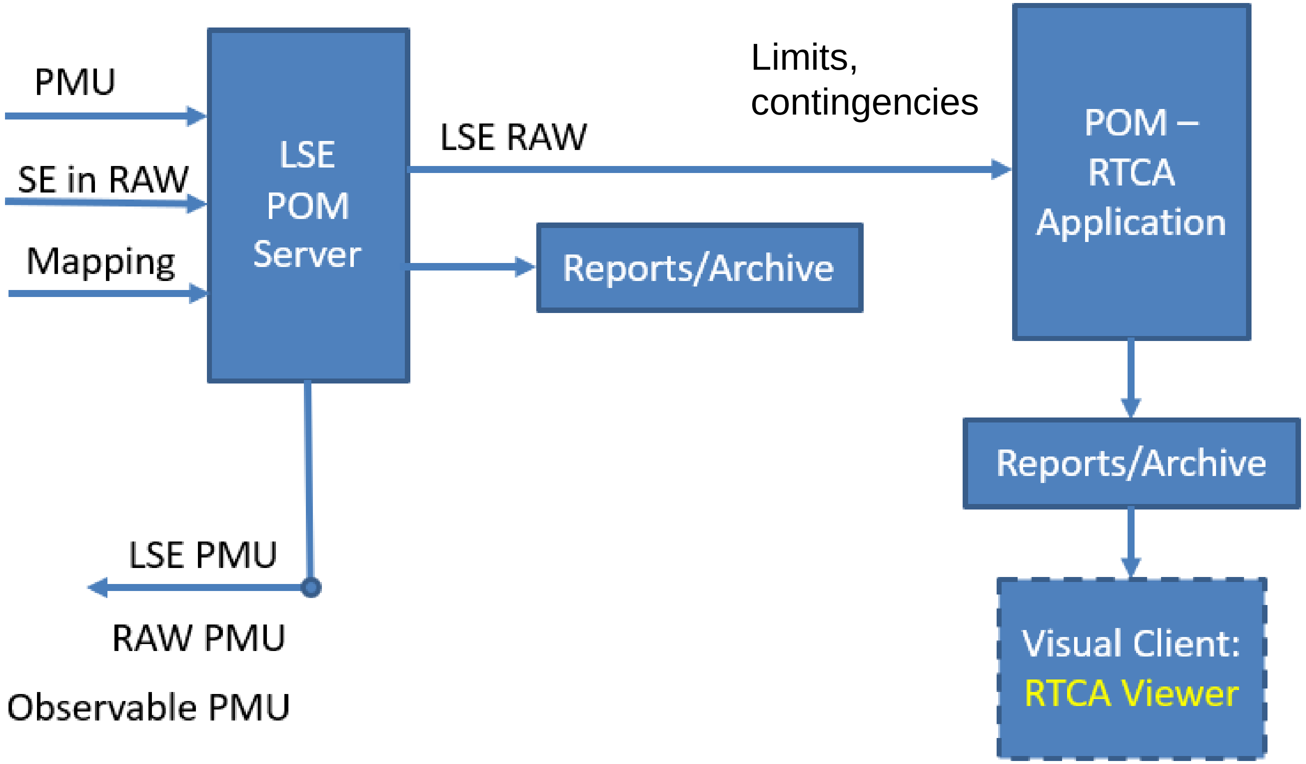
1. PMU - Voltage and current magnitude signals where PMUs are installed
2. SE in RAW - conventional State Estimator cases in Siemens PSS/E .raw data format
3. Mapping File – pmu signals mapped to bus and branches

Outputs:

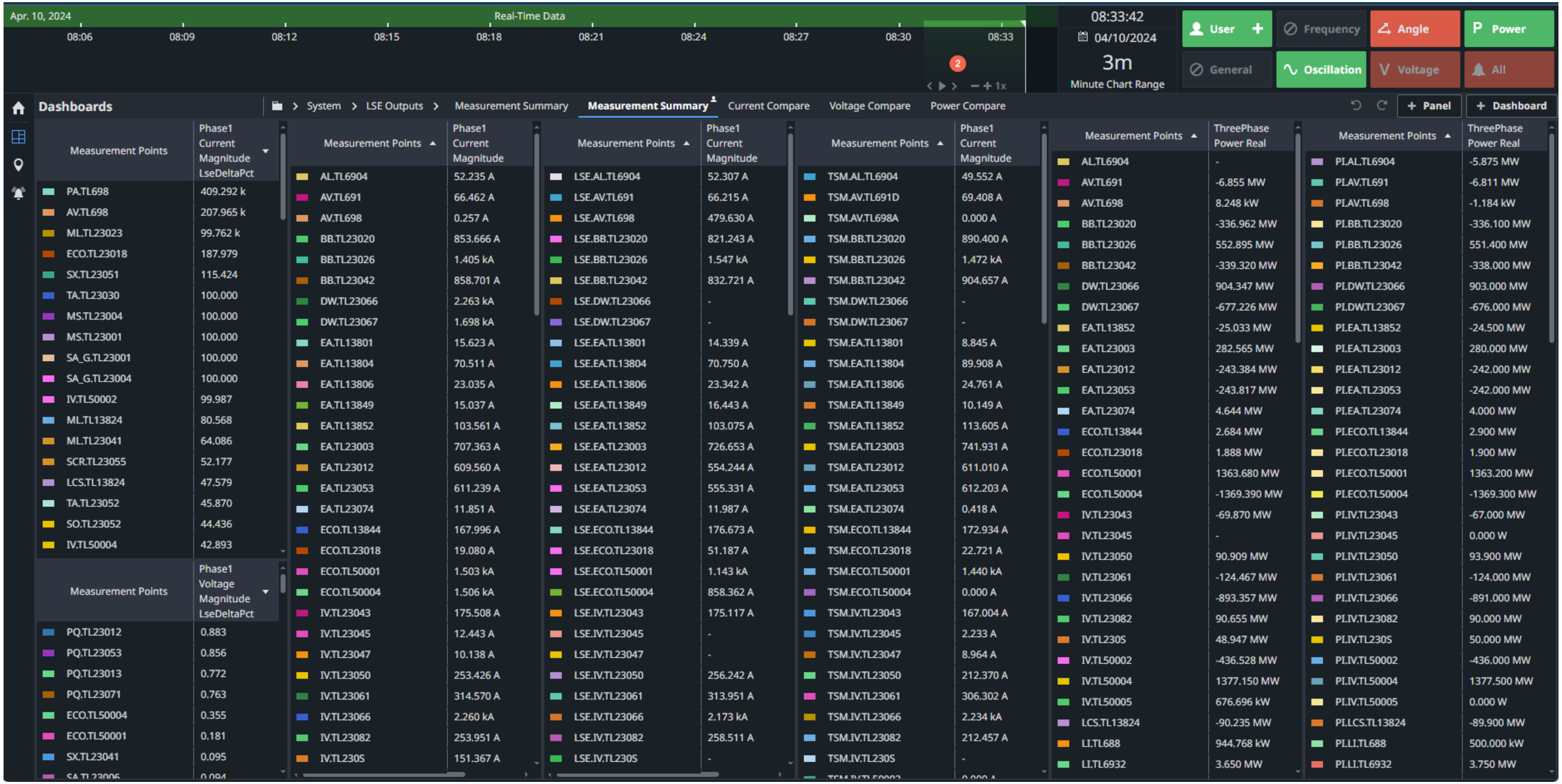
1. LSE PMU - LSE result at PMU locations
2. Observable PMU - LSE result at locations observable with existing PMUs
3. RAW PMU - Voltage and current from conventional State Estimator cases, converted to IEEE standard C37.118
4. LSE RAW - PMU-based State Estimator cases in Siemens PSS/E .raw data format

POM - Real-Time Contingency Analysis App

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



SEL Synchrowave: PMU streams vs LSE conditioned



PMU Additions / Mapping File Changes

(from 9/2022 to today)

	Version 11 (9/2022)		Version 14 (4/2024)	
	Voltage	Current	Voltage	Current
138kV Bus	**Internal Buses/w PMU: 30/8**		**External Buses/w PMU: 0/0**	
BUE 138	0	0	2	2
EA 138	0	0	4	3

69kV Bus	**Internal Buses/w PMU: (111+3 taps) / 19**		**External Buses/w PMU: 0/0**	
ARR 69	n/a	n/a	4	4
AV 69	2	2	3	3
BUE 69	0	0	1	1
CN 69	0	0	0	1
ES 69	0	0	2	2
FE 69	0	0	1	1
KNY 69	0	0	2	2
LL 125	0	0	1	1
LL 190	0	0	1	1
OR 69	0	0	2	2
SX 69	0	0	6	6
VC 69	0	0	1	1

PMU Additions / Mapping File Changes

(from 9/2022 to today)

	Version 11 (9/2022)		Version 14 (4/2024)	
	Voltage	Current	Voltage	Current
500kV Bus	**Count: Internal Buses/w PMU: 5/5**		**External Buses/w PMU: 6/0**	
N. Gila	2	4	0	0
Devers	2	5	0	0
Hassayampa	2	5	0	0
Palo Verde	3	3	0	0
Serrano	2	8	0	0
ValleySC	2	6	0	0

230kV Bus	**Internal Buses/w PMU: 23/23**		**External Buses/w PMU: 7/0**	
ALMITOSE	4	2	0	0
ALMITOSW	0	1	0	0
SANTIAGO 230	2	8	0	0
SERRANO 230	2	6	0	0
VIEJOSC 230	2	4	0	0
VILLA PK 230	2	7	0	0
S.ONOFRE	5	9	5	5
ARR 230	n/a	n/a	2	2

LSE – Observability Analysis and the LSE Case

Sep-22

Observability Analysis	Initial	Stage 1	Stage 2	Stage 3	Stage 4	LSE Case
Buses						78
Branches						112

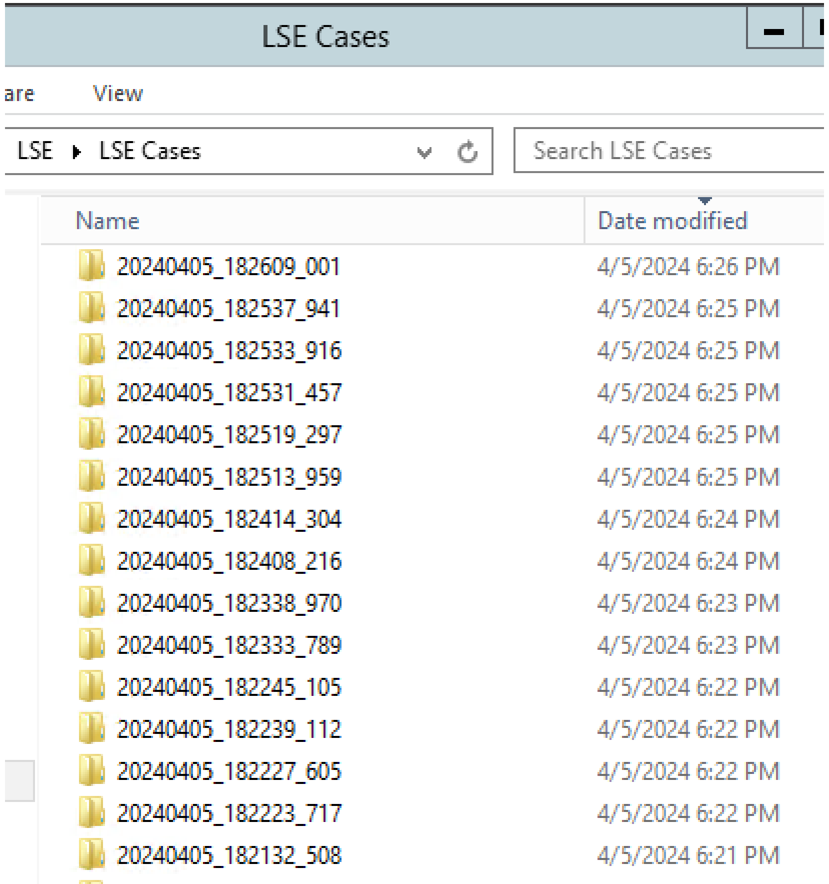
Sep-23

Observability Analysis	Initial	Stage 1	Stage 2	Stage 3	Stage 4	LSE Case	Delta
Buses	44	106	118	119	119	115	37
Branches	89	192	212	212	213	160	48

Apr-24

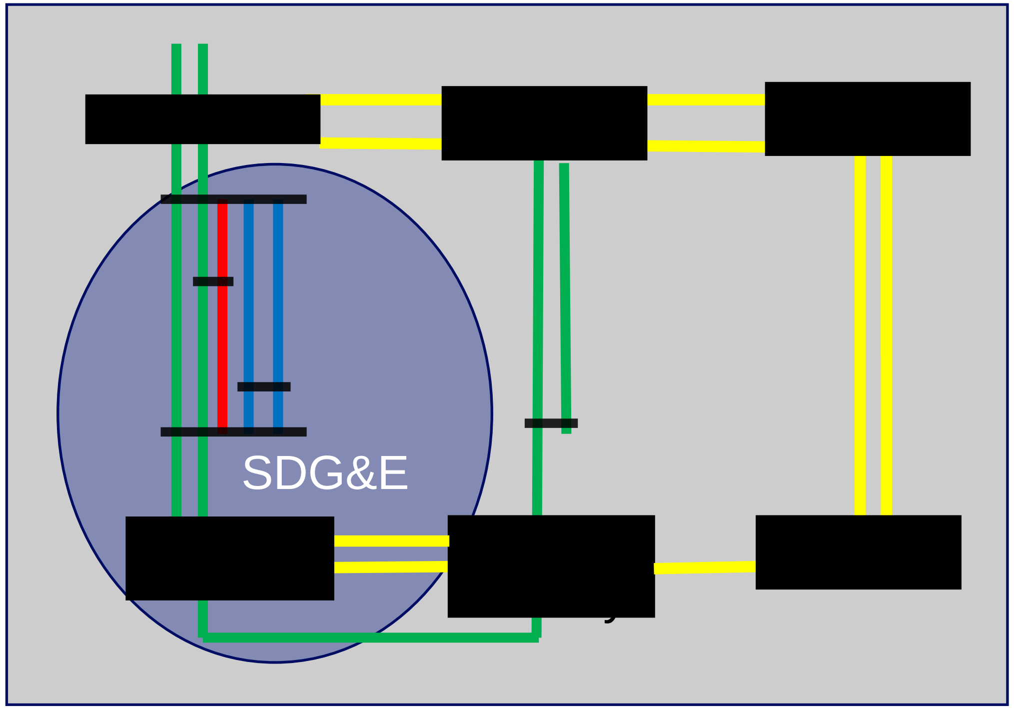
Observability Analysis	Initial	Stage 1	Stage 2	Stage 3	Stage 4	LSE Case	Delta
Buses	44	121	129	129	129	127	12
Branches	90	210	224	225	225	171	11

Apr-24	SE Case	Delta
Buses	278	151
Branches	567	396



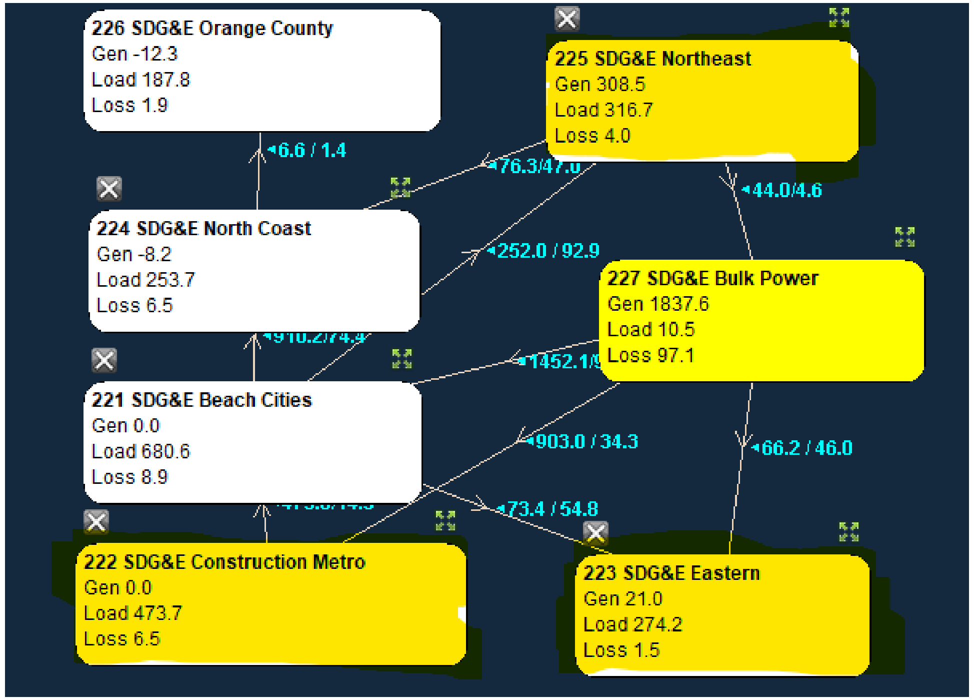
More installation of PMU data and bad data correction are needed to have meaningful comparison of the LSE case with the conventional SE case.

LSE Case – Pacific Southwest to local 69kV areas



Pacific Southwest Major Corridors

Adding PMUs of external entities in the corridors will be future endeavor to expand observability into external areas.

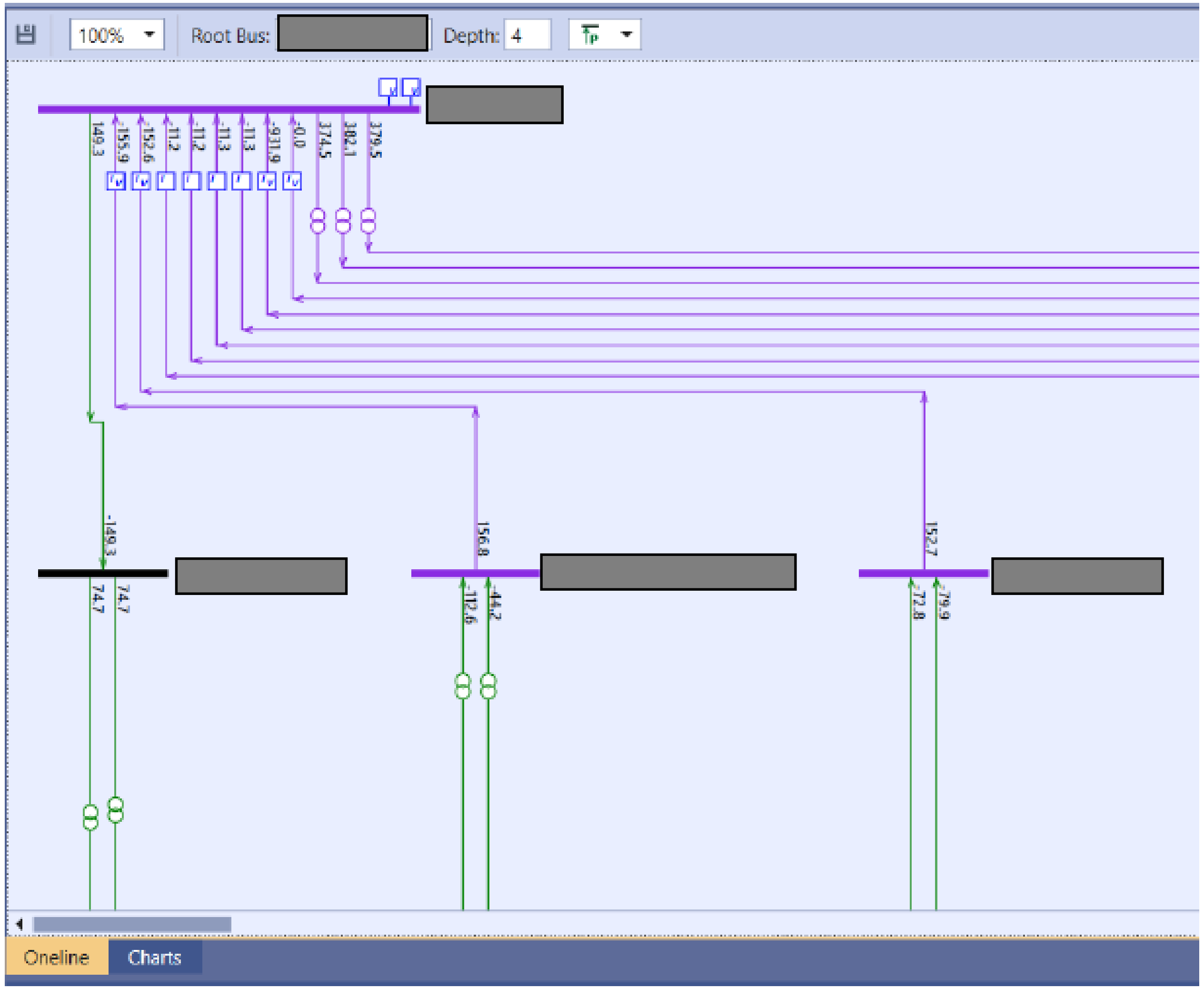


Shifting focus to local areas

As more IBRs connect to the local areas, creation of the LSE case for contingency analysis is more important as the actual condition changes quicker with batteries

Conclusions

- SDGE PMU ROSE is installed at SDG&E for LSE and RTCA.
- “Bad data” and modelling/mapping errors will continue to be investigated.
- More PMUs are needed to have good comparison between the SE and LSE case.
- Focus adding PMUs to the 69kV network (select buses) where existing and future batteries will be installed.



Thank you

Questions?

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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. He is a Principal Engineer with SDG&E. He is an IEEE member.

Project Costs & Benefits (slide for potential EPIC funding)

Enhance real-time monitoring, analysis, situational awareness, and control of SDG&E's grid. Facilitate transition to the dynamic grid of the future.

Estimated Budget: **$2.5M** | Estimated Project Duration: **24-36 Months**

Outcomes	Community Benefits	Communities

• Increased reliability
  • Fast and redundant SE and RTCA
• Increased size of observable parts of the system
• Improved accuracy and extent of PMU-based contingency analysis
• Deployment of other advanced application
	• Inverter based resources (IBR) connection at the transmission and distribution system.
	• System Operators
	• Plant Operators
		•Select 69kV local areas
		  •Existing batteries/new batteries
		• High Fire Threat Districts
		• Disadvantaged communities