PMU Placement at SDG&E® :
Initial Results and Lessons Learned

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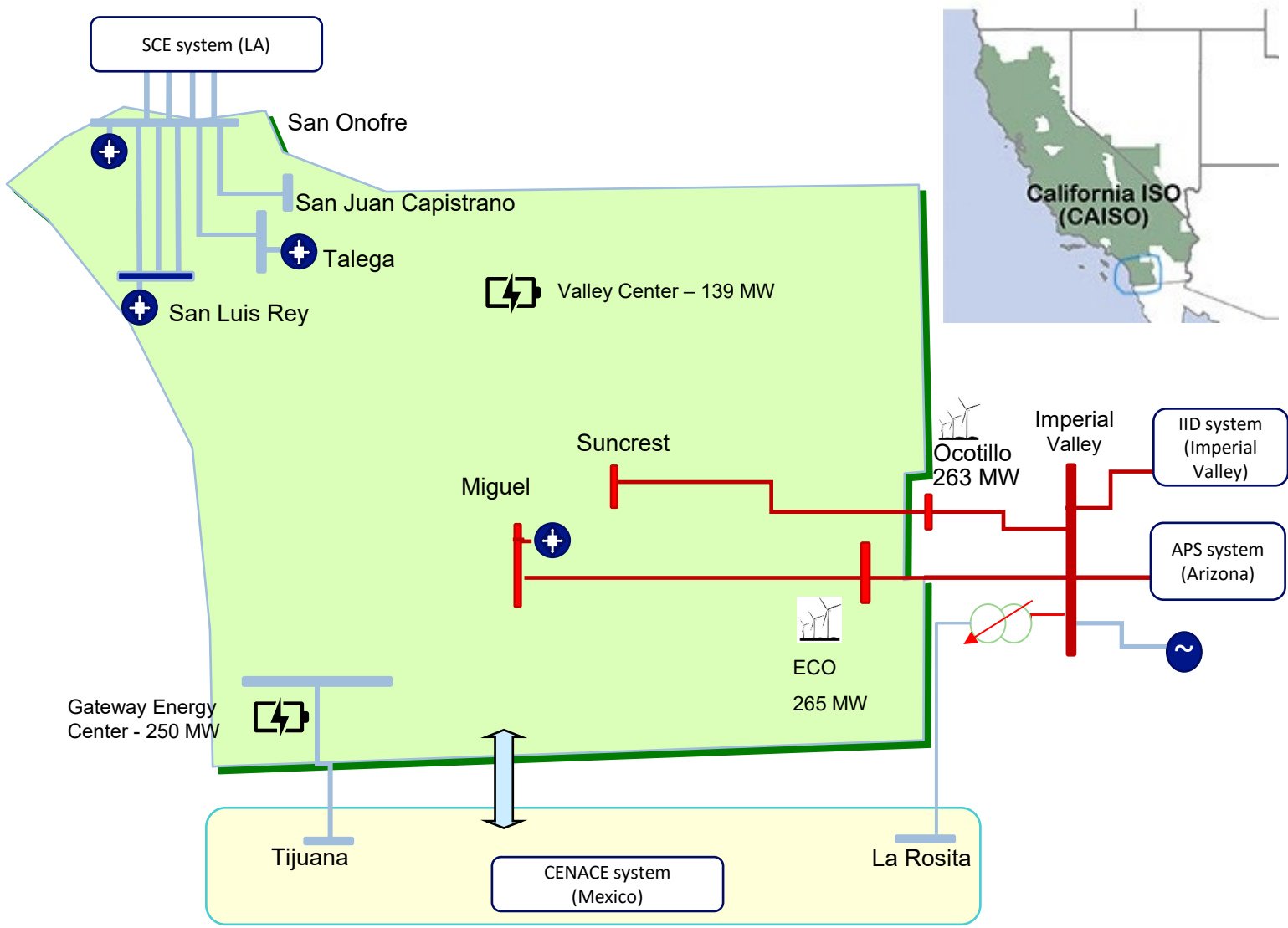
Contents

- SDG&E® System Overview
- RT Tools Deployment History and Current Status
- EPIC – 4 Project: Key Tasks and Objectives
- Optimal PMU Placement: Goal, Approach, and Initial Results

SDG&E® System Overview

About SDG&E®

- SDG&E is a regulated public utility in southern California.
- Serves San Diego & Southern Orange Counties: 1.49 million electric meters
- System Peak = 5,032 MW (9/8/24)
- 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



RT Tools Deployment History and Current Status

RT Tools Deployment History and Current Status For State Estimation

- 2006 – Enhancement of SE Results using real-time phasor data
  - This project was co-funded by SDG&E and CEC as part of PIER (Public Interest Energy Research, pre-EPIC Energy Program Investment Charge).
  - Successfully integrated real-time phasor data from the PMU at Miguel and Mission substations into conventional SE.
    - GE, EPG, SEL, OSISoft, CEC
  - No definite conclusion on SE accuracy with additional measurements from PMU. Existing RTU coverage already redundant.
- 2017 – PMU ROSE LSE and RTCA Platform Installed
  - DOE funded (Peak Reliability Synchrophasor Project)
  - All 500kV buses have PMUs
  - All 230kV buses have PMUs (voltage phasor have plenty of redundancy)
  - Observability was mostly limited to 500kV and 230kV system
- 2024 – EPIC-4 funding approved to help expand observability of SDG&E's 69kV network
  - Optimal PMU Placement Tool
  - 5-10 PMU additions in 1-3 operating regions initially forecasted for approved budget
  - LSE/RTCA Enhancements

SDG&E PMU ROSE Architecture

LSE POM Server

Inputs:

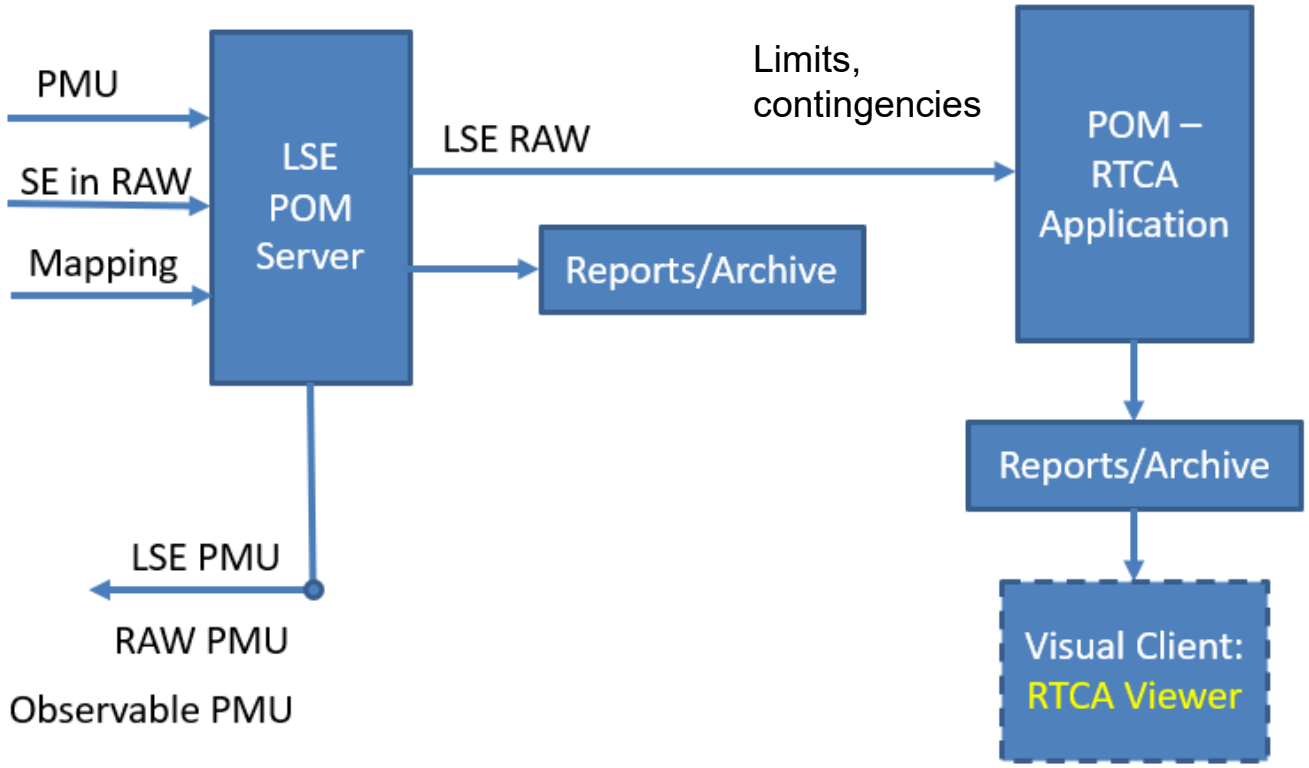
1. PMU - Voltage and current magnitude signals where PMUs are installed
2. SE in RAW - conventional State Estimator cases in Siemens PSS/E .raw data format
3. Mapping File – pmu signals mapped to bus and branches

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



PMU-based RTNA and Advance Apps @ SDG&E®

Measurements (Sources & Types)

- Sources:
  - **PMU** (phasor measuring units; time-synchronized)
- Types:
  - Voltage and current **phasors** (magnitude and angle)
- Acquisition:
  - **30 frames per second**

RTNA (Real-Time Network Analysis)

- Input:
  - Same network model exported from EMS
  - **limited number** of PMUs (138kV – 57%, 69kV - 43%)
  - Mapping of measurements
- Process: **solves fast, direct**
- Output:
  - **Various reports** including bad data reporting, mapping errors, etc.
  - **base case** but only those buses that have PMUs and those buses that become observable.
    - Voltage magnitude and angle
    - MW/MVAR injections and branch flows

Advance Applications

- From the base case created by RTNA
  - Runs RTCA (real-time contingency analysis screening for thermal overload or bus voltage limit exceedance)
  - Remedial action measures
    - Base case
    - Contingency case
- Near RTVSA - future

LSE (PMU Based for Data Quality and Monitoring)

Measurements from PMU

Estimates/Power Flow (direct process)

EPIC – 4: Background, Key Objectives, Project

What is EPIC

The Electric Program Investment Charge (EPIC) is a California statewide program that enables Utilities and CEC to invest in & pursue new/novel emerging energy solutions to meet California's energy goals & drive innovation in the industry.

EPIC-4 Investment Application Plan Approved

Strategic Objective	Strategic Initiative	Funding ($M)	Research Topic
1. Create a More Nimble Grid to Maintain Reliability	Grid Modernization	$7.3	1. Communication and Control Infrastructure for Power System Technology Advancement 2. Mobile Microgrid
2. Increase the Value Proposition of DERs to Customers on the Grid	DER Integration	$7.3	3. Optimizing Real-Time Net Energy Metering Hosting Capacity 4. Demonstrating Solutions for Inverter Integration Issues 5. Integrated DER Operational Flexibility

EPIC-4 is the 2021–2025 EPIC investment cycle, also called the fourth EPIC funding cycle.

EPIC-4 Project: PMU-Based Power Network Analysis for Improved Situational Awareness

Focus Areas.

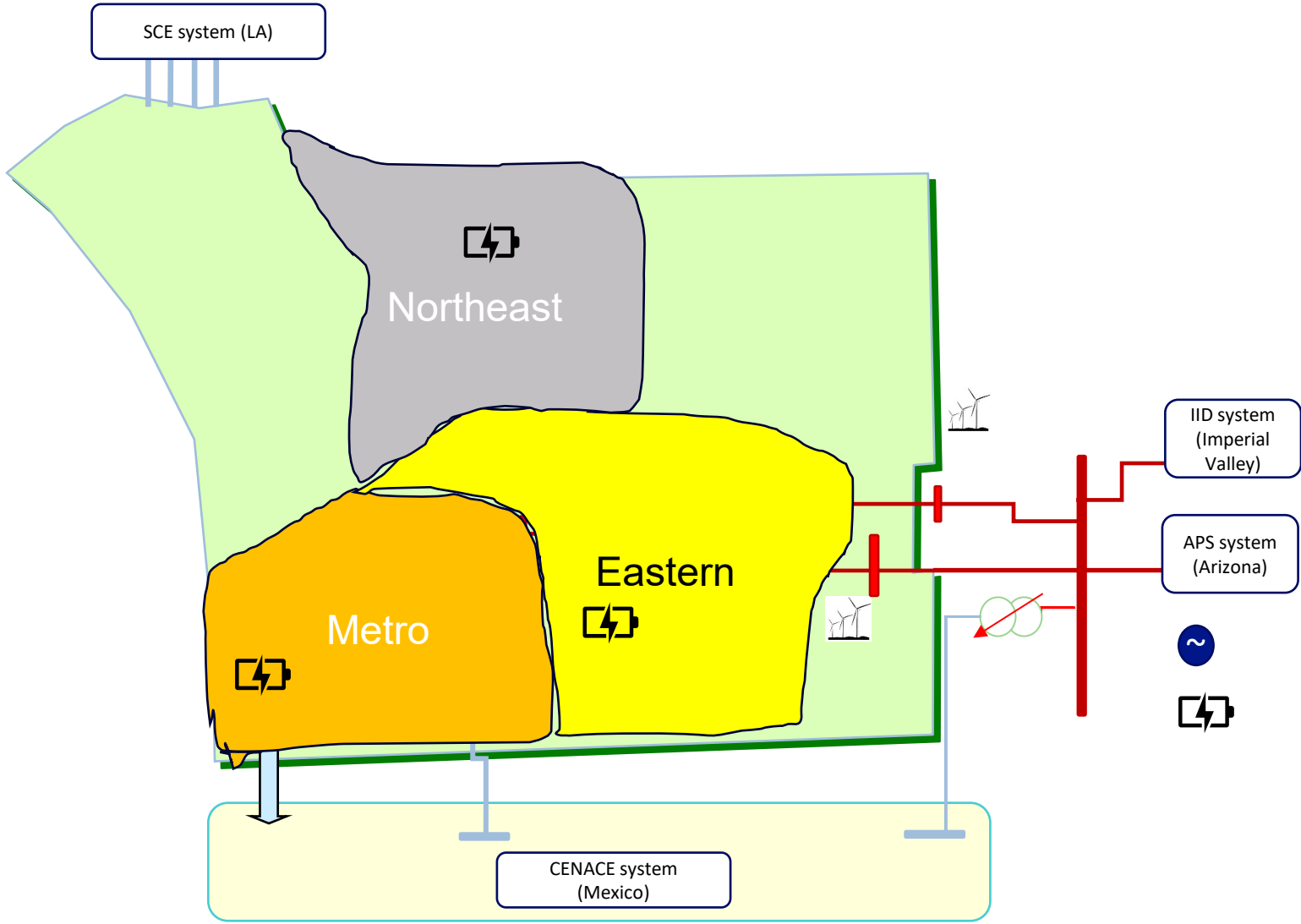
1. Develop the Optimal PMU Placement Tool
2. Add 5-10 PMUs in 1-3 operating region(s)
    1. Metro District
    2. Eastern District
    3. Northeast District

    These districts are selected as they have the most energy storage installations both on the distribution and transmission. There are also disadvantaged communities served by these districts.
3. LSE/RTCA Enhancements

Note – LSE/RTCA platform exists at SDG&E; just need to add limited number of PMUs (and not add to all 69kV substations) to get a bigger base case.

Focused 69kV Regions/Districts

- Metro, Eastern, & Northeast
  - Battery installations on the 69kV network and distribution
  - Disadvantaged communities
  - PSPS
- PMU already installed on all 230kV and 500kV buses owned by SDG&E



Optimal PMU Placement: Goal, Approach, and Initial Results

Optimal PMU Placement for Complete Network Observability

Formulation of PMU placement problem depends on the definition of a criterion for complete system observability

Observability Analysis

Identifies observable portions of the system using existing PMUs:

A power system network is considered to be observable if voltage vector at each node can be calculated based on the PMU measurements (most frequently used definition

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

* *Used in the SDG&E EPIC-4 project*

PMU Placement

Determines locations of additional installations of PMUs:

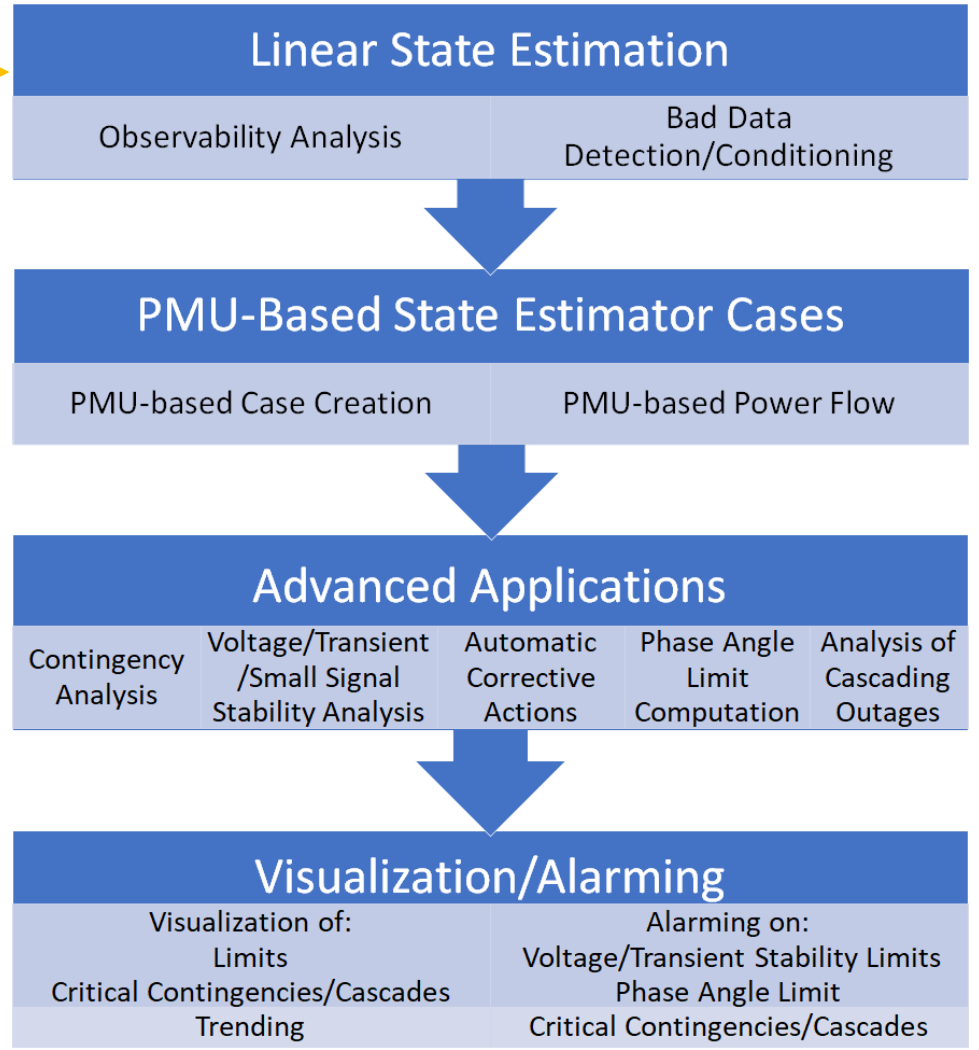
PMU placement for state estimation and creating network model refers to the minimum number of PMUs to be placed in the network to ensure observability of the entire network, or its portion

Formulating optimal PMU placement as a binary linear programming problem is a frequently used approach

- A set of PMU locations such that the entire system is observable
- PMU locations to satisfy a user-defined portion of the system, or a particular region, to be observable

LSE and Observability

- **PMU – based EMS system:**
  - PMU case/LSE case
  - PMU-based power flow
  - PMU-based advanced applications

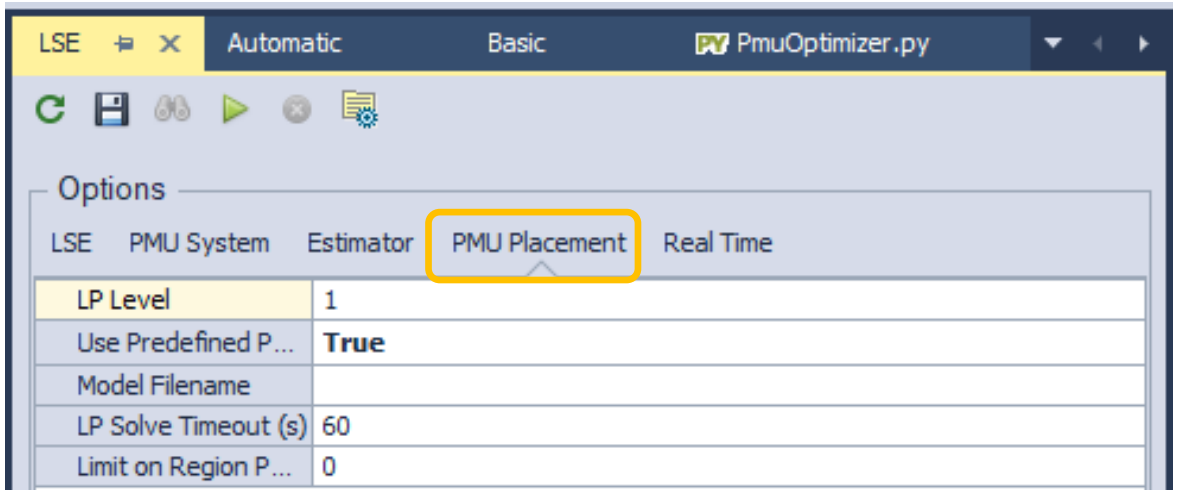


- PMU-based State Estimator cases can be created provided that there is sufficient system observability
  - These cases are used to solve PMU-based power flow and run advanced applications, such as, Real-Time Contingency Analysis (RTCA) and other applications
- Existing PMU infrastructure might not be sufficient to achieve the level of observability needed for creating PMU-based SE cases
- In this situation, **optimal PMU placement study/tool identifies new PMU locations** and is used to develop a plan for future PMU deployments

Optimal PMU Placement Tool

- The Optimal PMU Placement (OPP) tool determines the minimum number of PMUs to be placed in the region (e.g., portion of the network) and their locations in order to achieve full observability of the region
  - Identifying optimal PMU locations decreases the number of physical PMUs to be deployed in the field
- OPP tool is a part of the SDGE PMU ROSE platform
- The tool considers current PMU installations, while identifying the following:
  - PMU locations to satisfy a user-defined region to be observable
  - Locations of user-defined “x” number of PMUs within a region

OPP Tool Options Used for the Study



- **LP Level**

  The number of iterations in the linear programming model

- **Use Predefined PMUs**

  True - the existing PMU locations are used by OPP

- **Model Filename**

  A user-defined filename of the linear programming model

- **LP Solve Timeout (s)**

  The maximum amount of time allowed to find a solution

- **Limit on Region PMUs**

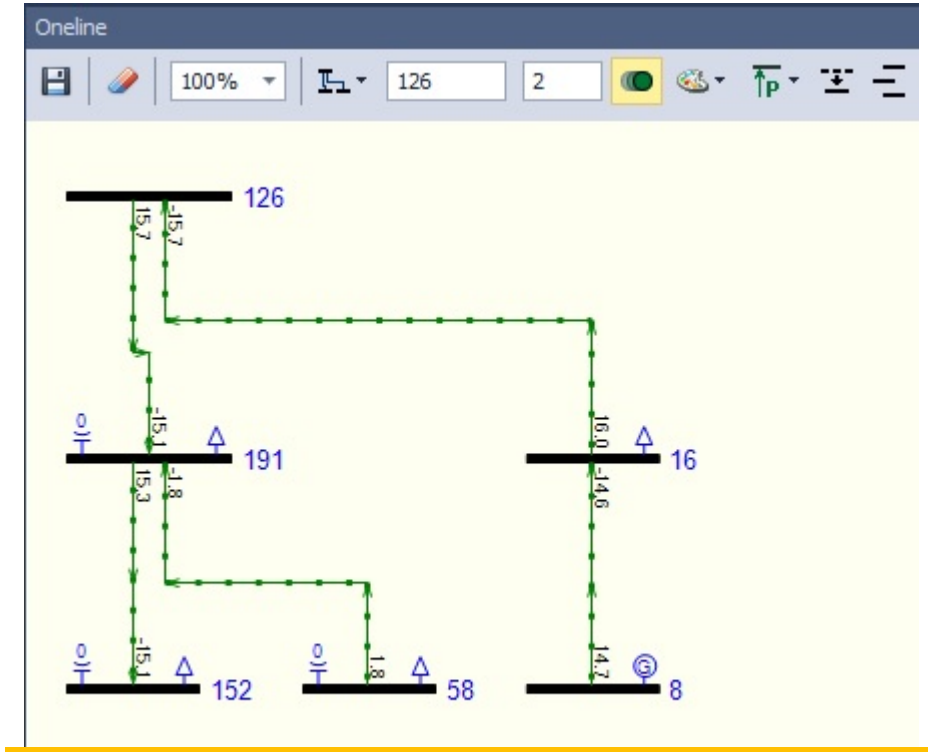
  The maximum number of PMUs allowed to be installed in the region; 0 – no limit

PMU Placement Study

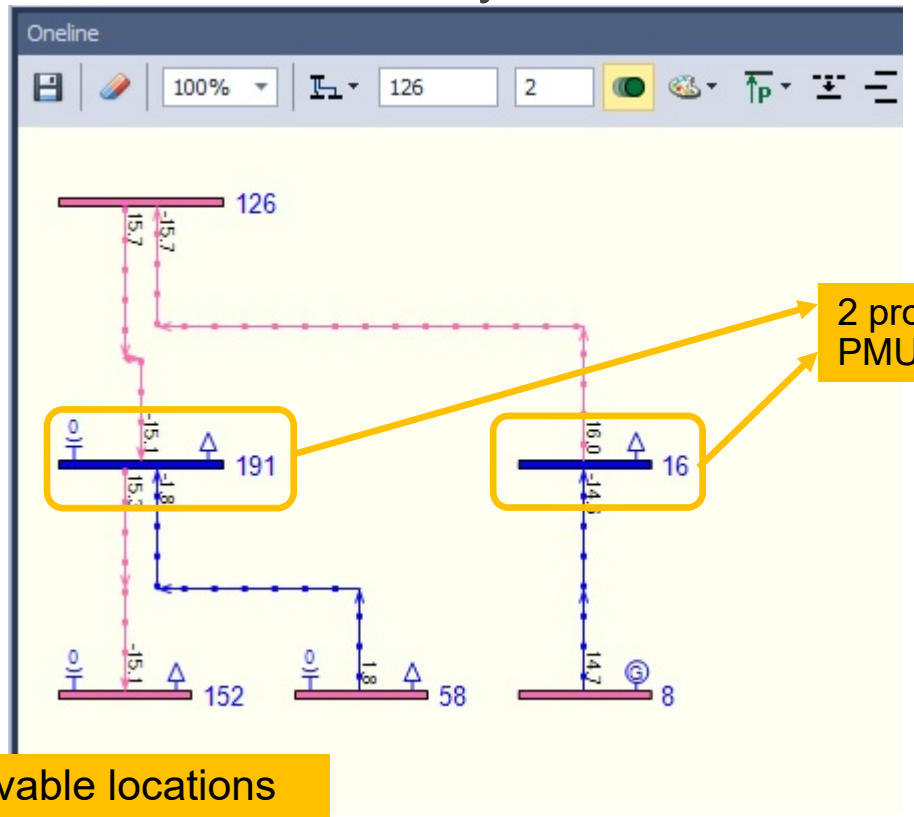
- PMU placement study was performed for three regions in SDG&E® network: Eastern, Metro, and Northeast
- We also compared 2026 observability and PMU placement results vs. 2024 observability
- Increase of observability was observed
- The increase is attributed to three factors:
  - Extensive work on verifying and updating PMU mapping file
  - Deployment of new PMUs in the regions
  - Deployment of new PMUs outside of the regions, that affect observability in the regions

Observability in Region *Northeast* (Fragment Shown): Aug. 2024

- **Before PMU Placement**
  - 36% of the region is non-observable



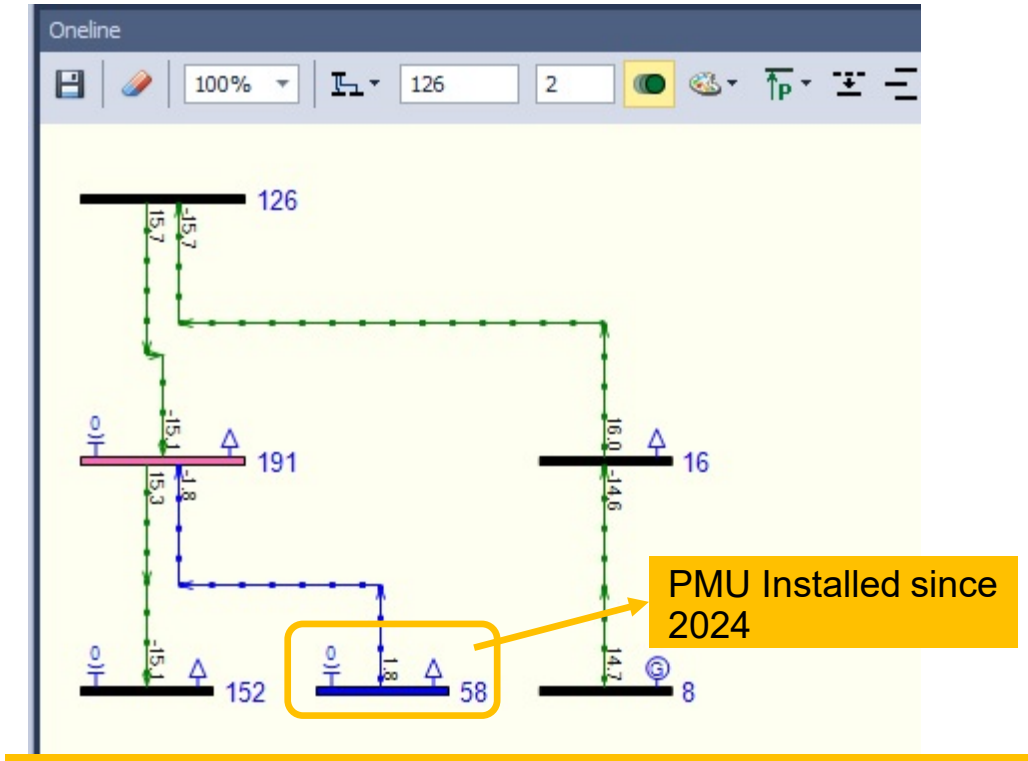
- **After PMU Placement**
  - Becomes fully observable with 6 new PMUs



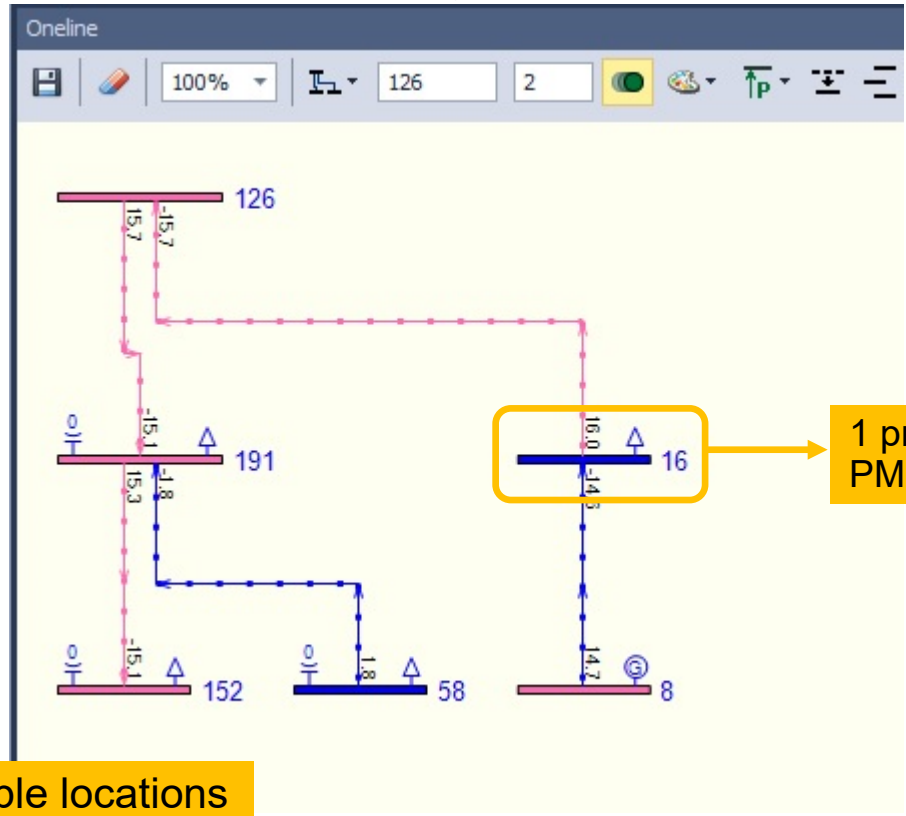
- Black busbars (circled) and green branches are non-observable locations
- Blue busbars and branches – PMU locations
- Pink busbars and branches – observable locations

Observability in Region *Northeast* (Fragment Shown): Mar. 2026

- **Before PMU Placement**
  - 16% of the region is non-observable



- **After PMU Placement**
  - Becomes fully observable with 3 new PMUs



- Black busbars (circled) and green branches are non-observable locations
- Blue busbars and branches – PMU locations
- Pink busbars and branches – observable locations

EPIC-4 Project: PMU Placement Results – Northeast

Aug. 2024		
No.	Bus No.	New PMU
1	2	New PMU 1
2	4	
3	13	
4	16	New PMU 2
5	19	
6	35	
7	58	
8	60	New PMU 3
9	64	
10	69	
11	94	New PMU 4 (diff line)
12	118	
13	126	
14	133	New PMU 5
15	139	
16	149	
17	152	
18	158	
19	191	New PMU 6
20	192	
21	199	
22	201	
23	266	
24	922	
25	899998	

Mar. 2026		
No.	Bus No.	New PMU
1	2	
2	4	
3	13	
4	16	New PMU 1
5	19	
6	35	
7	58	
8	60	
9	64	
10	69	
11	94	New PMU 2 (diff line)
12	118	
13	126	
14	133	
15	139	
16	149	
17	152	
18	158	
19	191	
20	192	New PMU 3
21	199	
22	201	
23	266	
24	922	
25	899998	

Legend
PMU
Observable
Non-observable
New PMUs

Region "Northeast" Buses	Aug. 2024	Mar. 2026
PMU	9	12
Observable	7	9
Non-observable	9	4
Total	25	25

Region "Northeast" New PMUs	Aug. 2024	Mar. 2026
New PMUs	6	3
Total Existing and New PMUs	15	15

Next Steps

- Incorporate PMU Placement Results into SDG&E's PMU Deployment Roadmap
- Expedite placement of selected PMU locations.
- Expand into other regions and neighboring utilities
- Review base case and contingency analysis results; shift and outage factors
- Enhance LSE/RTCA

Questions?