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PMU-ROSE Real-Time Synchrophasor Platform

Demonstrated under Peak Reliability PRSP Project

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Peak Reliability Synchrophasor Program

- PRSP – Peak Reliability Synchrophasor Program
- Project Team - BPA, CAISO, IPC, Peak, SCE, SDGE
- Real-time monitoring and control based on the Region Of Stability Existence (ROSE) platform
- Demonstration of V&R Energy's Liner State Estimator (LSE) using all PMU signals available at Peak:
  - Observability analysis;
  - Bad synchrophasor data detection and conditioning;
  - Creation of PMU cases using LSE;
  - Validation of PMU cases and their applicability to voltage stability analysis.

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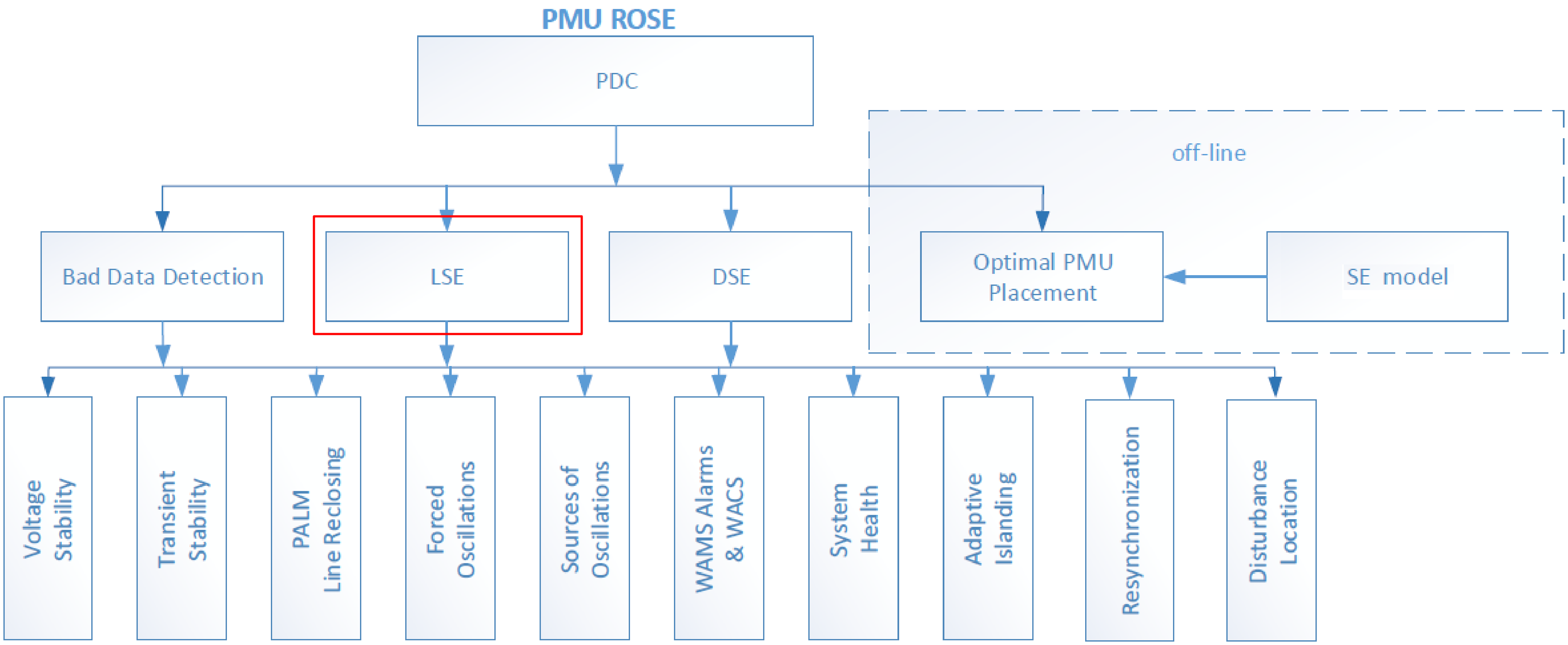
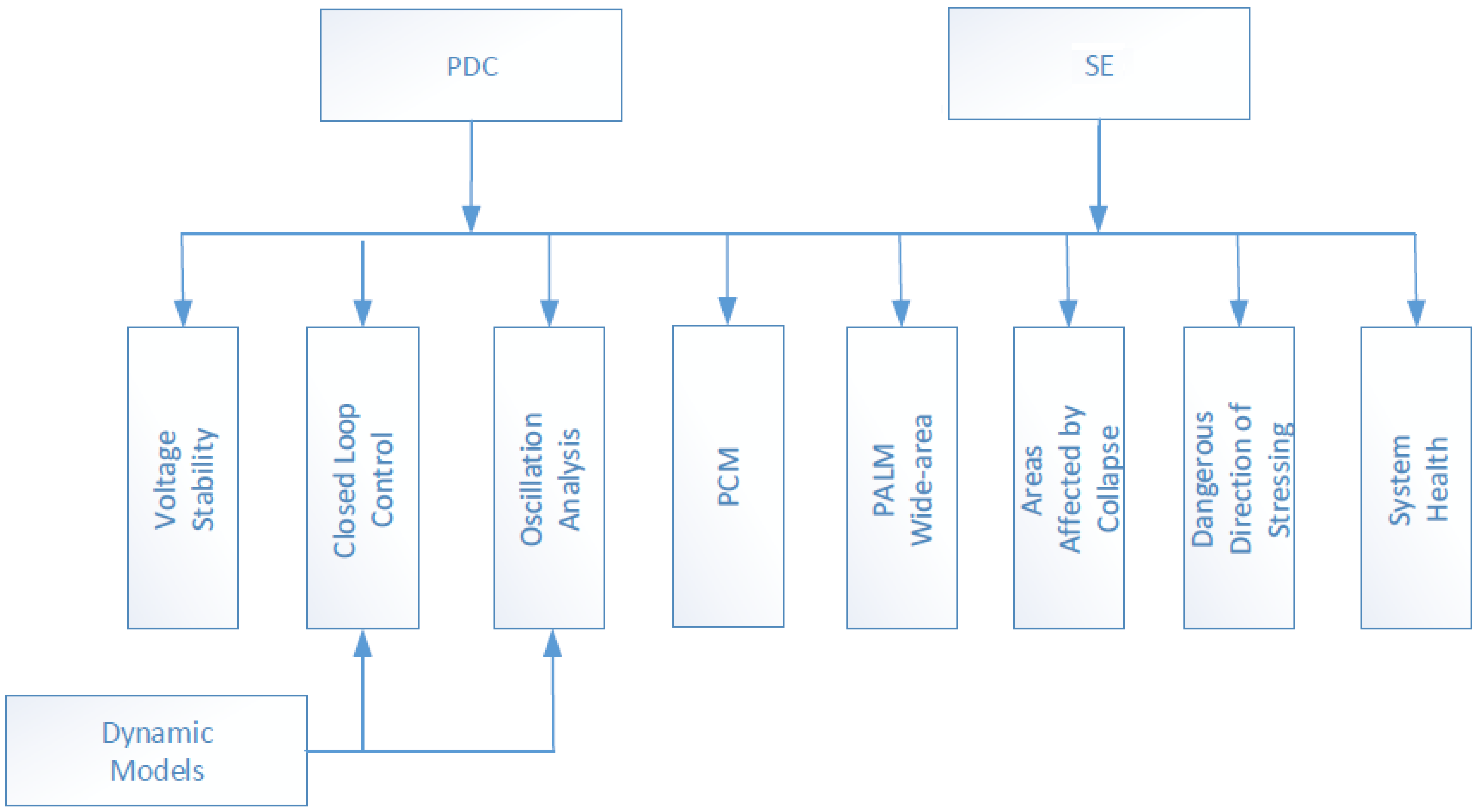
Synchrophasor Monitoring and Control Apps



"Hybrid" Monitoring and Control Apps



Importance of Linear State Estimator

- Linear State Estimator (LSE) is based on PMU measurements of voltage and current
- 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 or 60 times/sec)

Framework for Real-Time Situational Awareness

Linear State Estimation

Observability Analysis	Bad Data Detection/Conditioning

↓

Advanced Applications

Contingency Analysis	Voltage Stability Analysis	Automatic Corrective Actions	Phase Angle Limit Computation	Analysis of Cascading Outages

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Visualization/Alarming

Visualization of: Limits Critical Contingencies/Cascades Trending	Alarming on: Voltage/Transient Stability Limits Phase Angle Limit Critical Contingencies/Cascades

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PMU ROSE: LSE Demonstration under PRSP

- Real-Time analysis:
  - Identifying observable parts of the system
    - Includes PMU buses/branches; buses where we can compute voltages based on PMU data, branches where we can compute current based on PMU data
  - Kalman filtering combined with LSE
    - Bad data detection and conditioning
  - Creation of PMU-based WECC-wide state estimator case (e.g., *PMU Case*)
  - Performing full VSA using *PMU Case*
- Off-Line analysis:
  - Optimal PMU placement, which identifies minimum number of PMUs to achieve full system observability

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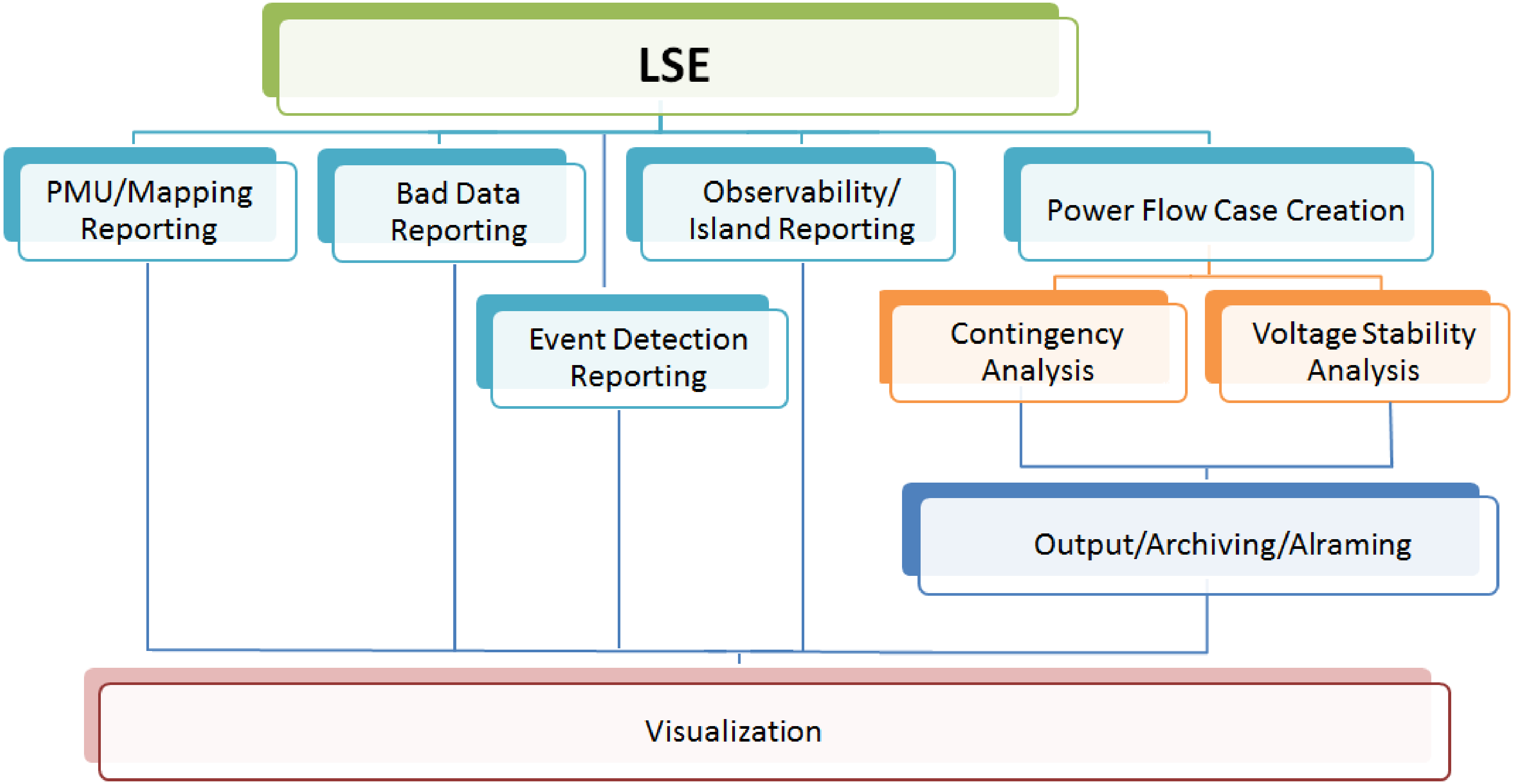
PMU ROSE Components for PRSP



Output of the Process

- Conditioned PMU data;
- Bad data reporting and statistics;
- A list of observable islands and their details;
- PMU-based WECC-wide state estimator case (e.g., PMU Case).

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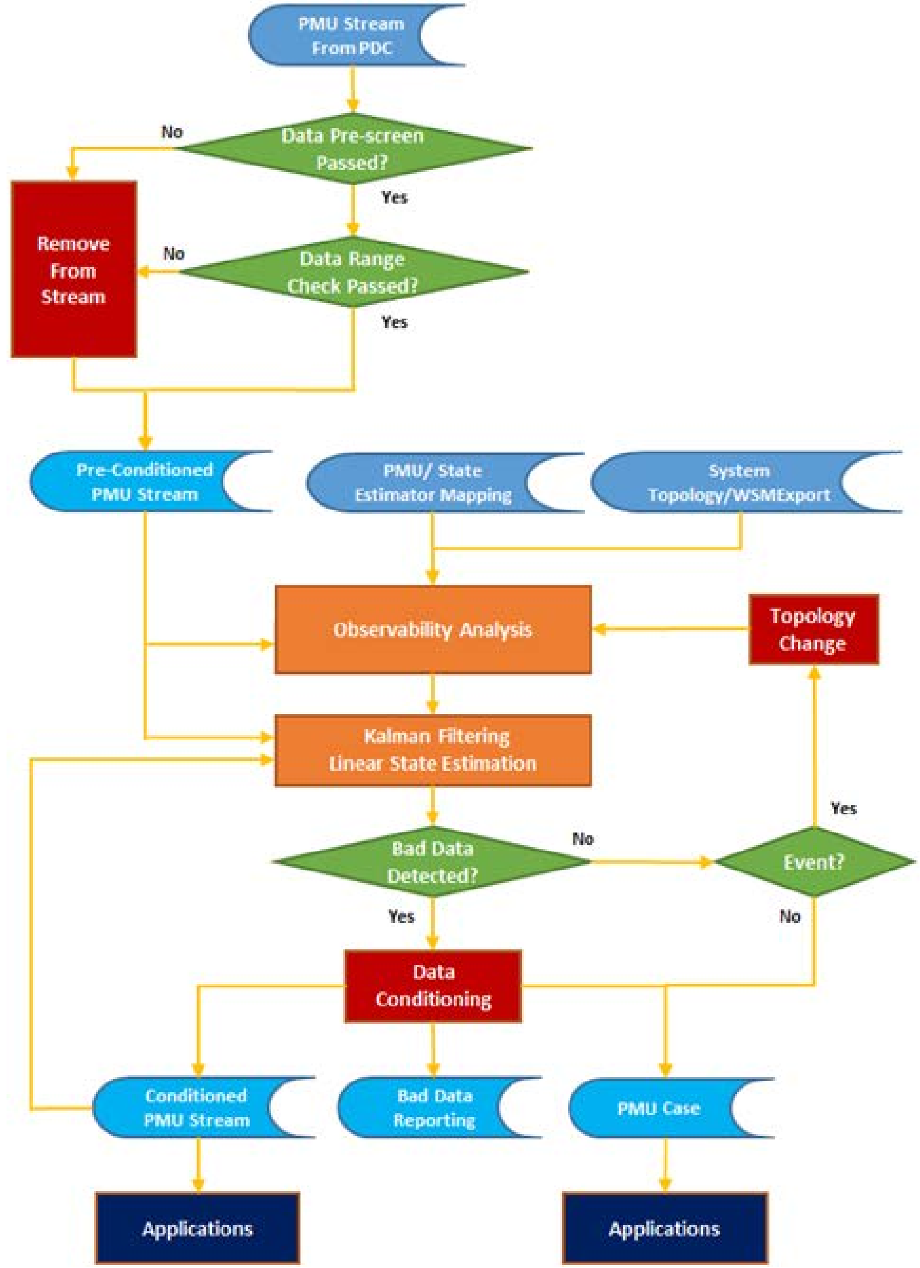
Components of LSE Framework

- Multi-step process:
  1. Several pre-screening techniques
  2. Data range checks
  3. Combination of filtering and smoothing techniques based on Kalman filter
  4. Linear state estimation
  5. End-to-end machine learning



Observable Islands in WECC Network

- A power system network is considered to observable if voltage vector at each node can be calculated based on PMU measurements
- Uses all signals available at Peak RC
- Data sets used for observability analysis:
  - PMU data
  - State Estimator (SE) data
  - PMU/SE mapping
- The results change when topology changes or PMU signal is lost

Island No.	Number of Observable Buses	Number of Observable Branches	Number of Voltage PMU Signals	Number of Current PMU Signals
1	635	809	318	549
2	11	11	12	8
3	70	78	19	43
4	13	15	6	6
5	3	2	1	2
6	2	4	2	0
7	8	8	2	2
8	21	26	15	14
9	25	32	20	14
10	2	1	1	1
11	8	8	4	4
12	5	6	2	3
13	[illegible]	13	2	3
14	4	3	2	2
15	2	1	1	1
16	6	[illegible]	4	4
17	2	1	1	1
18	4	3	2	2
19	1	0	4	0
20	7	8	8	6
21	1	0	1	0
22	2	1	2	1
23	7	7	6	6
24	3	4	4	2
25	3	2	4	2
26	1	0	1	0
27	1	0	5	0
28	8	9	8	5
Total	**868**	**1058**	**457**	**681**

One continuous "island" from SDGE to BC-HYD

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Kalman Filtering

- An algorithm that:
  - Uses a series of measurements observed over time, containing statistical noise and other inaccuracies, and
  - Produces estimates of unknown variables that tend to be more accurate than those based on a single measurement alone
- **The Kalman filter is created for each observable island**
- The Kalman filter approach is a two-stage algorithm:
  - The first stage is **prediction**, which projects the previous time step state forward in time by means of a predefined process model
  - The second stage is **correction/estimation**, which corrects the predicted state by accounting the available measurements and the accuracies of both process model and measurements
  - LSE is used at the second stage

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Correction Using Kalman Filter and LSE

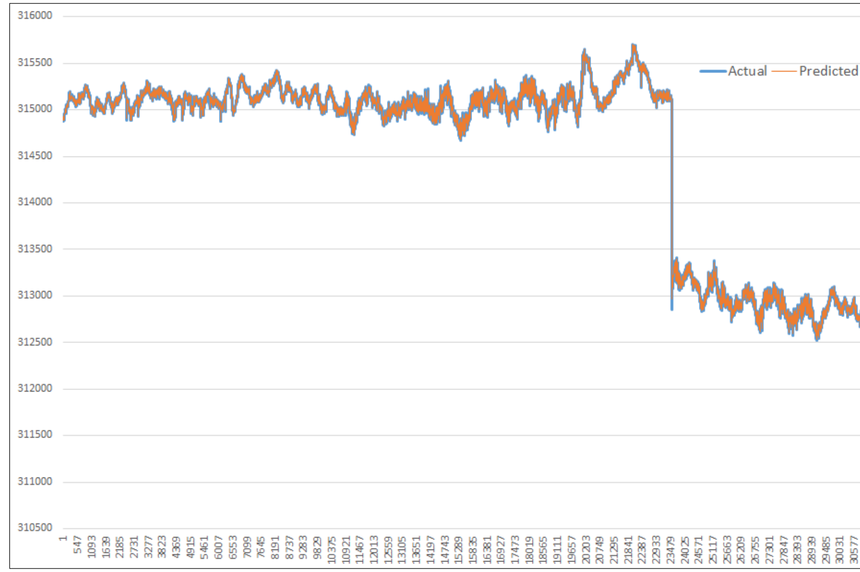
- Displays up to three values for each signal:
  - Value from WSMExport file (State Estimator)
  - Value measured by PMU
  - Conditioned value (corrected value) using Kalman Filter/LSE

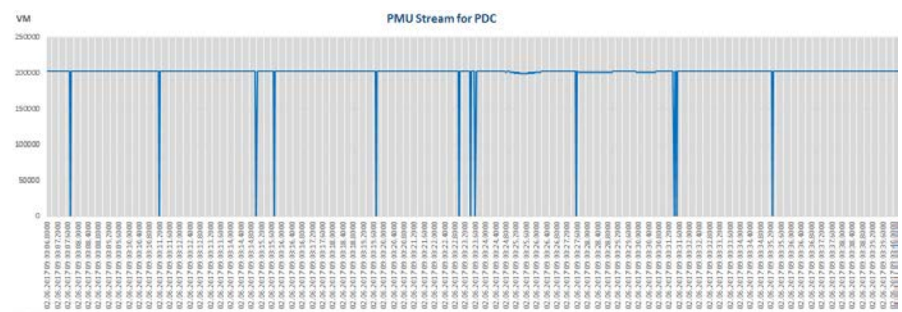
LSE for Bad Data Detection

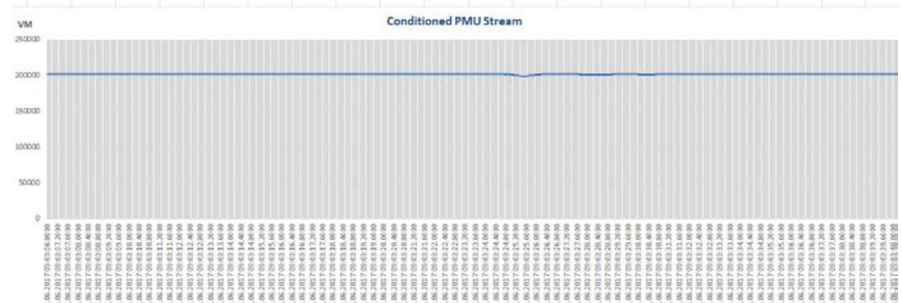
- Bad data detection, including:
  - Bad PMU data;
  - Bad SCADA data;
  - Bad system parameters;
  - Errors in the process of conventional state estimation.
- Topology estimation, if breaker status is not available
- Separating bad data with an onset of an event

Bad Data Detection and Conditioning

- Step 1: Data pre-screening
- Step 2: Kalman filtering
  - Two-stage algorithm:
    Stage 1 – prediction
    Stage 2 – correction/LSE
- Stage 2: Correction/LSE
  - Applies both heuristic and statistical methods to identify suspected bad data points and topology changes
  - Considers relationship between signals







Statistical Analysis

- The chi-square criterion after performing least square minimization.
  - Measurements with high values of residual differences are not used;
  - If high number/ majority of measurement points show high values of residual differences, topology mismatch of the system model is suspected.

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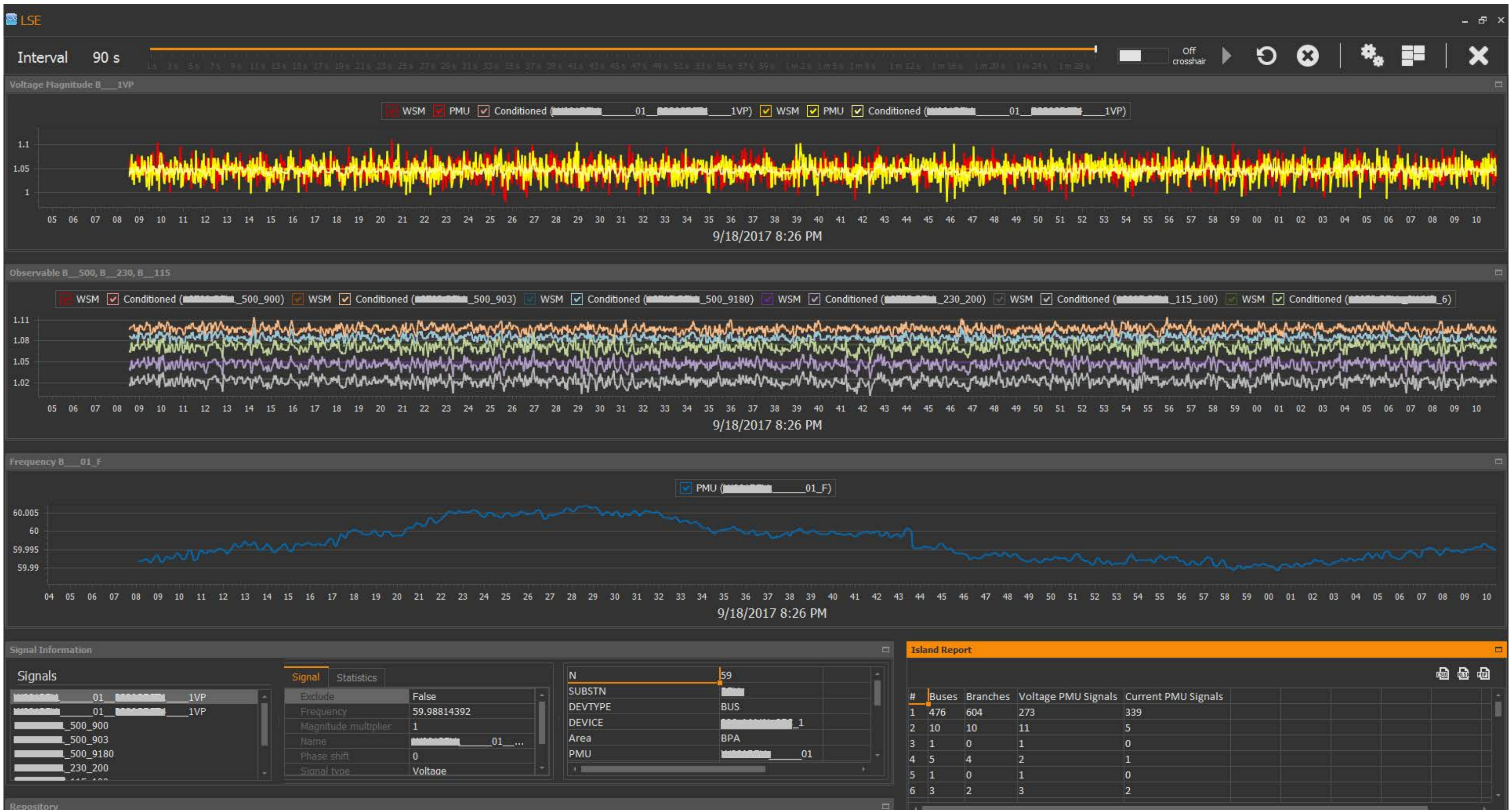
PMU-ROSE Visualization

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



#	Buses	Branches	Voltage PMU Signals	Current PMU Signals
1	476	604	273	339
2	10	10	11	5
3	1	0	1	0
4	5	4	2	1
5	1	0	1	0
6	3	2	3	2

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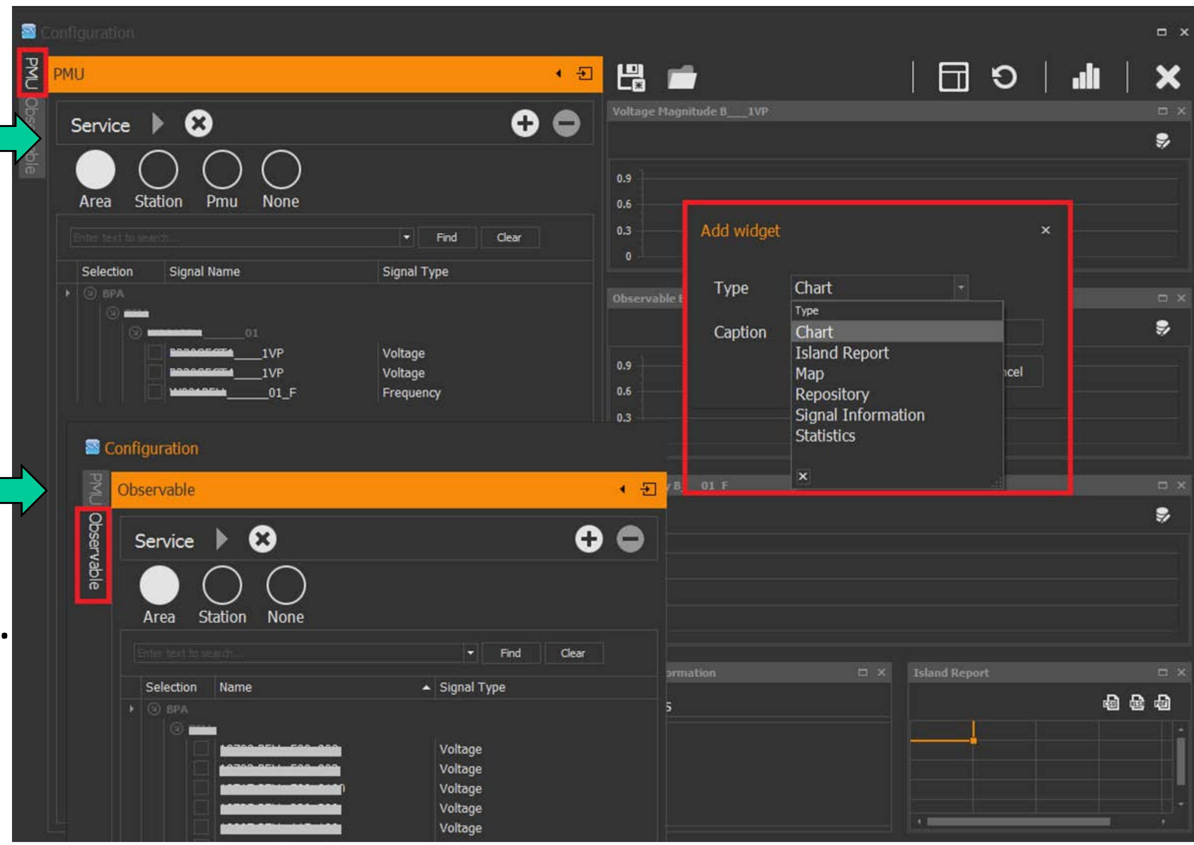
Configuration Panel

- Allows the user to select locations, both directly measured by PMUs and those observable using PMU measurements for visualization and analysis:
  - PMU measurements are selected from the **PMU Section** of the **Configuration Panel**;
  - Quantities computed based on PMU measurements are chosen from the **Observable Section** of the **Configuration Panel**.

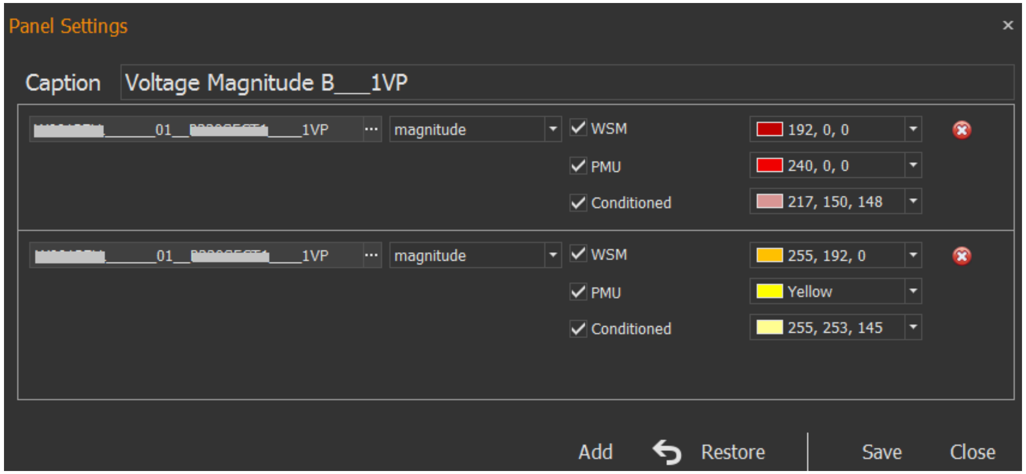


Widgets

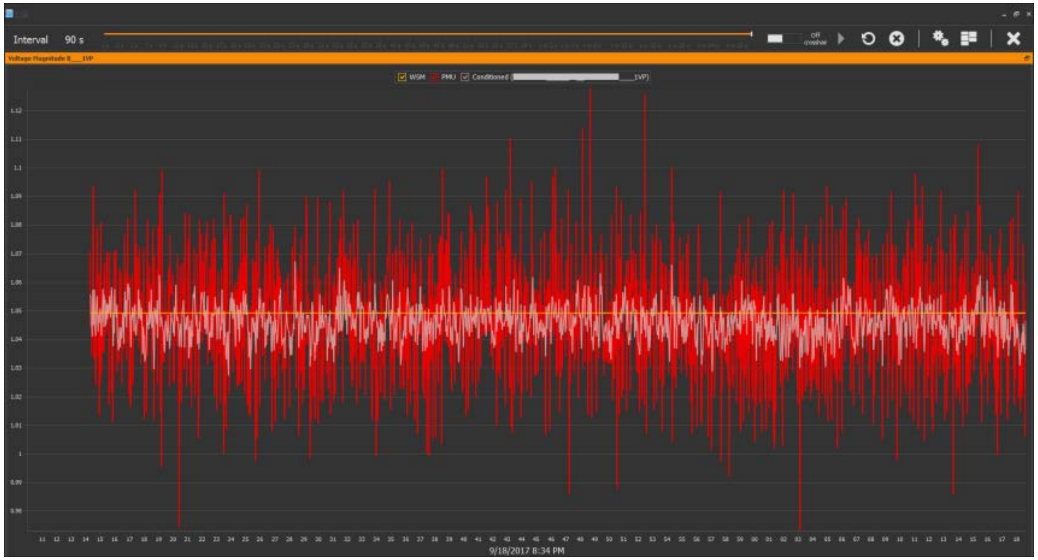
- Visualization of input data and results is enabled using the **Add widget** menu:
  - Chart
    - View real-time and historical plots of PMU measurements and computed quantities
  - Island Report
    - Summarized information about the observable islands
  - Map
    - View information about observable islands on the map
  - Repository
    - Shows the structure of input/output data sets
  - Signal Information
    - Displays both input and post-LSE information about selected signal
  - Statistics
    - Visualizes bad data statistics

Chart Widget

- Displays PMU values and values computed by LSE, compares PMU and LSE values with State Estimator values

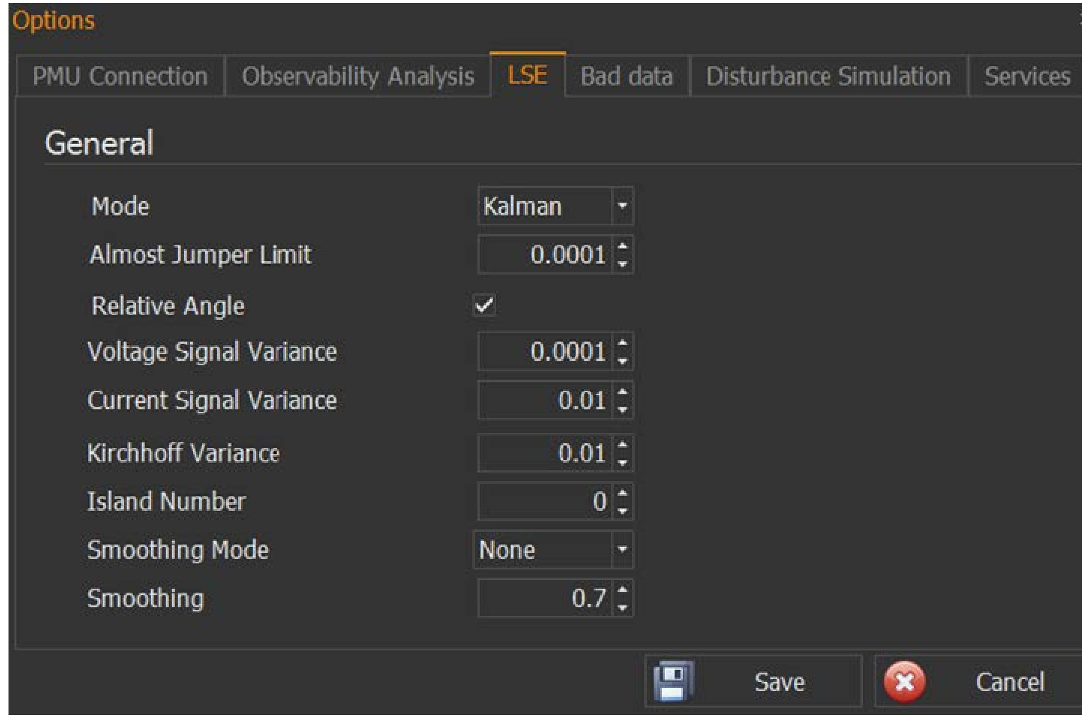


- Red graph – real-time PMU measurements;
  Pink plot – the same PMU measurements processed by the LSE (conditioned values);
  Orange line – State Estimator value.



PMU-ROSE Options

- Options Panel:
  - PMU Connection
  - Observability Analysis
  - LSE
  - Bad Data
  - Disturbance Simulator
  - Services



- Changing options from the **Options Panel** affects computation results

Island Report

#	Buses	Branches	Voltage Signals	Current Signals
1	476	604	273	339
2	10	10	11	5
3	1	0	1	0
4	5	4	2	1
5	1	0	1	0
6	3	2	3	2
7	2	1	6	0
8	2	1	2	1
9	2	4	2	0
10	1	0	1	0

Island Report

#	Buses	Branches	Voltage Signals	Current Signals
1	514	657	276	383
2	10	10	11	5
3	1	0	1	0
4	5	4	2	1
5	1	0	1	0
6	3	3	6	1
7	2	1	2	1
8	2	4	2	0
9	1	0	1	0
10	1	0	1	0

PMU Case!

- A new concept and a different definition of a “model”
- Creates **PMU-based WECC-wide state estimator case** (e.g., ***PMU Case***)
  - Node-breaker model
  - Dimensions: Example using one of the past cases – 10,300 nodes/800 collapsed buses
- Performs voltage stability analysis using ***PMU Case:***
  - Based on scenarios like conventional VSA (stressing, contingencies)

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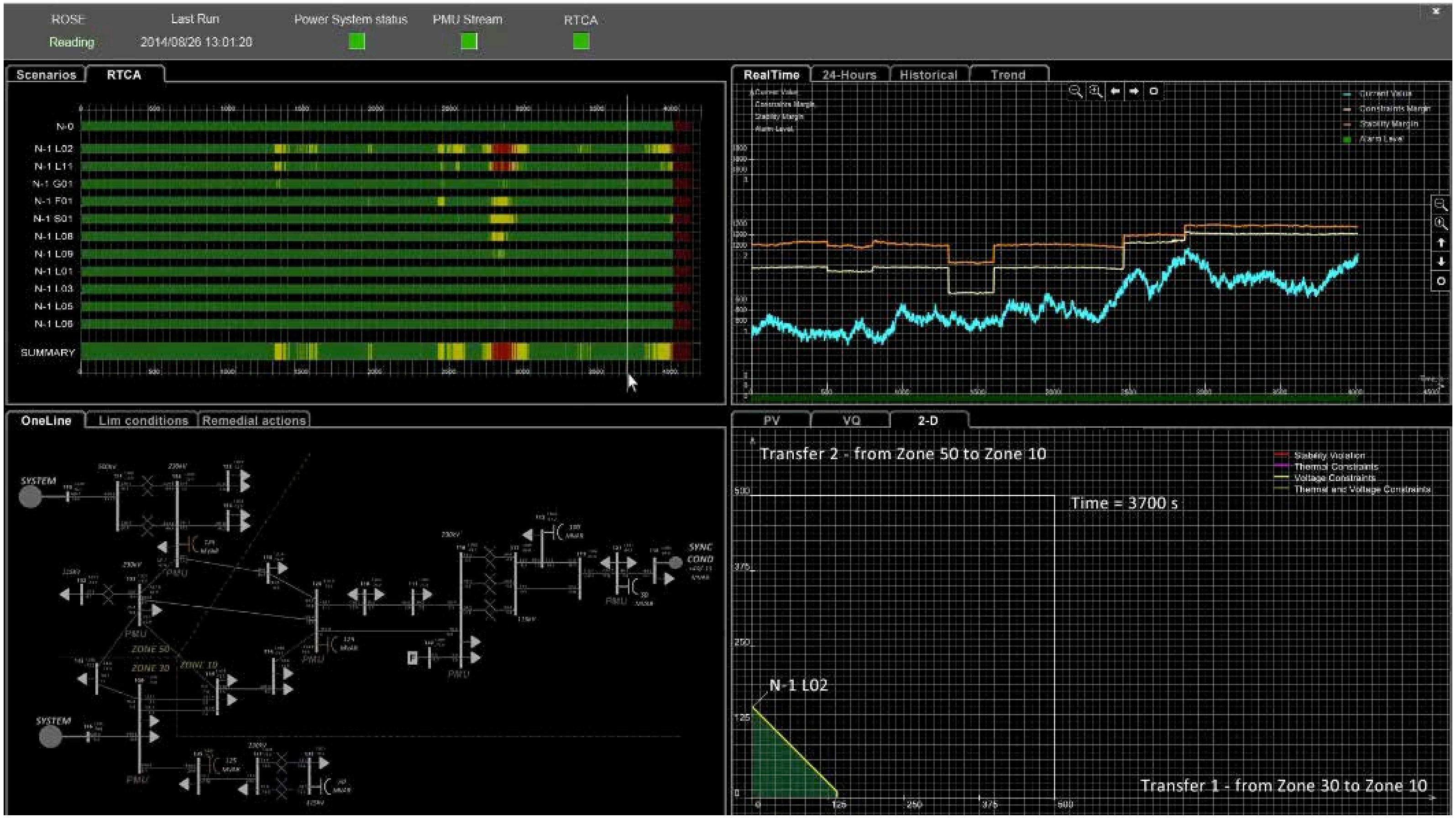
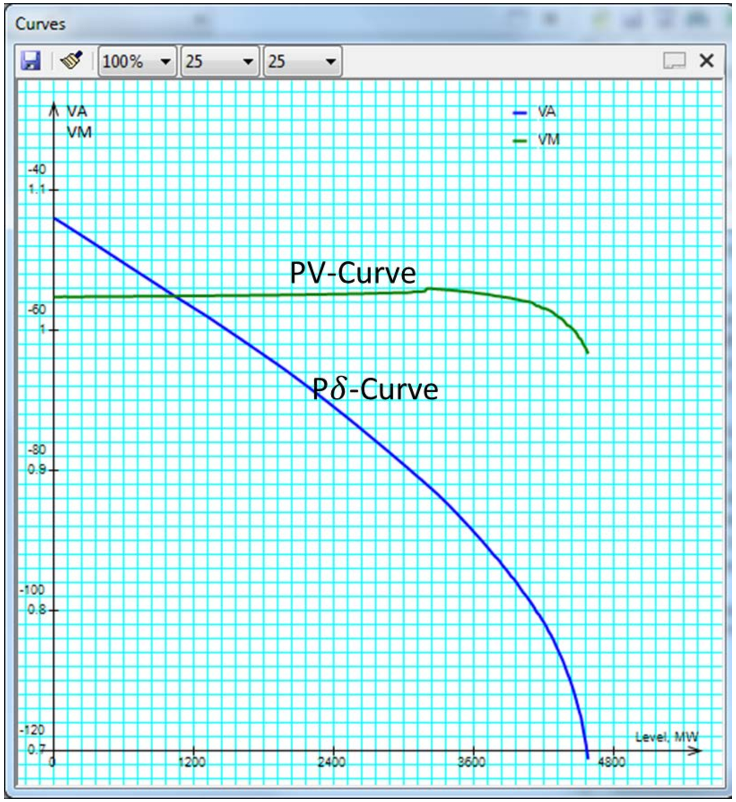
Measurement – Based VSA

- Based on PMU Cases created by Linear State Estimator
- "Traditional" VSA – contingencies, stressing, etc.
- NOT an index!

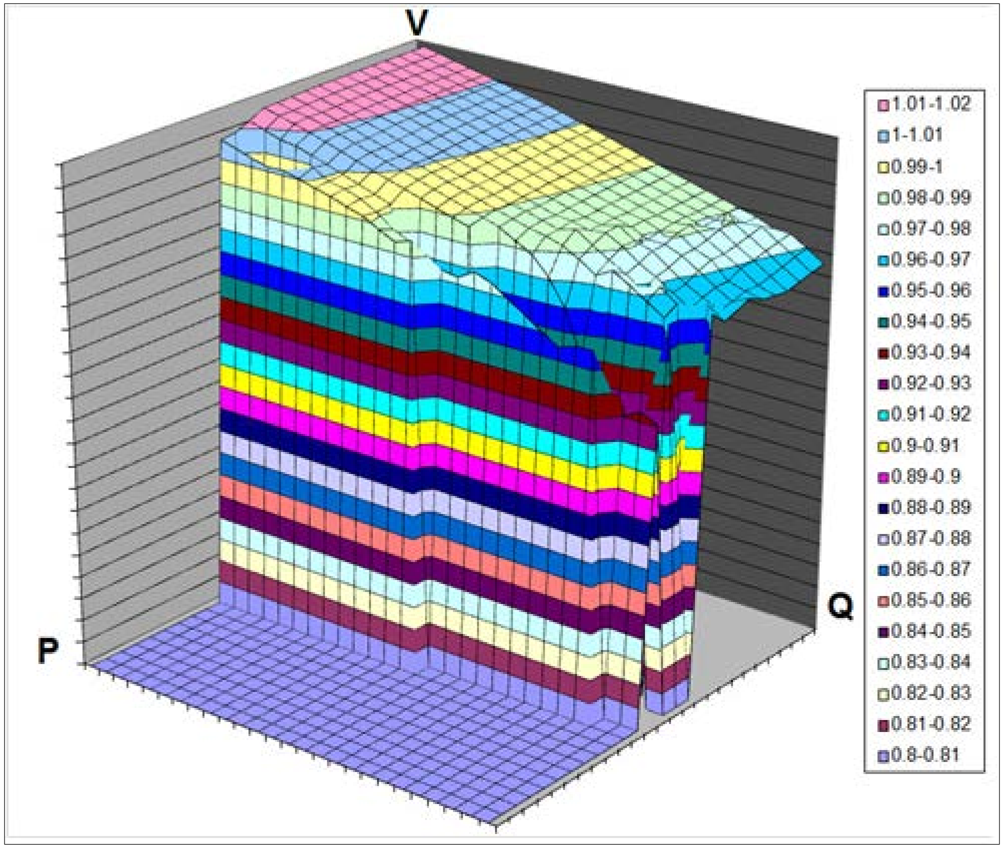


Phase Angle for Steady-State Voltage Stability Analysis

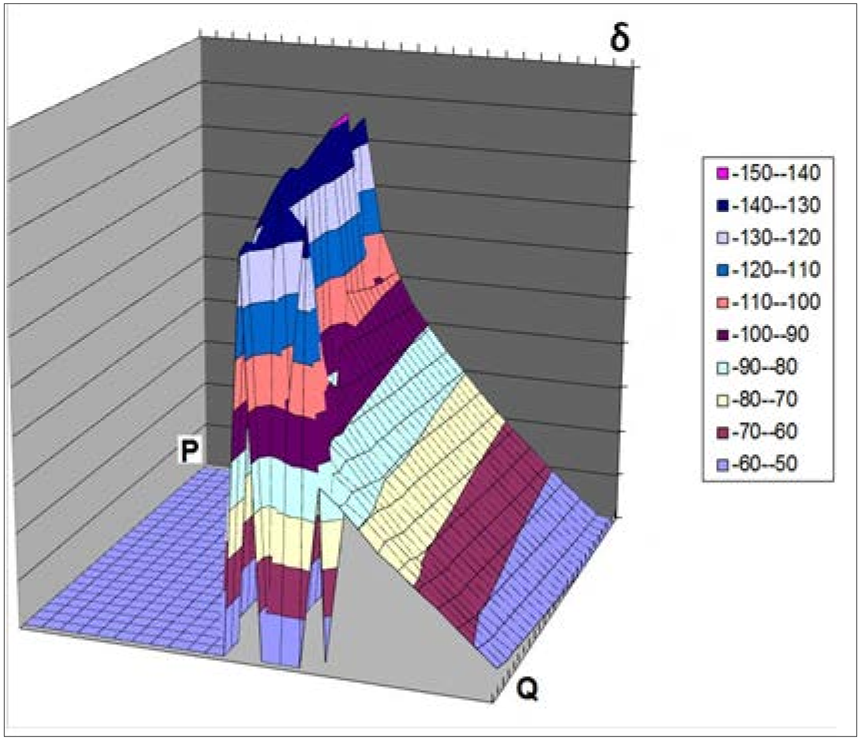
- **Voltage magnitude and phase angle are equal indicators of voltage collapse because**
  - Voltage collapses and angle experiences uncontrollable change at the same level of stressing
- In many cases, it's more effective to monitor **Pδ-curve** than PV-curve
  - Voltage remains almost constant over a wide range of stressing, while angle significantly changes (for the same monitored buses)



Angle: An Indicator of Voltage Collapse



$V(P, Q)$



$\delta(P, Q)$

Phase Angle Limit Computation

- Phase angle limit should be determined in real time, and not based on historical data:
  - This is not a data mining application – this is real-time computation!
- Two types of phase angle limit:
  - Phase angle limit and monitoring for line reclosing
  - Phase angle limit for wide-area monitoring
- Phase angle limit is a physical limit:
  - Depends on system topology and conditions and how the system is stressed;
  - **The limit changes with system conditions**.
- Computed during system stressing, contingency, cascading event
- Phase angle limit can be computed using different data sets:
  - SCADA data; combination of SCADA and PMU data; PMU data

Optimal PMU Placement

Observability Analysis and PMU Placement

- Identifies observable portions of the system
- Determines locations of additional installations of PMUs
- PMU placement problem refers to the minimum number of PMUs to be placed in the network while maintaining observability of the entire electric power system network
- There are multiple definitions of power system network observability:
  - Since voltages are state variables for the steady-state model of a power system network, a power system network is considered to be observable if voltage vector at each node can be calculated based on the PMU measurements

Formulating PMU Placement Problem

- Formulation of PMU placement problem depends on the definition of a criterion for complete system observability
- There are two types of criteria to define system observability - numerical and topological:
  - Numerical methods deal with matrix computations
  - Topological methods are based on graphs of a power system
    - Identifies nodes where voltage either is measured by PMU or may be computed based on a PMU measurement at another node
- Formulating optimal PMU placement as a binary linear programming problem is the most frequently used approach:
  - Optimization approaches for optimal PMU placement are either based on search algorithms or some assumptions, and do not guarantee identification of minimum number of PMUs

Optimal PMU Placement

- Considers current PMU installations
- The software for observability analysis identifies the following:
  - A set of PMU locations such that the system is observable
  - One “best” next location for system observability
  - Locations of user-defined “x” number of PMUs
  - PMU locations to satisfy a user-defined portion of the system to be observable (e.g., 50% of the system to be observable)
- The approach demonstrated under the PRSP requires a smaller number of PMUs to achieve system observability as compared to published algorithms

Results of Optimal PMU Placement for Idaho Power Co. (IPC)

- IPC already installed PMUs:

IPC buses	= 360
PMUs installed	= 21

- Number of additional PMU installations to achieve complete system observability identified using V&R's approach used under the PRSP (Peak Reliability Synchrophasor Program):
  - **56 PMUs**
  - **So, the total number of PMUs to achieve complete observability is 21 + 56 = 77 PMUs**
- Number of additional PMU installations to achieve complete system observability identified using previously developed methods:
  - **67 PMUs**
  - **21 + 67 = 88 PMUs**

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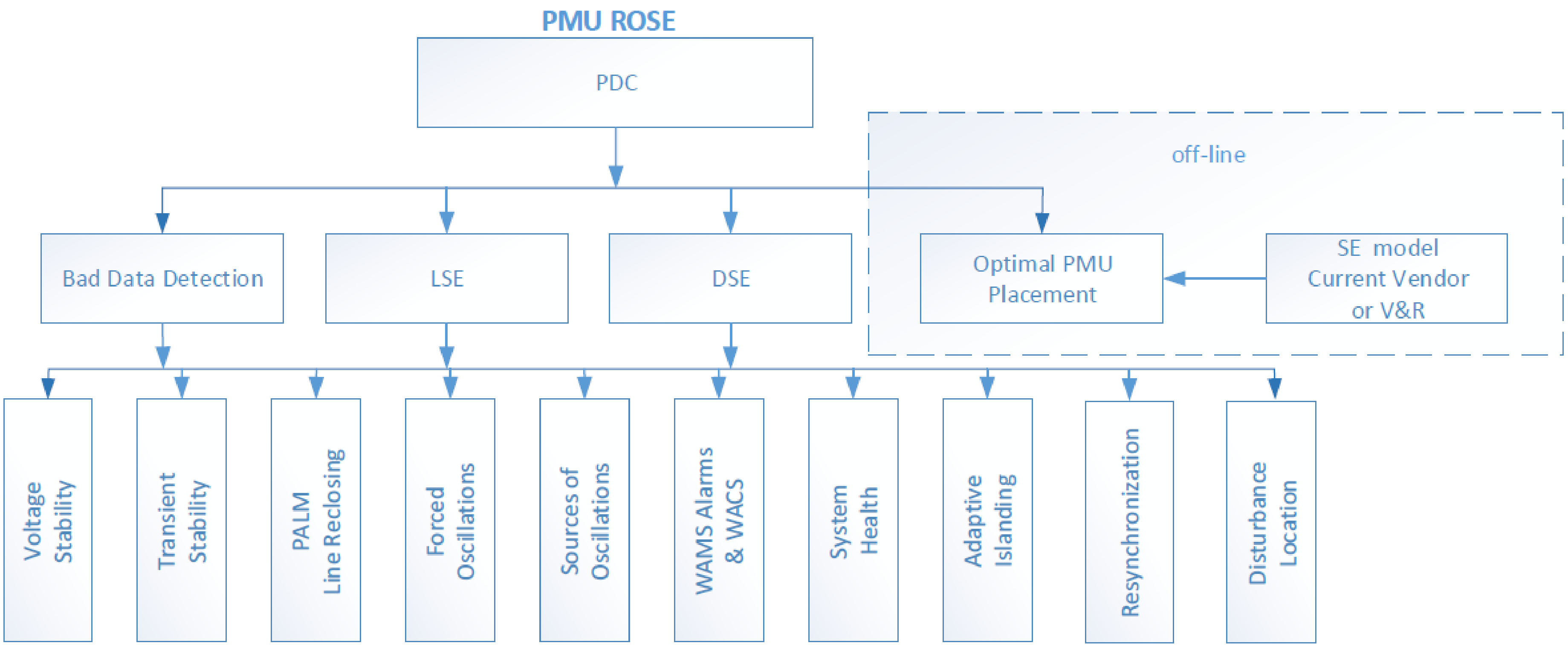
V&R's PMU-Based Package



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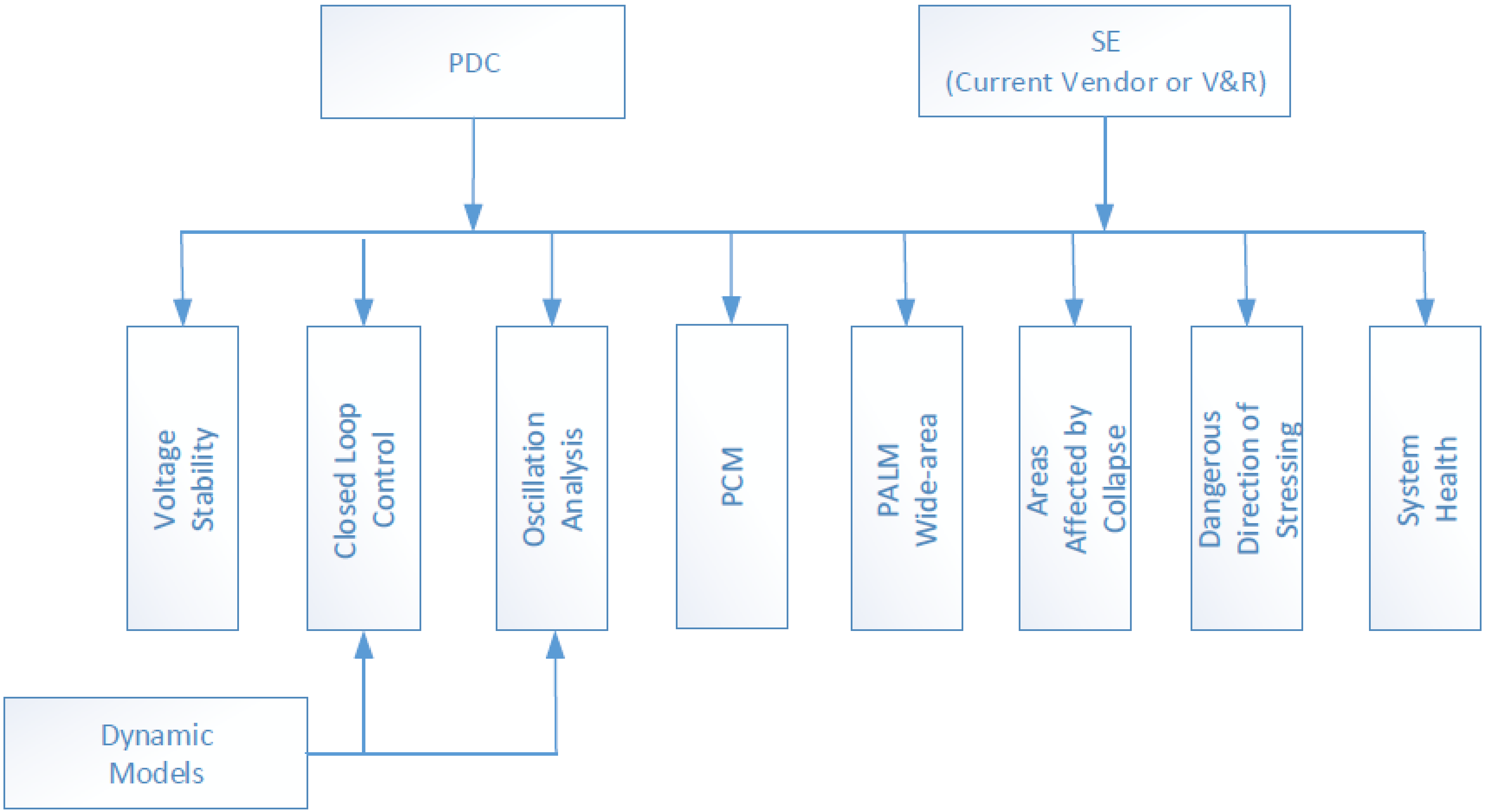
V&R's Hybrid Analysis Package



THANK YOU!