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Synchronized Measurements in Distribution Systems

March 31, 2021

Paul Pabst, P.E. and Heng (Kevin) Chen, P.E.
ComEd

Outline

- ComEd Overview
- ComEd Distribution PMU Strategy
- Distribution PMU Deployment
- Applications
  - Microgrid Situational Awareness and Control
  - DER Management
  - Critical Customer Monitoring
  - SIMPLE
- Roadmap and Next Steps

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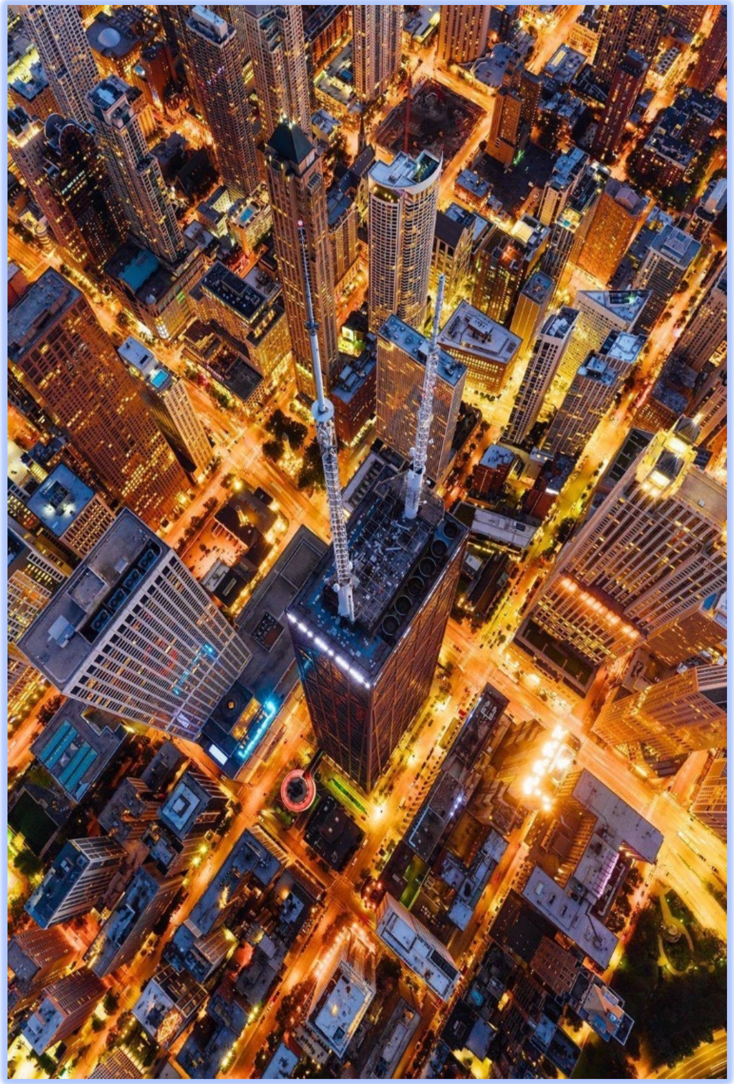
Our Company:
- One of six utilities owned by Exelon. (Exelon also owns generation and energy sales businesses.)
- 6,400 Employees
- Service Territory: 11,428 square miles

Our Customers:
- 4 million customers in northern Illinois, including the City of Chicago

Our Grid:
- Peak Load: 23,753 MW (7/20/2011)
- 553,800 distribution transformers
- 66,200 circuit miles of primary distribution
- 52% overhead, 48% underground
- 5,800 circuit miles of transmission
- 93% overhead, 7% underground



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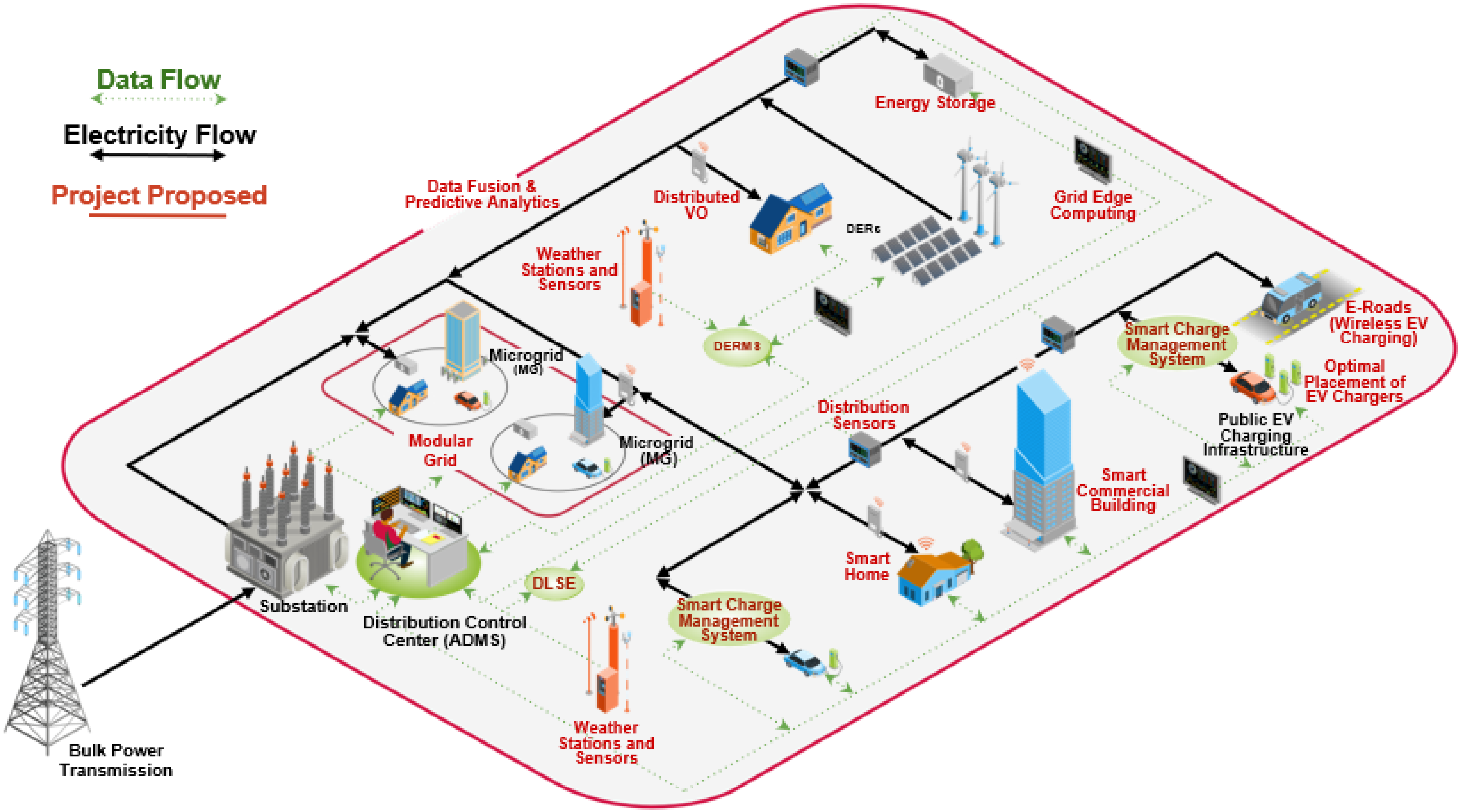
Vision of Future Grid



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ComEd PMU History

In 2015, ComEd initiated development of a road map and strategy for wide-scale operational use of Phasor Measurement Units (PMUs) in its transmission and distribution system.

In this roadmap, many distribution functions/applications were identified for PMUs in the following five categories:

- Distributed Energy Resource (DER) Integration
- Distribution System Operations
- Wide-Area Monitoring, Protection, Automation and Control (WAMPAC)
- Asset Management and Reliability
- Planning and Analysis

There were also several benefits and deployment challenges identified and qualitatively compared for the distribution applications.

Key Distribution Synchrophasor Functions

- Pilots focused on demonstrating key synchrophasor capabilities at various levels of complexity
  - Microgrid operation
  - Distribution state estimation
  - Voltage and current profile monitoring
  - Real-time system operations (limited scope)
  - DER monitoring (Solar PV and Energy Storage)
  - Condition monitoring and asset management
  - Smart inverter monitoring and control
  - Incipient fault and failure detection
  - Root-cause and post-mortem analysis
  - Monitoring of critical infrastructure and large customers

Where it Began: 2018 Pilot Installations

- ComEd targeted installation of distribution PMUs, PDCs (Phasor Data Concentrators), and other associated equipment at 7 key locations:
  - Substations feeding ComEd’s ICC-approved microgrid
  - Substation serving a 10MW solar farm in Southeast Chicago
  - Substations feeding Chicago’s two international airports

- Synchrophasor data is collected by substation PDCs and sent to a central PDC and synchrophasor data management system.
- In addition to the above pilots, the project team has installed a Proof-of-Concept (PoC) synchrophasor data system in a laboratory environment for troubleshooting and demonstration purposes.

Substation Level PMU

- 12kV and 34kV feeder relays
- Transformer relays
    - Situational awareness of feeder heads and medium voltage busses

Feeder Main-Stem PMU

- Distribution automation devices (in-development)

Feeder Edge PMU

- Standalone microPMU
- Distributed generation

Programmatic Deployment Strategy

2018

7 substations
59 PMU streams
$1.6M

2019

10 substations
25 microPMUs
91 PMU streams
$3.5M

2020

5 substations
29 PMU streams
$2M

2021

Analytics
State Estimation
$2M

2022

$2M

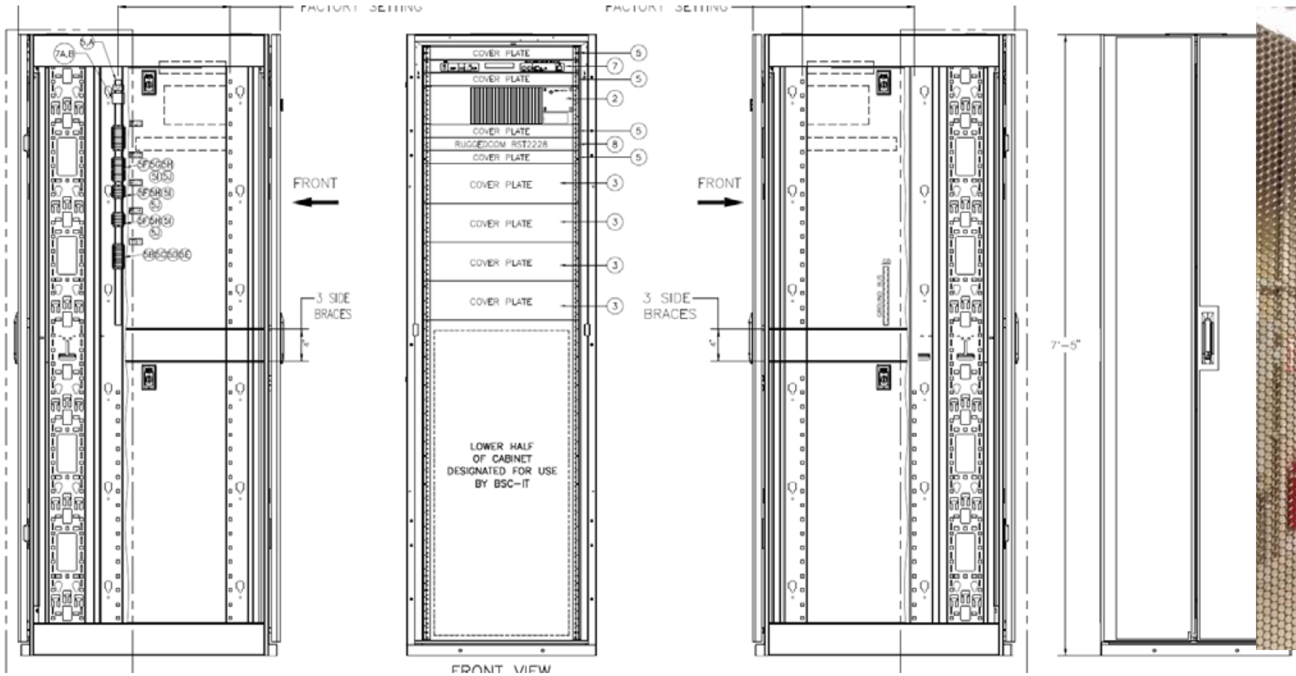
2023

$2M

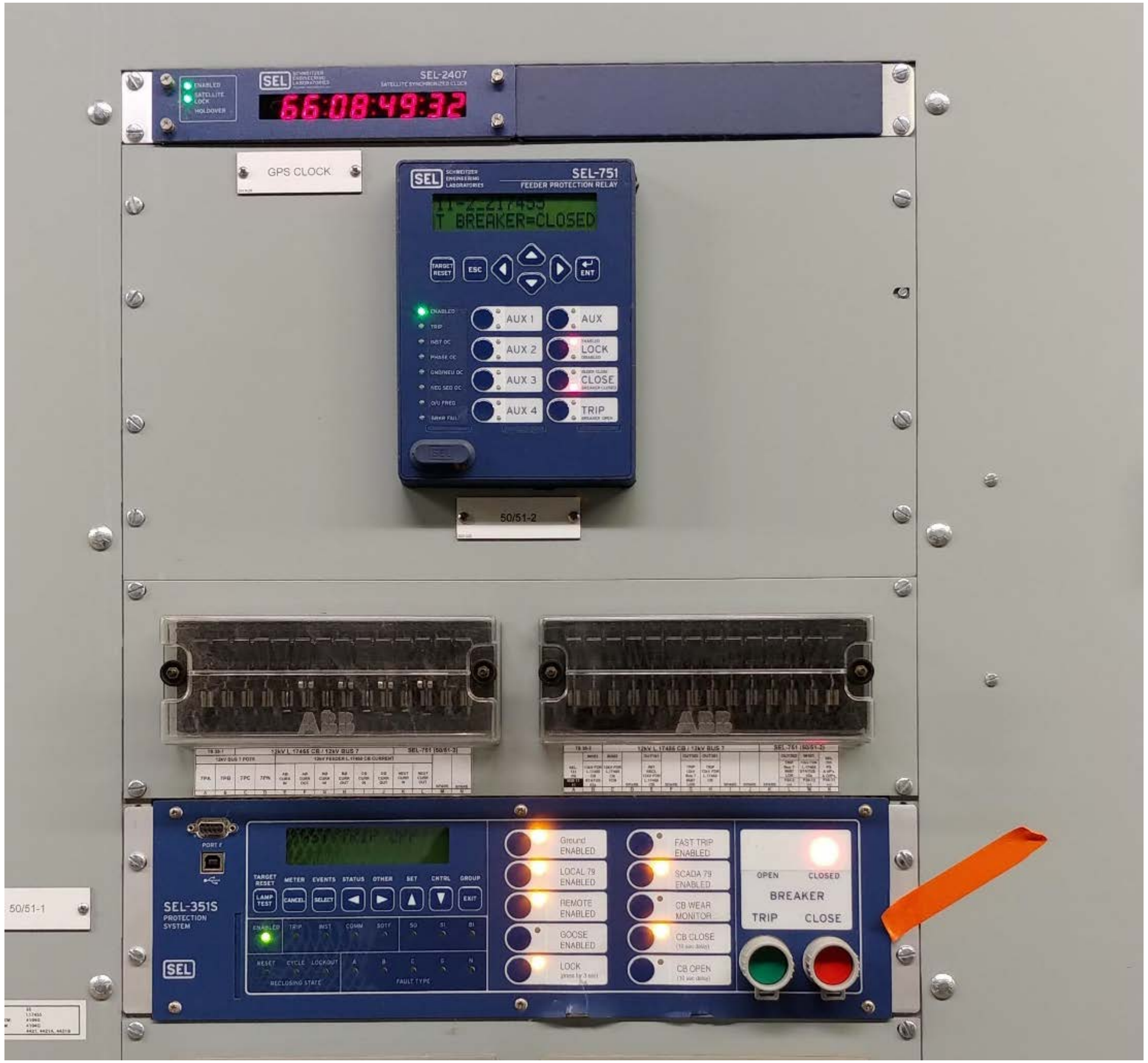
2024

$2M

Distribution PDC Cabinet and GPS Standardization



Relay Standardization



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Project Scope: Substation

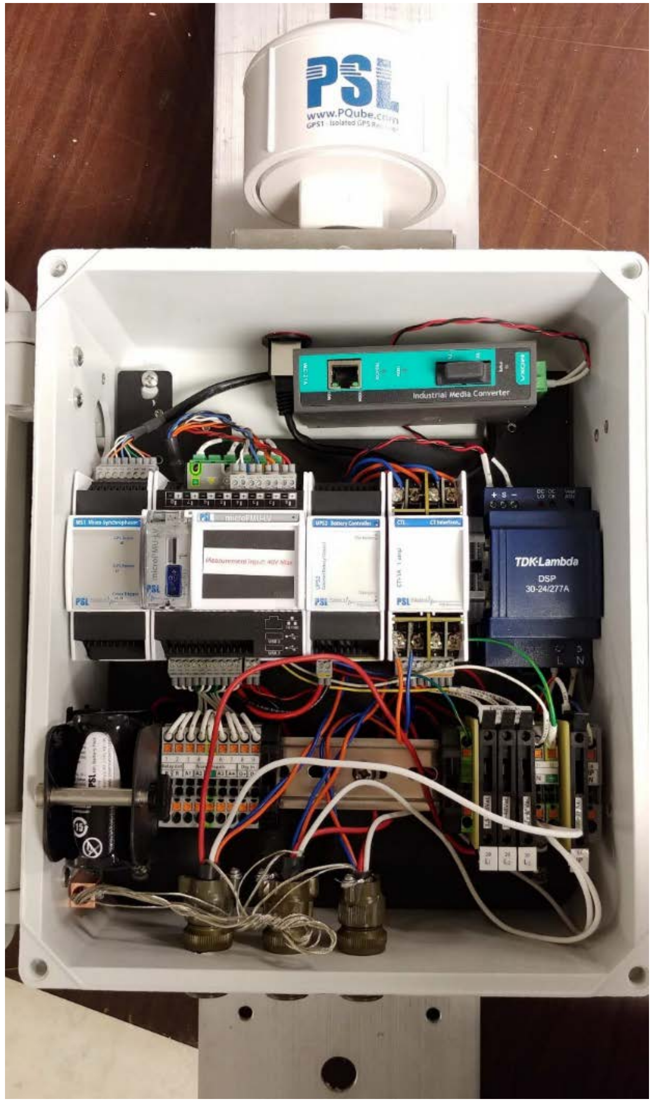
- Project mostly mirrors transmission PMU deployment
- A new PDC cabinet is deployed in each substation. Cabinet includes GPS clock and network switch
- PMU functionality is enabled on existing relays when possible. Some relays may need firmware upgrade.
- New relays are installed if PMU functionality not available.

S&C Vista Gear With SEL Relays

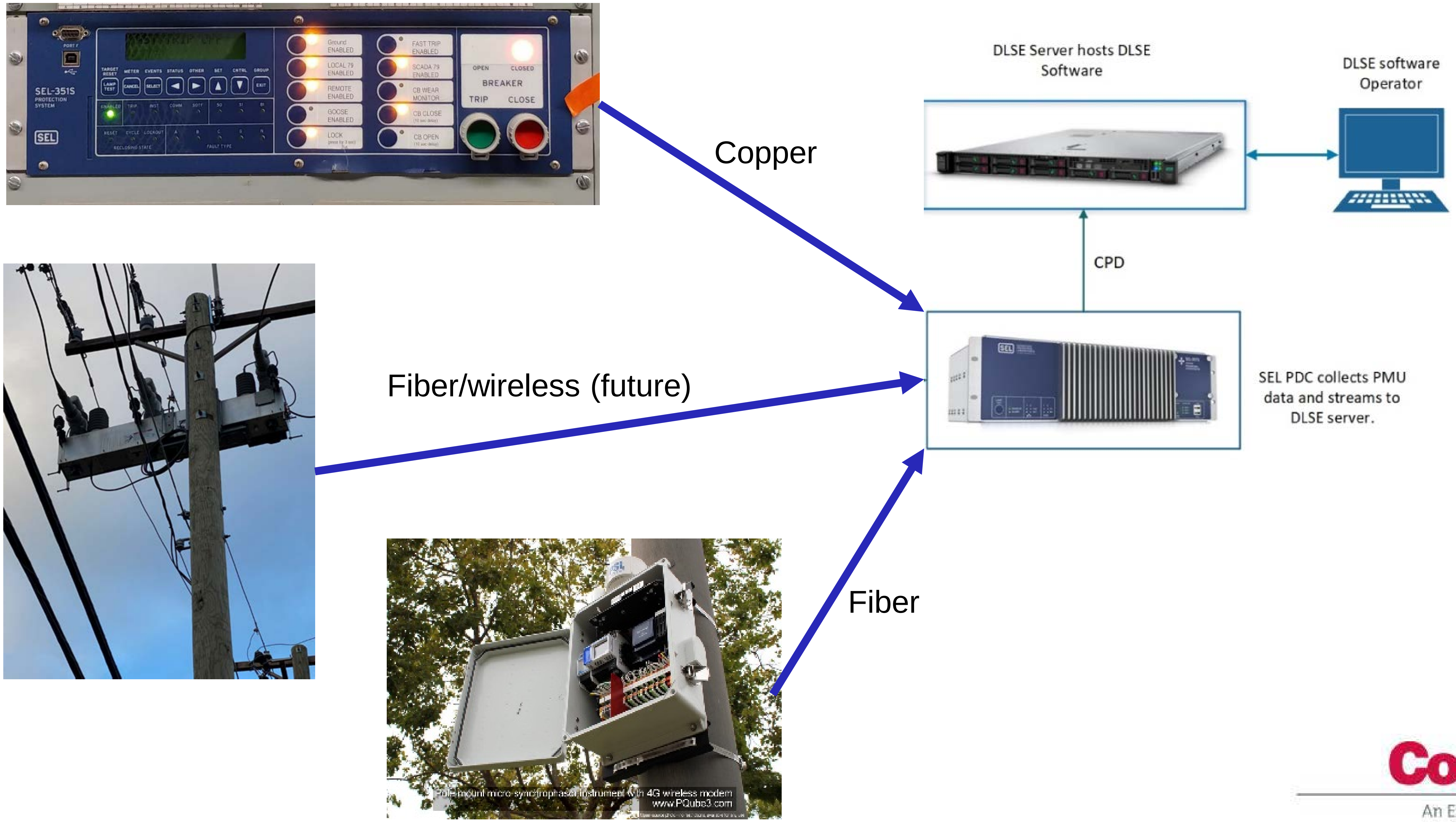
- The gear will be operated by SEL 751 relays instead of S&C controls providing protection functionality
- The Remote Supervisory functionality will remain in the S&C 6802 control
- PMU C37.118 streams will be supported

MicroPMU

- Out-of-substation PMUs (microPMUs) are housed on outdoor rated enclosures and have:
  - GPS module for time synch
  - Network communications interface
  - Backup battery
- Voltage/current sensors integral part of system
- Adequate communications required (fiber)
- Data streamed to Phasor Data Concentrator (PDC) then to archive and applications



Architecture



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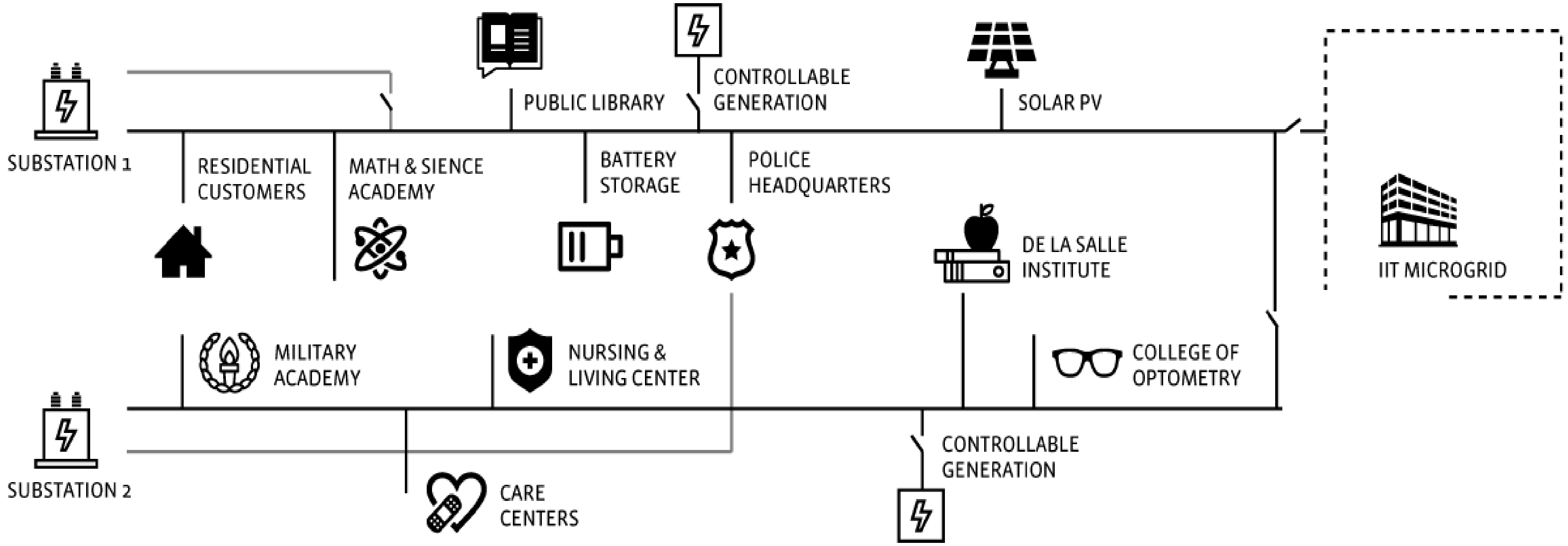
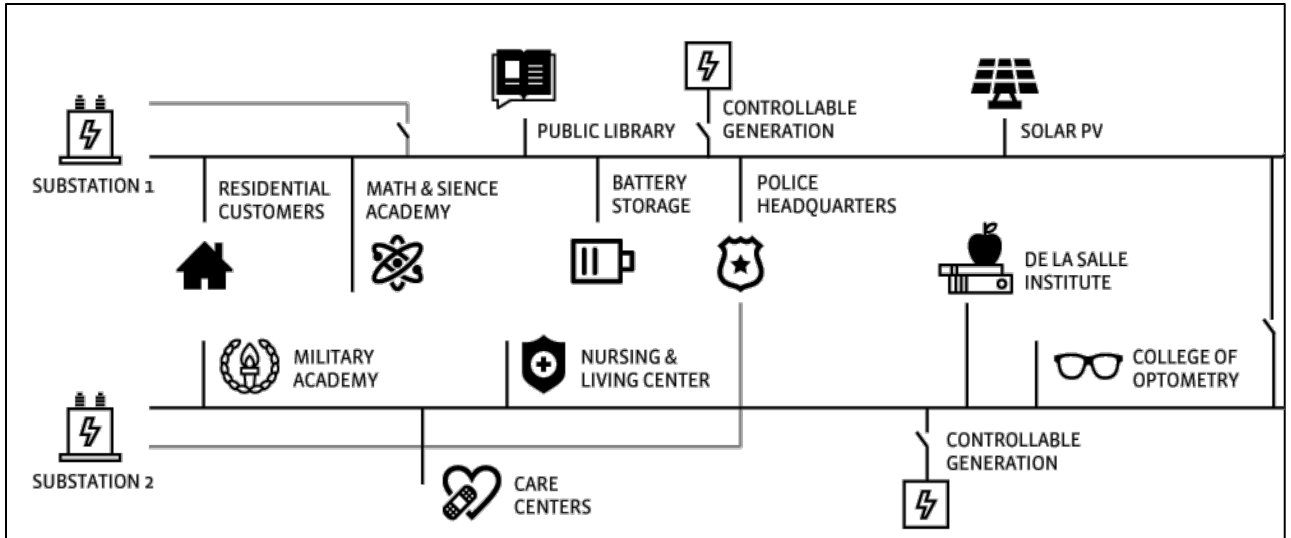
APPLICATIONS

- The Bronzeville Community Microgrid enables a green, resilient, sustainable neighborhood for consumers.
- 7 MW aggregate load, serving approximately 1,000 residences, businesses and public institutions
- Installation of first utility-operated microgrid cluster powered by DER including solar PV and energy storage
- Demonstration of advanced technologies supported by six grants from the Department of Energy
- These technologies have been developed with partnerships with universities, vendors, and national labs

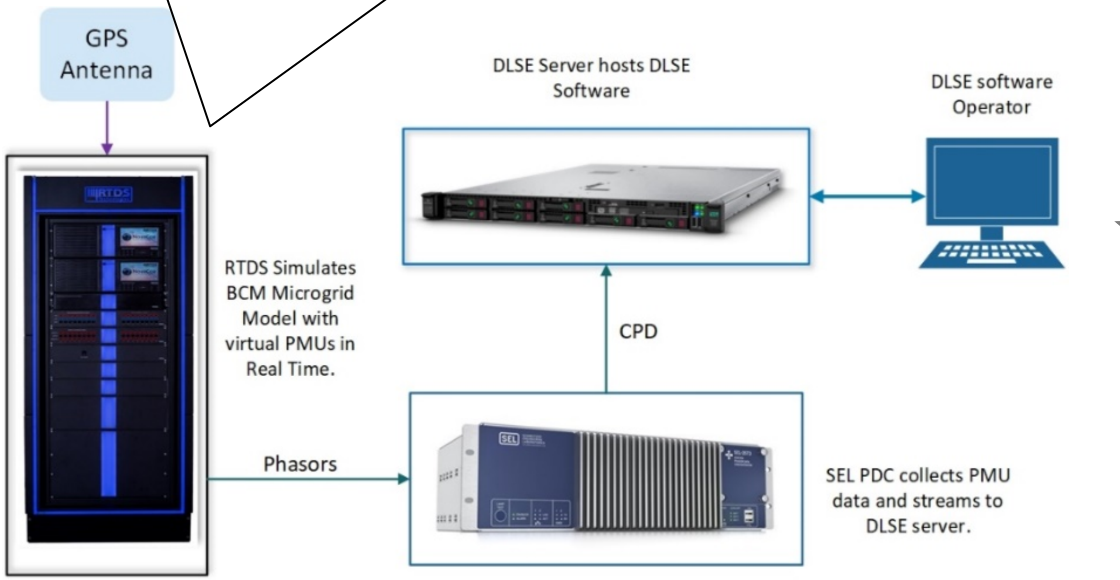


Distribution Linear State Estimator (DLSE)

- Three-phase DLSE platform has been developed to leverage the PMU data that provides
  - observability analysis,
  - optimal PMU placement,
  - bad-data detection,
  - monitoring the microgrid and microgrid controller,
  - alarming, archiving and visualization for situational awareness
- Tested and demonstrated in ComEd's GrIT lab using RTDS that simulates virtual PMUs modeled within BCM
- Developing the ability to identify switching and other events in the microgrid



Bronzeville Community Microgrid Model



- R&D focused on showing core functionality in a lab environment:
  - o D-LSE application development and customization to ComEd microgrid (46 PMUs)
  - o Testing and demonstration in GrIT Lab using RTDS
  - o Functionality enhancement based on test results and user feedback

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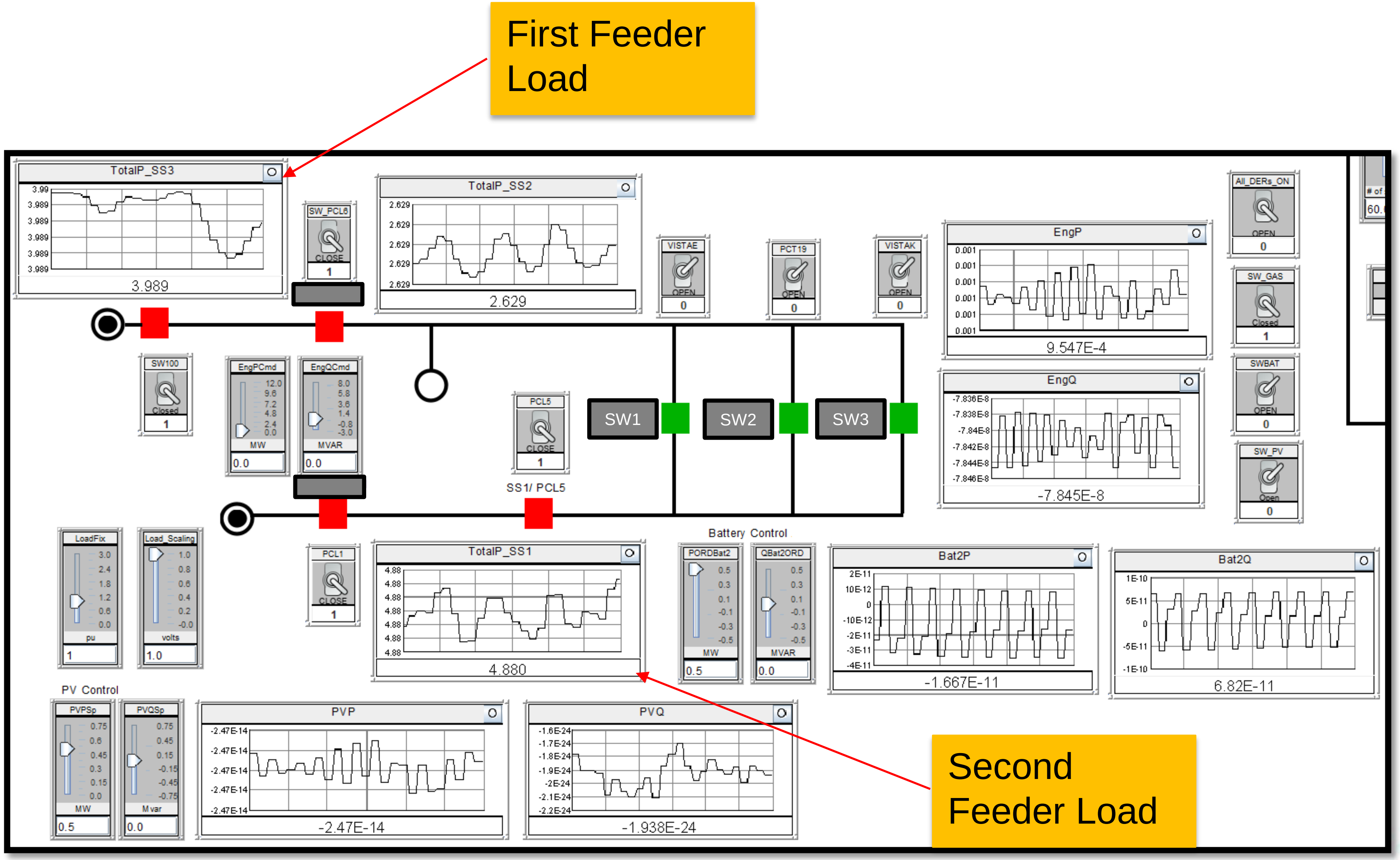
RTDS Normal Configuration Load

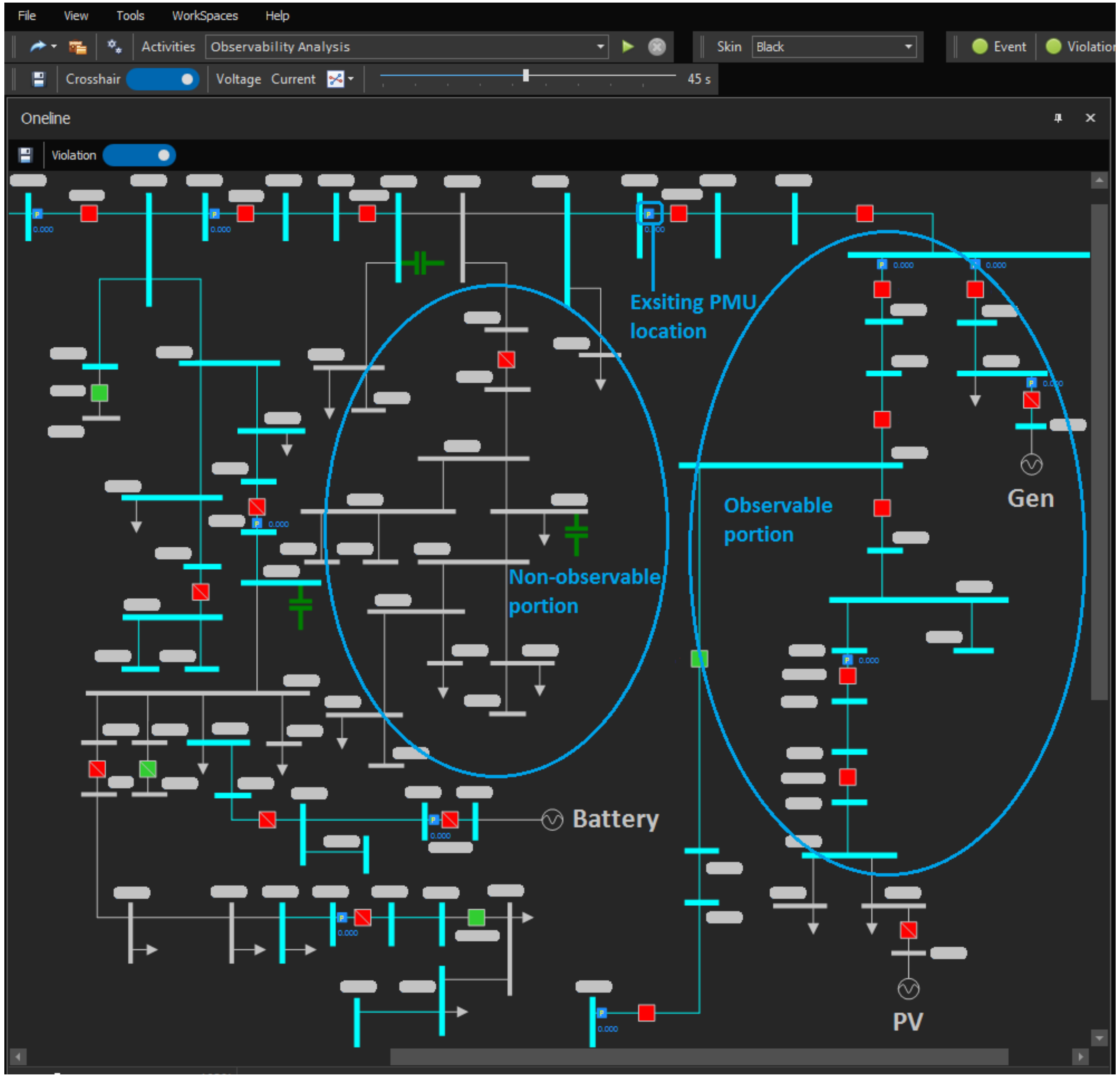


RTDS Test Scenarios

- Simulated different operating conditions and system topology
- Tested both offline and in real-time

No.	Test Cases	Description
1	Base Case	Previously provided, no new data set required
2	Load variation	Base Case with injected load variation
3	Observability analysis	Adding/removing PMUs
4	Change of PV profile	Use High Variable PV Profile for PV output
5	Alarming capability on violations	Trigger Under Voltage and Over Voltage
6	Under bad data conditions	Data dropout for 2 seconds, All phases, Voltage and Current
		Data dropout for 0.5 second, Only A phase, Current
		Noisy data, 5-10%, All phases, Voltage and Current
		Measurement constantly dropping to an offset of normal value and immediately comes back every 1-3 samples, repeating for 1 min, All phases, Only Voltage and Current
7	Under topology change conditions	Base Case → DER on
		DER on → Sub-Island 1
		DER on → Sub-Island 2
		DER on → Transfer 1 → Full Island
		DER on → Transfer 2 → Full Island

D-LSE Result – Observability Analysis & Visualization



D-PMU ROSE considers a power system network to be observable for a given network topology if voltage vector at each node can be calculated based on the PMU measurements

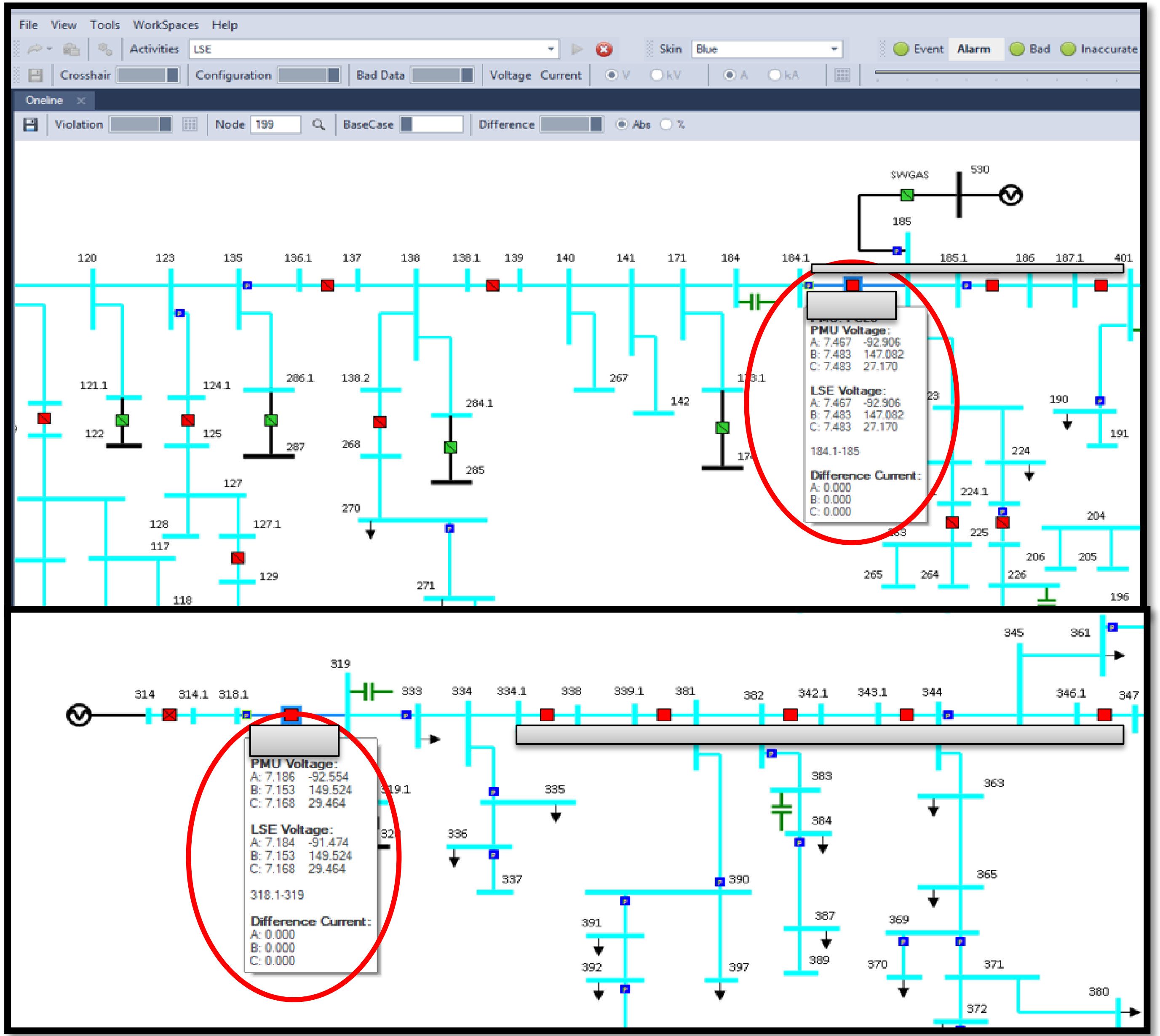
Blue – nodes and branches that are observable with planned PMU installations (for current network topology)

Black – non-observable nodes and branches

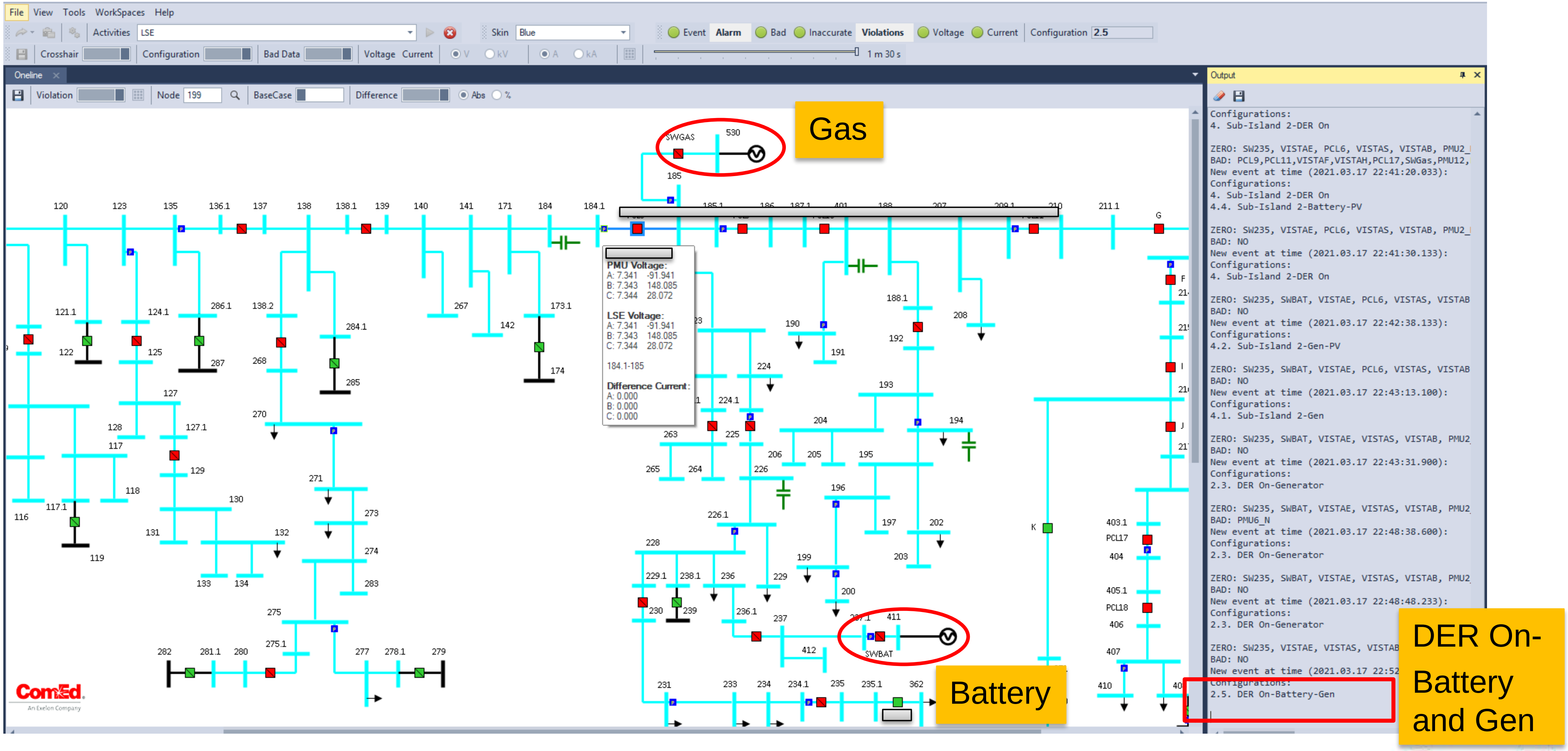
P – Planned PMU installations

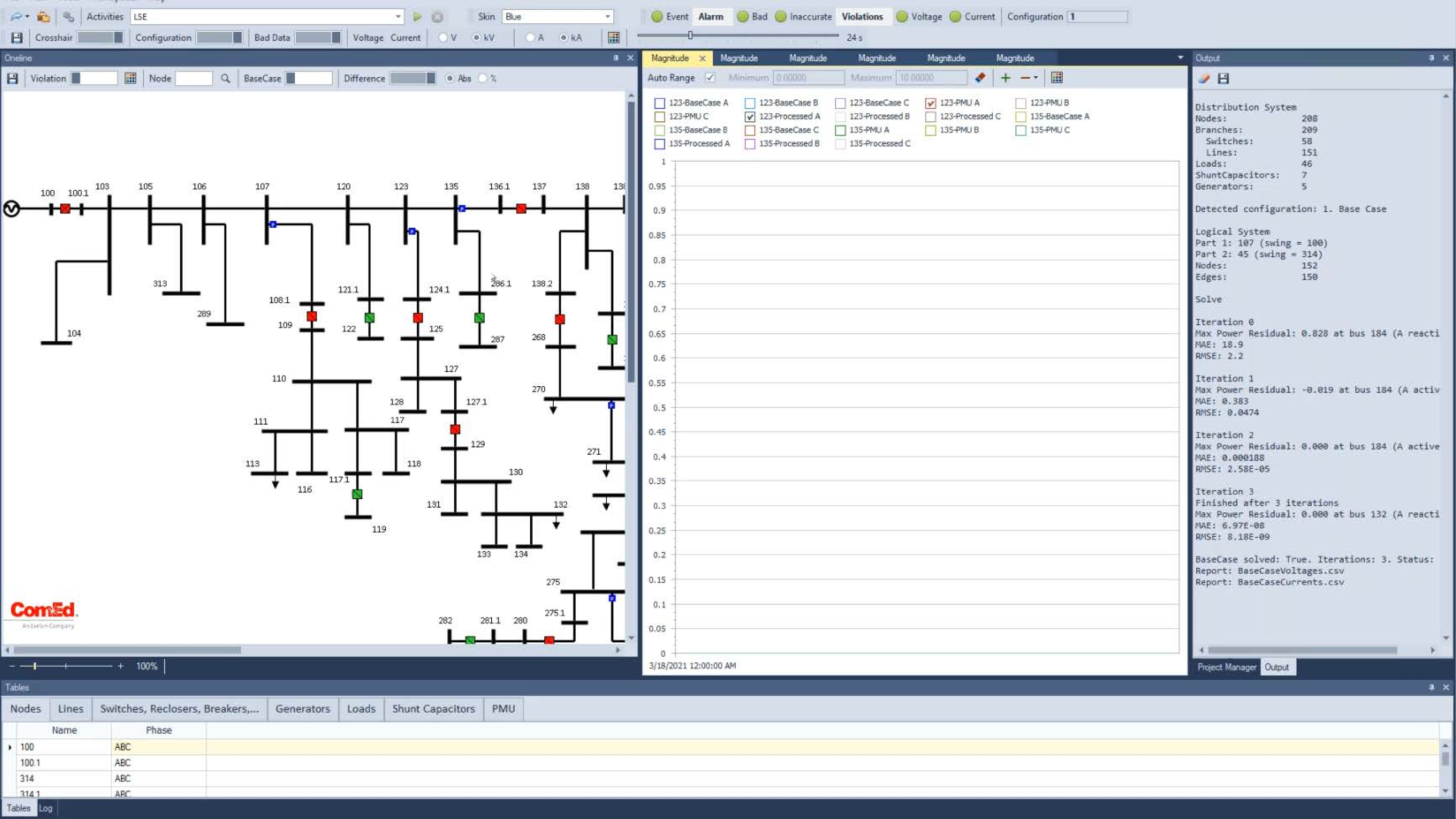
DLSE Estimate with Changed Load

- The values with loads changed (RTDS vs DLSE) match well.



Generator + BESS ON in RTDS





Activities
LSE
Skin
Blue
Event
Alarm
Bad
Inaccurate
Violations
Voltage
Current
Configuration
1
Crosshair
Configuration
Bad Data
Voltage
Current
V
kV
A
kA
24 s
Oneline
Violation
Node
BaseCase
Difference
Abs
%
100
100.1
103
105
106
107
120
123
135
136.1
137
138
313
289
104
108.1
109
121.1
122
124.1
125
286.1
287
138.2
268
270
110
127
128
127.1
111
117
113
116
117.1
118
119
129
130
131
132
133
134
271
275
275.1
282
281.1
280
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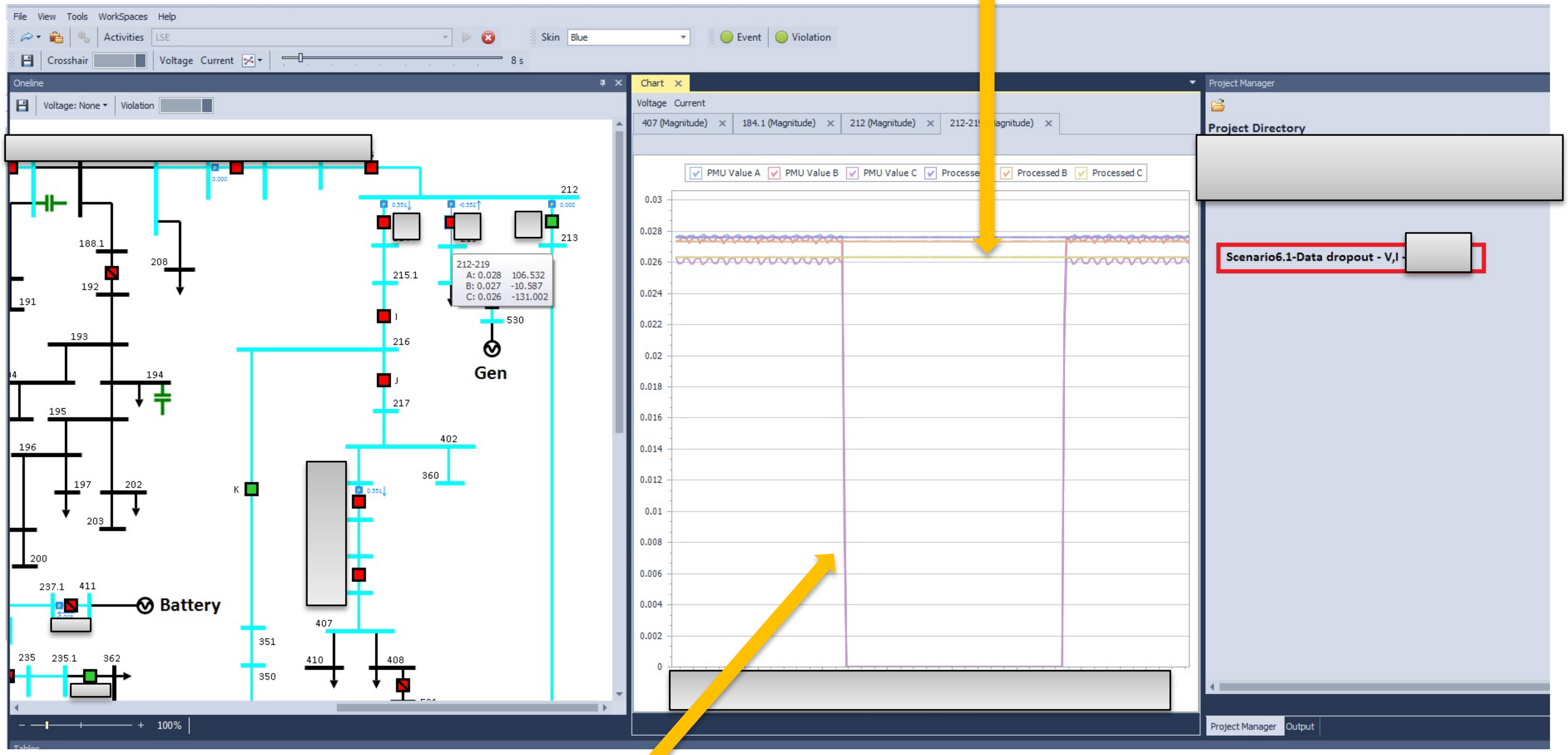
100%
Magnitude
Auto Range
Minimum
0.00000
Maximum
10.00000
123-BaseCase A
123-BaseCase B
123-BaseCase C
123-PMU A
123-PMU B
123-PMU C
123-Processed A
123-Processed B
123-Processed C
135-BaseCase A
135-BaseCase B
135-BaseCase C
135-PMU A
135-PMU B
135-PMU C
135-Processed A
135-Processed B
135-Processed C
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3/18/2021 12:00:00 AM
Output
Distribution System
Nodes: 208
Branches: 209
Switches: 58
Lines: 151
Loads: 46
ShuntCapacitors: 7
Generators: 5
Detected configuration: 1. Base Case
Logical System
Part 1: 107 (swing = 100)
Part 2: 45 (swing = 314)
Nodes: 152
Edges: 150
Solve
Iteration 0
Max Power Residual: 0.828 at bus 184 (A reacti
MAE: 18.9
RMSE: 2.2
Iteration 1
Max Power Residual: -0.019 at bus 184 (A activ
MAE: 0.383
RMSE: 0.0474
Iteration 2
Max Power Residual: 0.000 at bus 184 (A active
MAE: 0.000188
RMSE: 2.58E-05
Iteration 3
Finished after 3 iterations
Max Power Residual: 0.000 at bus 132 (A reacti
MAE: 6.97E-08
RMSE: 8.18E-09
BaseCase solved: True. Iterations: 3. Status:
Report: BaseCaseVoltages.csv
Report: BaseCaseCurrents.csv
Project Manager
Output
Tables
Nodes
Lines
Switches, Reclosers, Breakers,...
Generators
Loads
Shunt Capacitors
PMU
Name
Phase
100
ABC
100.1
ABC
314
ABC
314.1
ABC
Tables
Log

Bad Data Detection and Conditioning

Estimated values after the D-LSE (filtering and weighted least squares method): Yellow



Raw PMU values (phase B)

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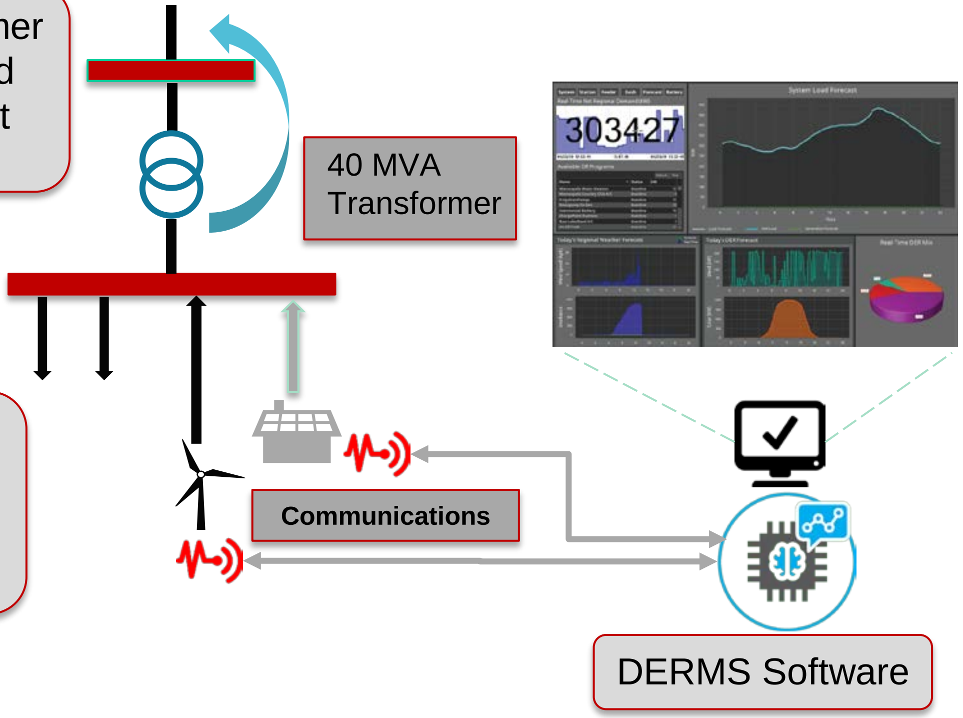
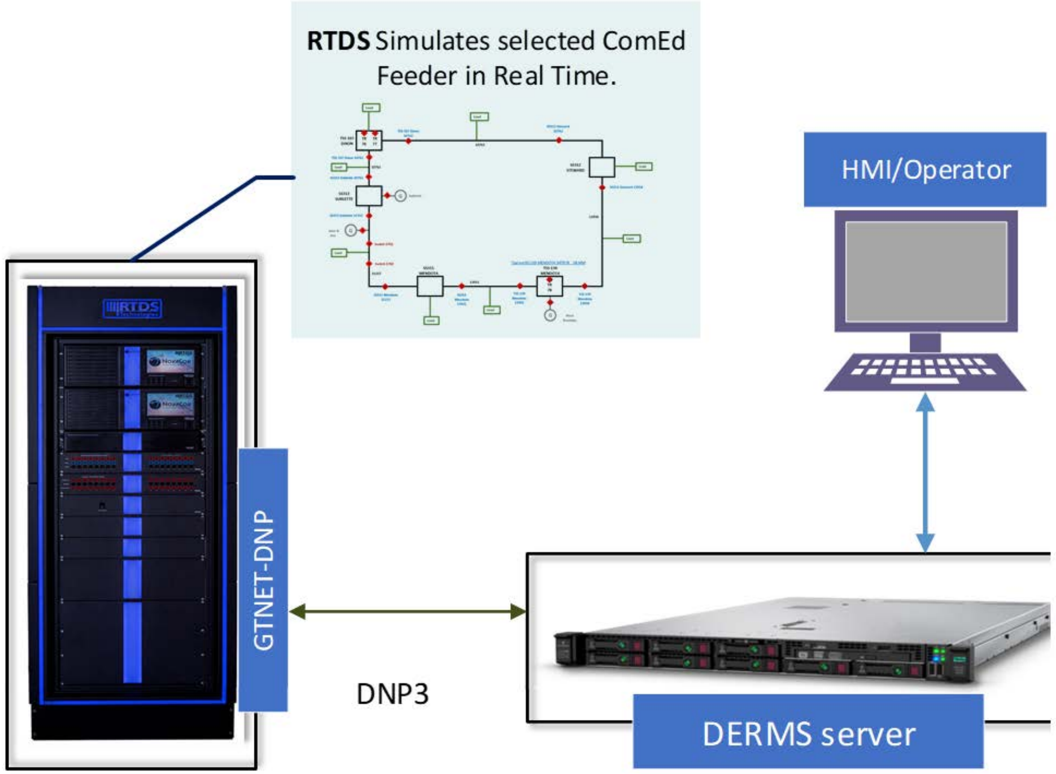
DERMS for Renewable Integration

ComEd is deploying DERMS as a non wire alternative (NWA) to mitigate the overloading of substation transformer due to higher level of PV integration. DERMS monitors transformer loading, DER output, system conditions, and will send signals to manage DERs if any system violations occur.

The substation transformer will experience back feed beyond its allowable limit with added PV

High-speed, low-latency reliable communications is needed for DERMS operation.





- Traditional method requires significant upgrades including one substation transformer and 138kV line extensions
- DERMS provides an alternative solution to customers by monitoring and managing the DER in real time, which could avoid costs of about $30M
- For this pilot, it will need to curtail only up to 5% of total energy per year based on the analysis using annual historical data and solar forecast, for the 6 MW of solar scenario

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Project SCOPE

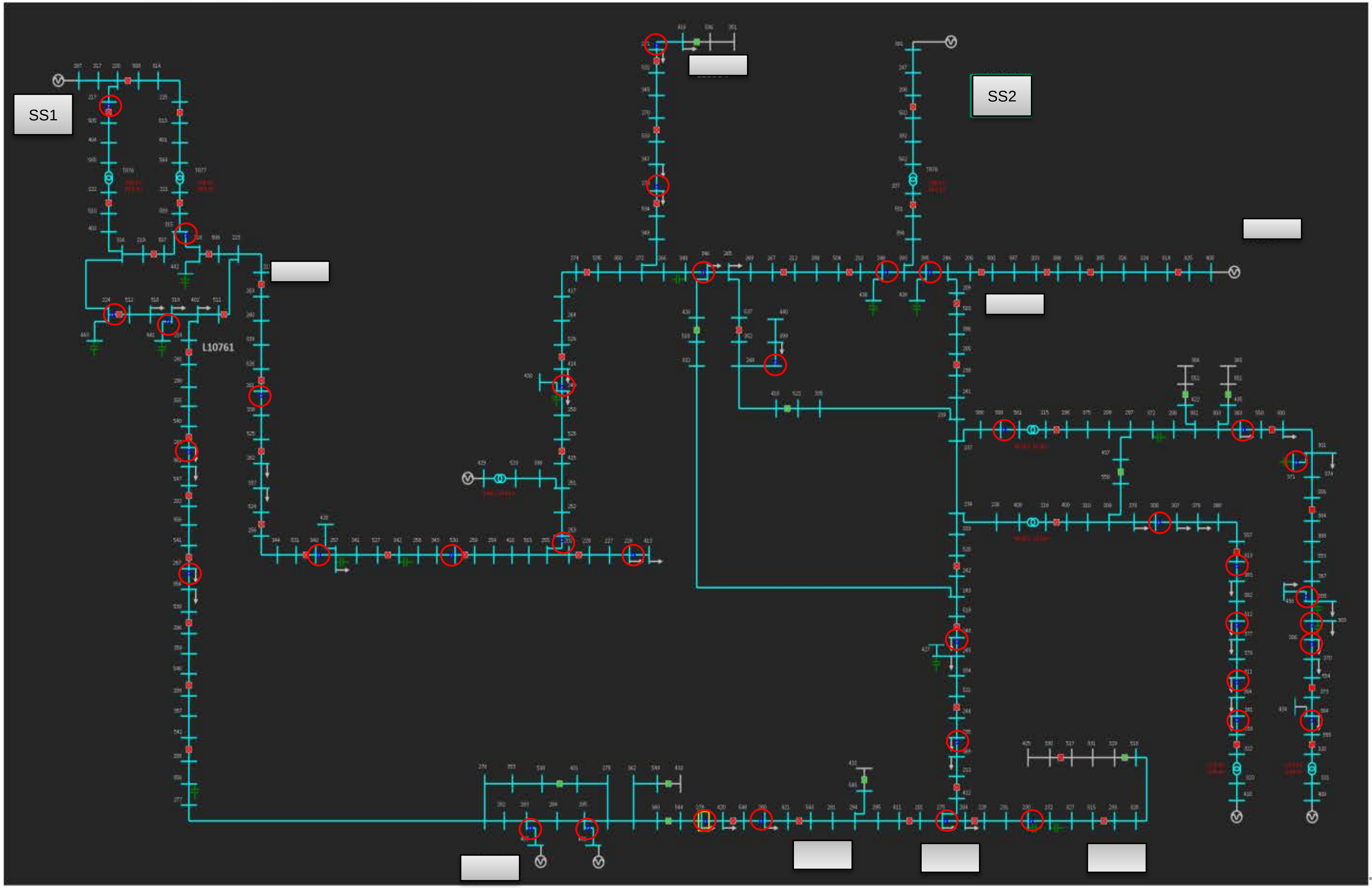
- Optimum PMU placement to enable Distribution Linear State Estimation.
  - Based on the model of the circuit rich in DER penetration.
  - Observability analysis for Chicago Airport Area, a ‘critical customer’
  - “Optimum” doesn’t consider field implementation limitations, rather, focuses on optimized PMU placement to enable full observability with DLSE assuming PMUs can be installed where required.

- Two key stages:
  - Model reduction/refinement from CYME to DLSE, including model corrections, and PMU placement for base topology
  - PMU placement revision considering key topology changes (covering main modes of operations/maintenance)

Observability Analysis for DER Rich Area

- Mendota / Dixon 34 kV loop, with addition of some 12 kV portions with Solar PV
- Includes 3 windfarms and 3 solar PVs
- Model reduction/refinement from CYME to DLSE complete – more than 300 nodes
- PMU placement complete and single-line-diagram (SLD) was created – 39 PMUs
  - Ten additional operating modes and topologies considered for full observability

Single Line and PMU Placement Location



Topology Cases Considered

1. Different topologies can affect observability of the system
2. As part of the Study ComEd considered 10 different events generating different topologies
3. Events and topologies are not discussed here due to confidentiality reasons

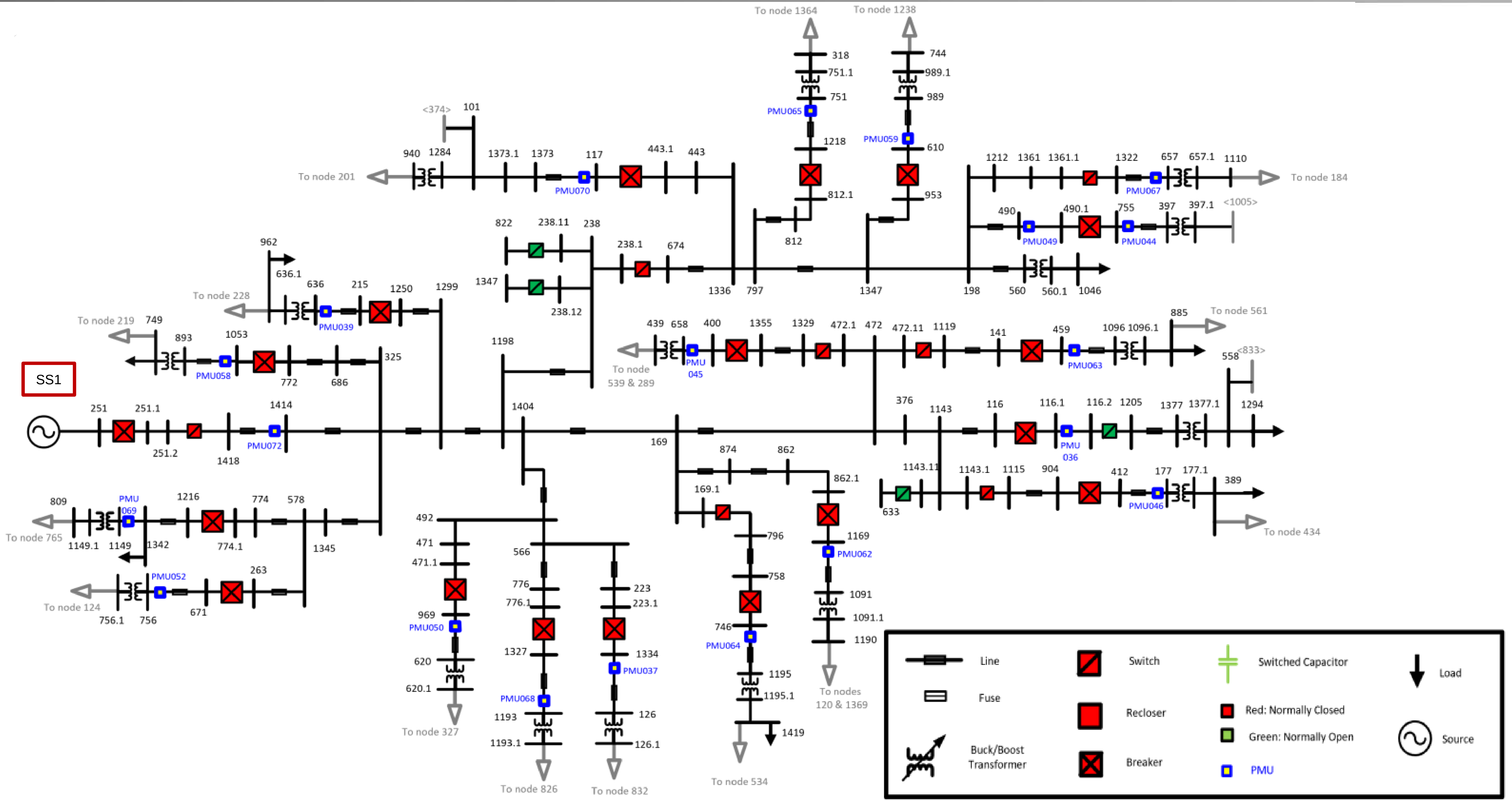
Results of PMU placement and observability analyses under different topologies/events are summarized below:

- 36 PMUs were sufficient for the Base Case to be fully observable.
- Placing the same 36 PMUs during Event 1 is sufficient for the Mendota system to be fully observable.
- PMU placement analysis for Event 2 showed that one additional PMU was needed to achieve full system observability, for the total of 37 PMUs.
- Observability analysis for Events 3 – 10 was performed with these 37 PMU locations.
- Placing 37 PMUs during Events 3 – 6, 8, and 9 is sufficient for the Mendota system to be fully observable.
- PMU placement analysis for Event 7 showed that one additional PMU (e.g., in addition to 37 PMU locations in item 3 above) was needed to achieve full system observability, for the total of 38 PMUs.
- PMU placement analysis for Event 10 showed that one additional PMU (e.g., in addition to 37 PMU locations in item 3 above) was needed to achieve full system observability, for the total of 38 PMUs.

Key Customer Monitoring: Airport Observability Analysis Study

- Chicago Airport area consists of critical customers
- ComEd has carried out observability analysis and PMU placement study to assess the PMU infrastructure required for complete observability of key customers in the area
- Airport area consists of Networked and Radial circuits
- The 6 feeders which supply the core airport 480 V bus (in “Networked” configuration) from two substations
- The 19 feeders arranged in radial configuration (the “Radial” circuit) feeding areas around the airport
- 6 Networked feeders require 72 PMUs for complete observability in base case operation
- 19 Radial feeders require 98 PMUs for the complete observability in base case operation

PMU Placement Study on One Feeder



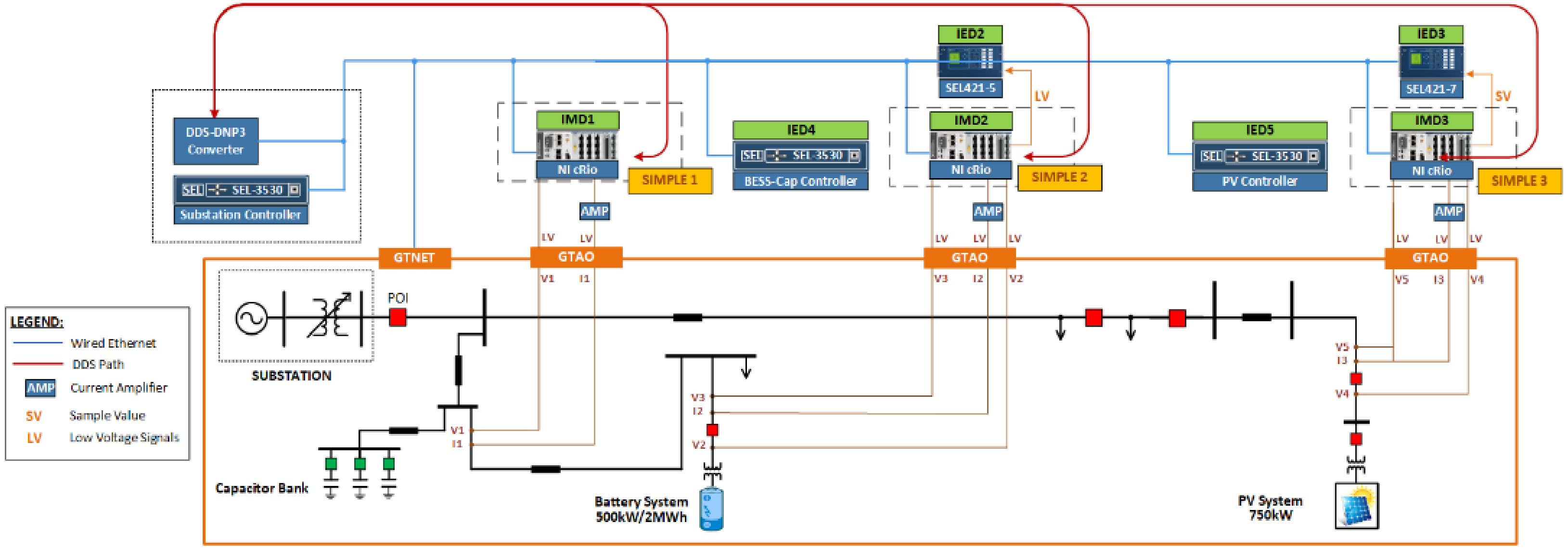
SIMPLE (Sensors with Intelligent Measurement and Low-cost Equipment)

Budget: $2.7M DOE Project

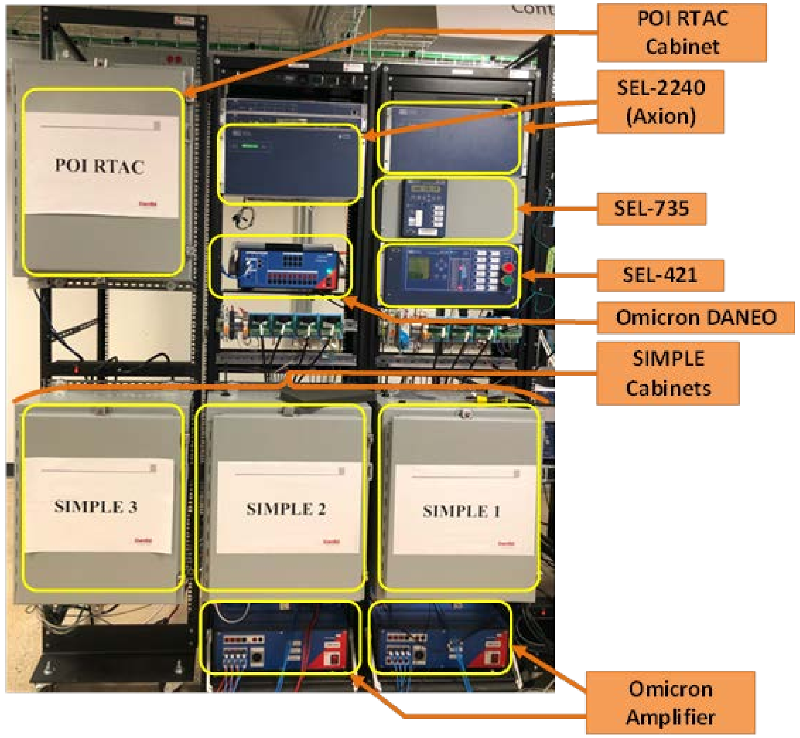
Objective: Development and introduction of voltage/current sensors with enhanced characteristics (accuracy, bandwidth and harmonic range) and high measurement granularity for medium voltage distribution system monitoring, DER monitoring, protection, and controls

Use Cases:

1. Distribution Circuit Monitoring (DCM)
2. Automatic Resource Control (ARC)



HIL Testbed schematic



HIL laboratory test setup

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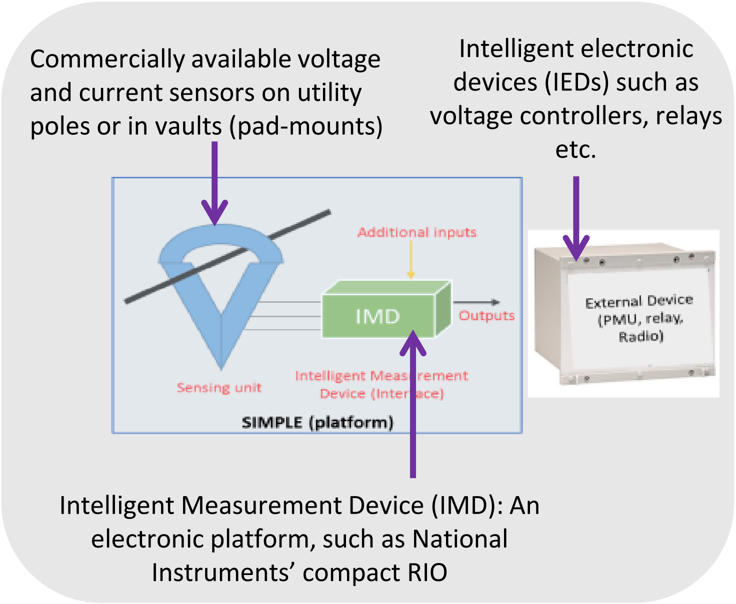
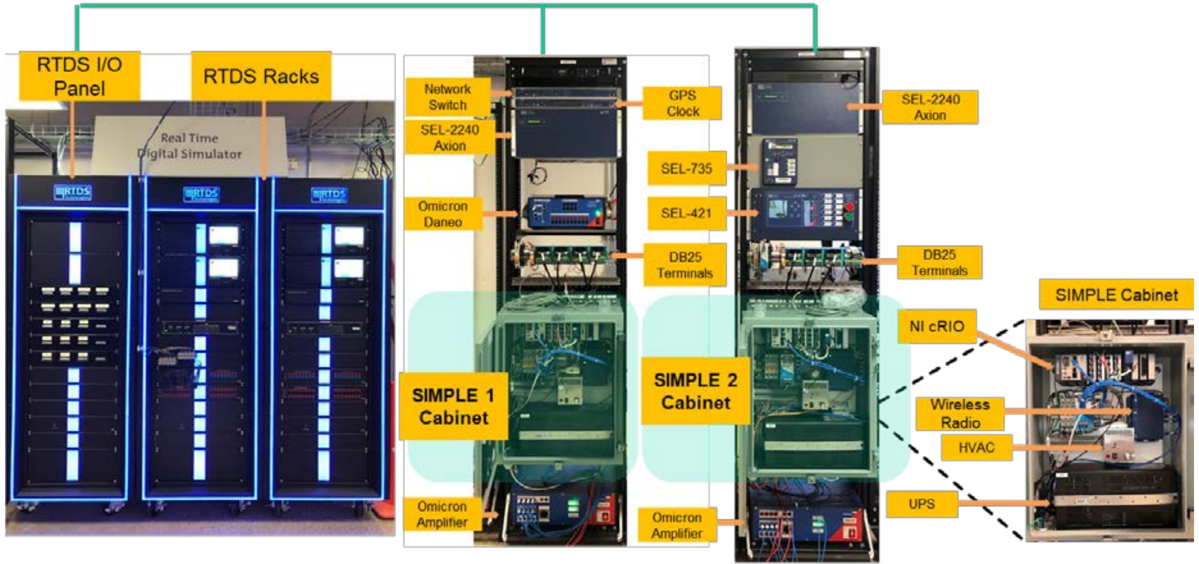
Sensors with Intelligent Measurement Platform and Low-Cost Equipment (SIMPLE)

- $2.69M Project with $1.50M Fed Share (DOE grant) to develop and demonstrate voltage/current sensors with enhanced characteristics (accuracy, bandwidth and harmonic range) for medium voltage distribution system monitoring, DER monitoring, protection, and controls
- 3 SIMPLE prototypes were successfully developed, and extensive testing done in ComEd's Grid Integration & Technology Lab, followed by demonstration of technology feasibility for medium voltage applications
- Deployed three SIMPLE units and communication equipment for field testing in Bronzeville area
- Field demonstration completed in 2020
- **Duration**: October 1, 2017 – December 31, 2020
- **Partners**: ComEd (lead); Quanta Technology; NuGrid; Illinois Institute of Technology





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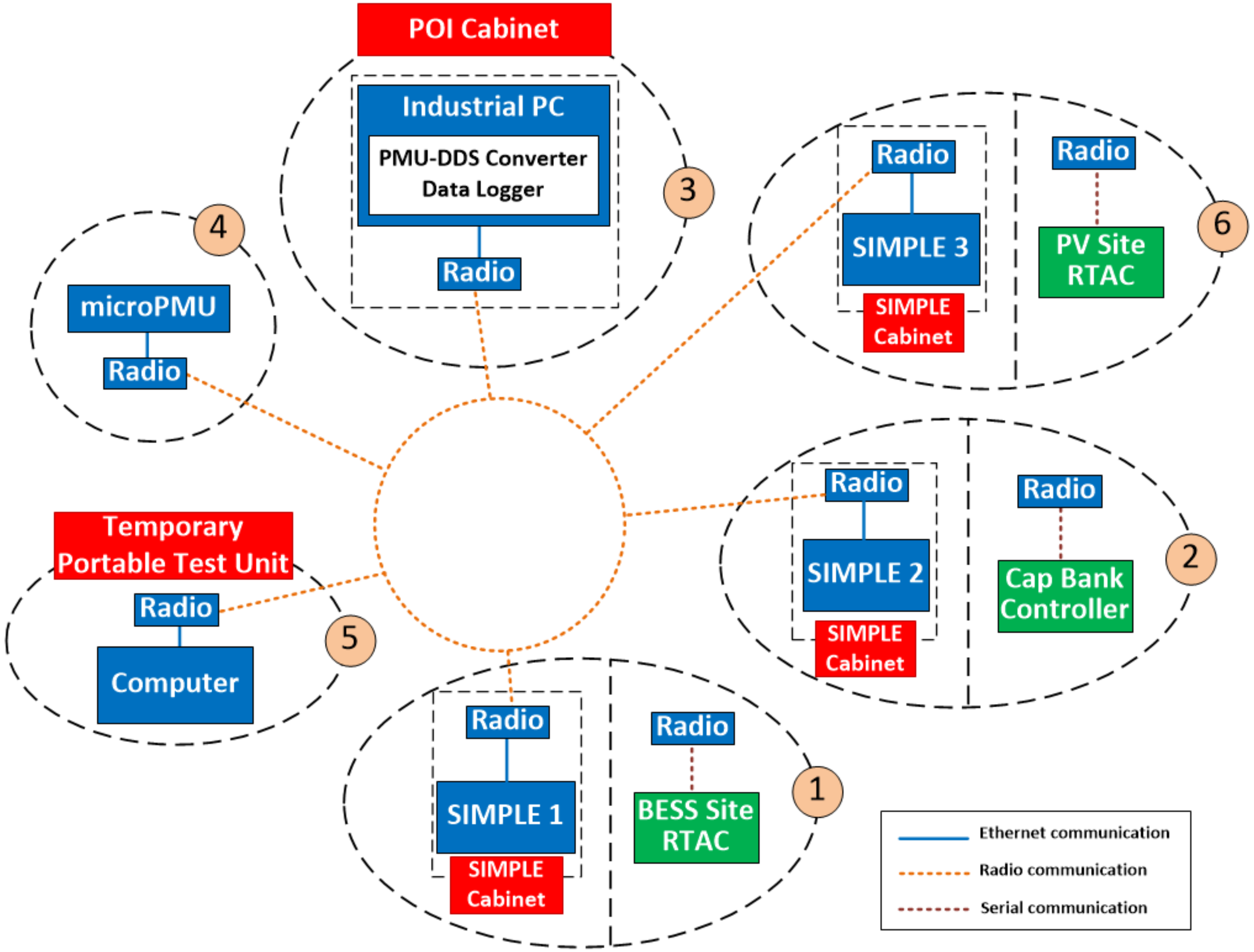
SIMPLE – Field Architecture



SIMPLE 1, SIMPLE 3 and the POI cabinet

SIMPLE 2 and MVCAL Cabinet

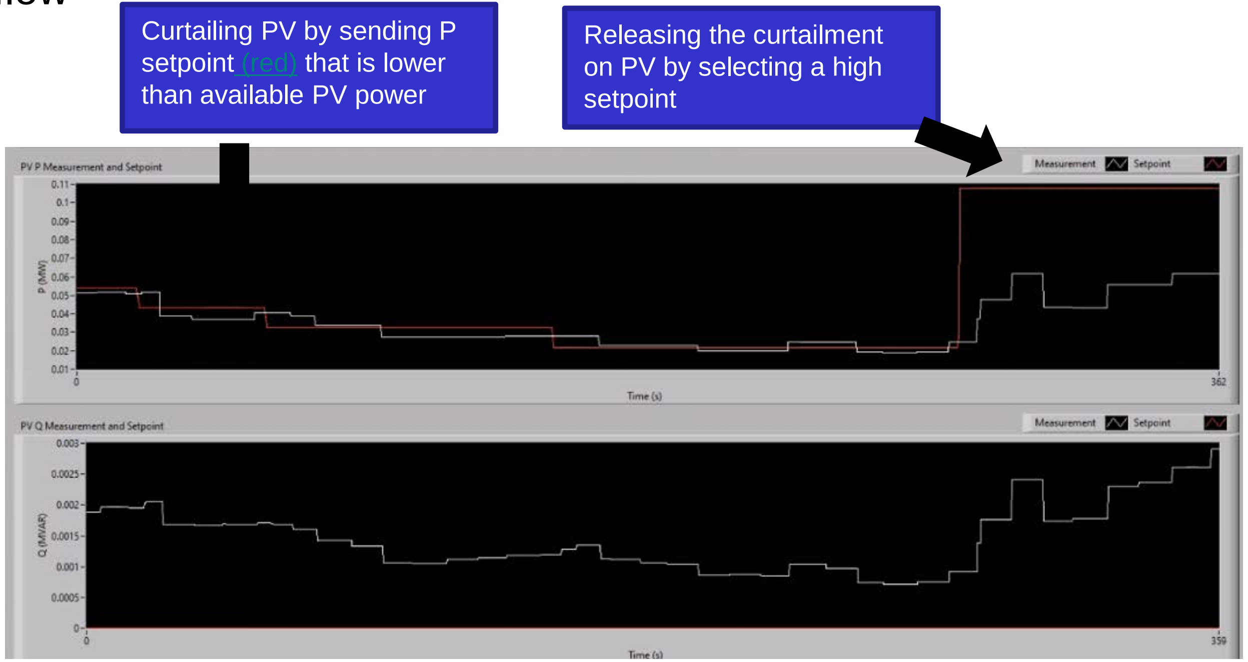
SIMPLE: Field Demonstration Use Cases

Use Case 1: Distribution Circuit Monitoring (DCM)

a) Monitoring voltage and power flow across the distribution system
b) Obtain data for root-cause analysis, maintenance, and pre-event analysis

Use Case 2: Automatic Resource Control (ARC)

a) Manage operation of DERs with feeder-level devices to improve feeder voltage profile
b) Coordinated dispatch of DERs to manage feeder power flow



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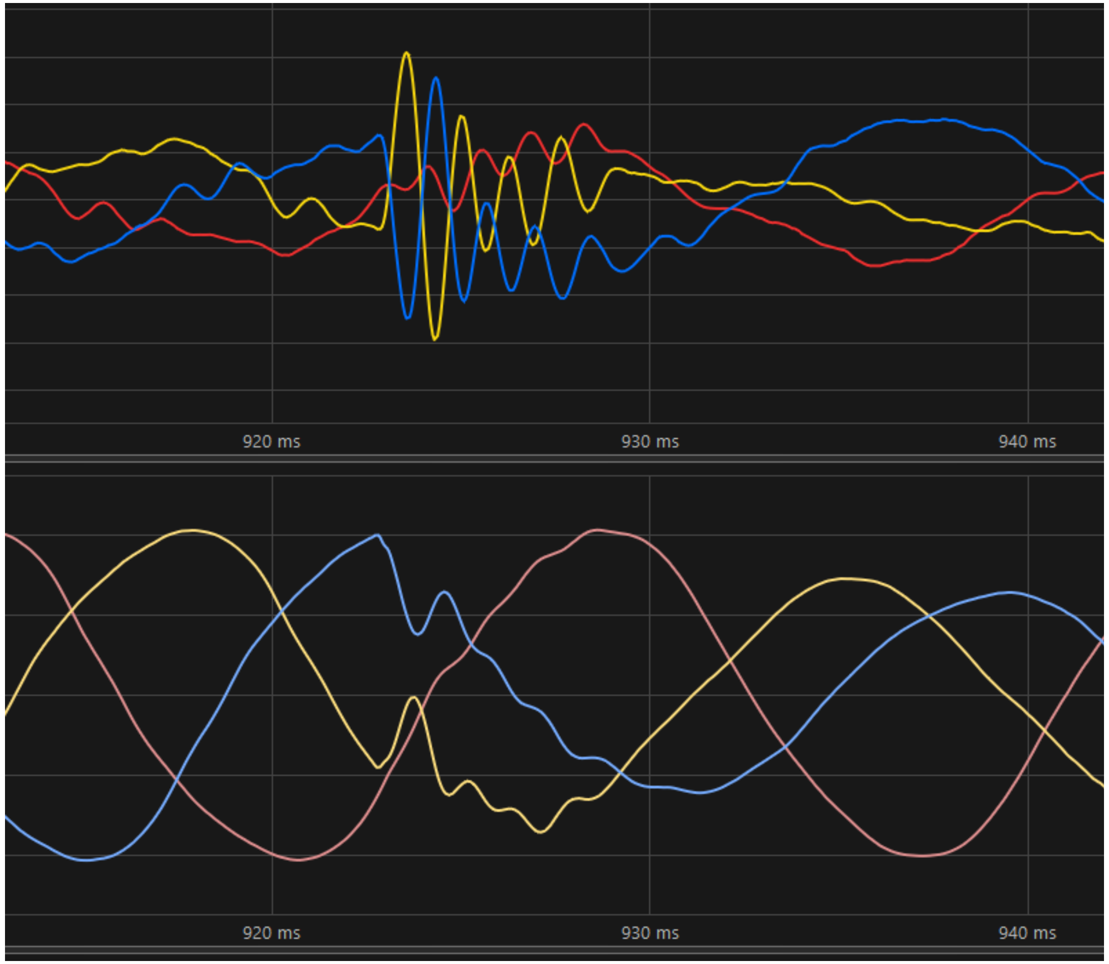
Lessons Learned

- Accurate labor forecasts are essential
  - Engineering for substation prints and designs
  - Internal substation crews
  - Internal testing engineers
  - Contracted resources
- Scheduling volatility
  - Critical feeders → hard to take outages
  - Normal work schedules
- Material availability
  - Long-lead items
  - Backorders and delays
  - Lost material

Roadmap and Next Steps

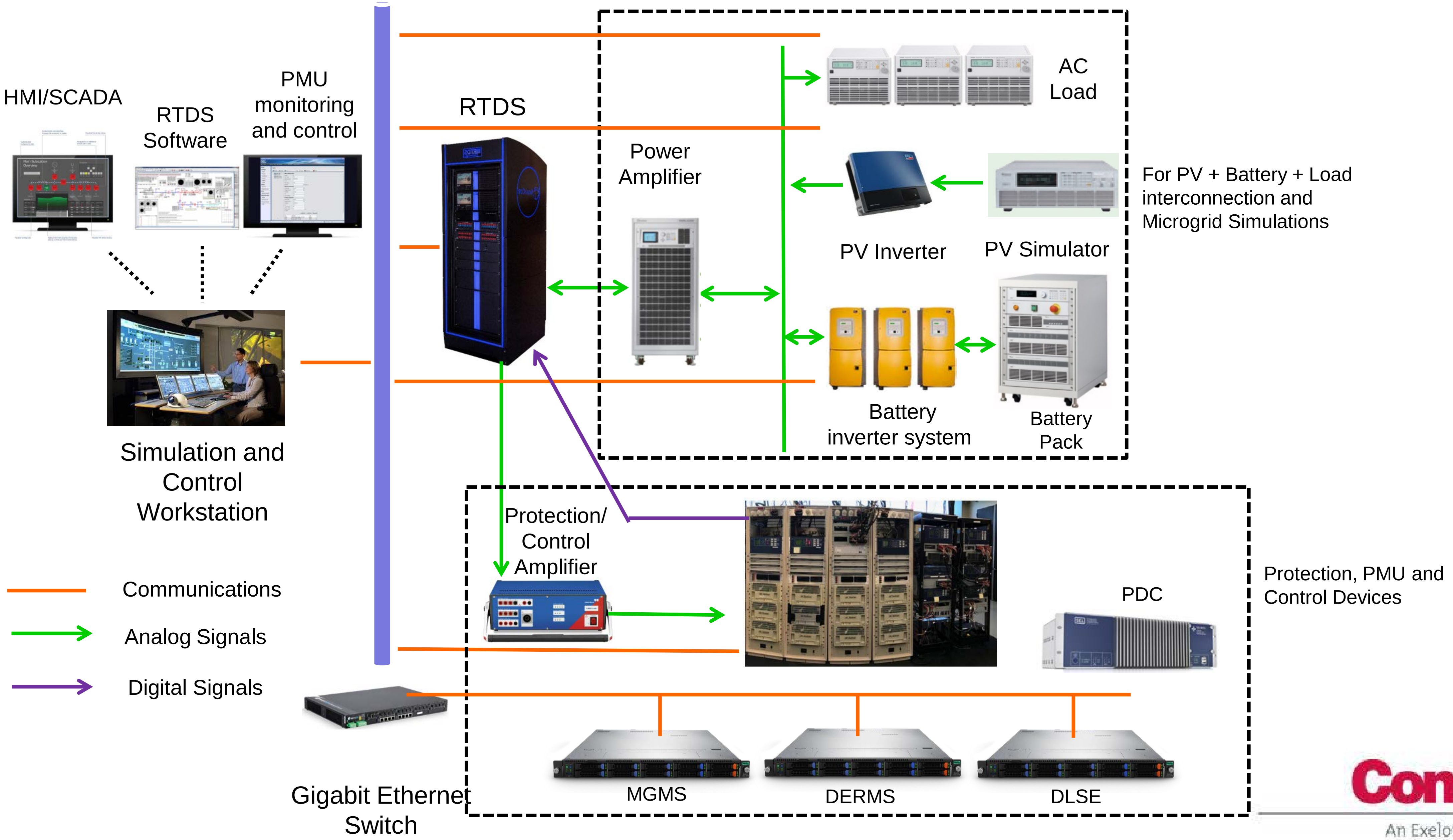
- Leverage point-on-wave data
  - o Predictive modeling
  - o Pre-event detection
- 5-year programmatic strategy
- Stream C37.118 data from capable DA devices
- Three-tiered approach
  - o Substation
  - o Distribution main-stem
  - o Feeder edge
- DLSE Field Deployment
- Grid Analytics Platform Pilot



THANK YOU!

Paul Pabst, P.E. | paul.pabst@comed.com
Heng (Kevin) Chen, P.E. | heng.chen@comed.com

ComEd Grid Integration and Technology (GrIT) Lab Architecture



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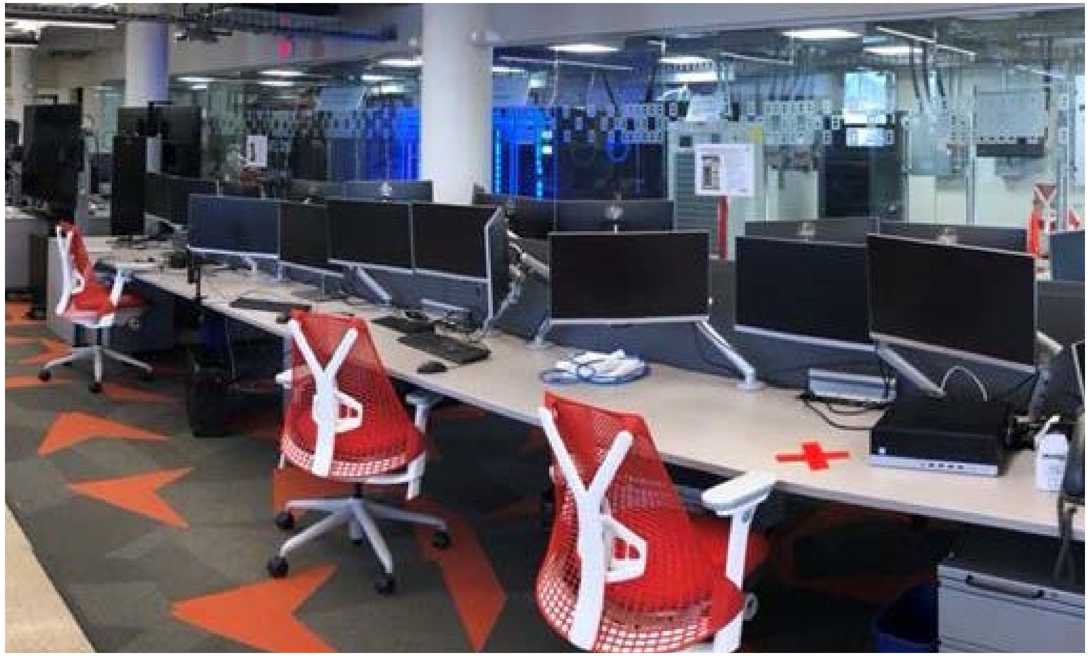
ComEd Grid Integration and Technology (GrIT) Lab



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Demonstrating Cutting-Edge Technologies

SHINES
- Awarded $4M to support the use of solar PV, Battery Energy Storage System, smart inverters and microgrid master controller to demonstrate microgrid integrated solar storage technology (MISST)

SIMPLE
- Awarded $1.5M to develop sensor platform with advanced features to support distributed energy resource (DER) penetration: Sensors with Intelligent Measurement Platform and Low-Cost Equipment (SIMPLE)

XFC EV
- Partnership with Virginia Tech to develop and test a cyber-secure extreme-fast charging (XFC) station for electric vehicle (EV) within the Bronzeville area
- 350kW XFC charger will be tested in ComEd lab

MUD EV
- Partnership with the Center for Sustainable Energy (CSE) to install EV charging stations serving multi-unit dwellings (MUD) and curbside charging needs in Bronzeville
- Will support the development of best practices for this type of program

Blockchain Technology
- Develop and test a blockchain-secured transactive energy and demand response platform
- Partnership with BEM Controls & Virginia Tech (VT)

FAST DERMS
- Develop and demonstrate a federated architecture – FAST-DERMS with management of both utility-scale and small-scale DERs
- For reliable, resilient, and secure distribution and transmission grid services

CITADELS
- Enable networked microgrids (NMG), and their component DERs, to operate distributedly using collaborative autonomy concepts implemented in an OpenFMB (Open Field Message Bus) architecture.

ENERGISE
- Demonstrate cost-effective integration of behind the meter PV by utilizing Battery Energy Storage and DER real time management system

BTM DER-AMI Integration
- Risk-informed Hierarchical Control of Behind-the-Meter (BTM) DERs with AMI Data Integration
- Helping advance integration, monitoring and control of increasing number of DER assets in electric power grid

Microgrid Master Controller

Completed (2018)
- Develop, design and test the microgrid master controller (MMC) capable of managing clustered microgrids.

SECURE
- A de-centralized Autonomous Control System (DAC) for Resilient Community Microgrids – The technology will be tested in ComEd lab
- Partnership with EPRI, NREL, GridScape, Yashaw Solectria Solar, ComEd, PG&E, Xcel, SCE

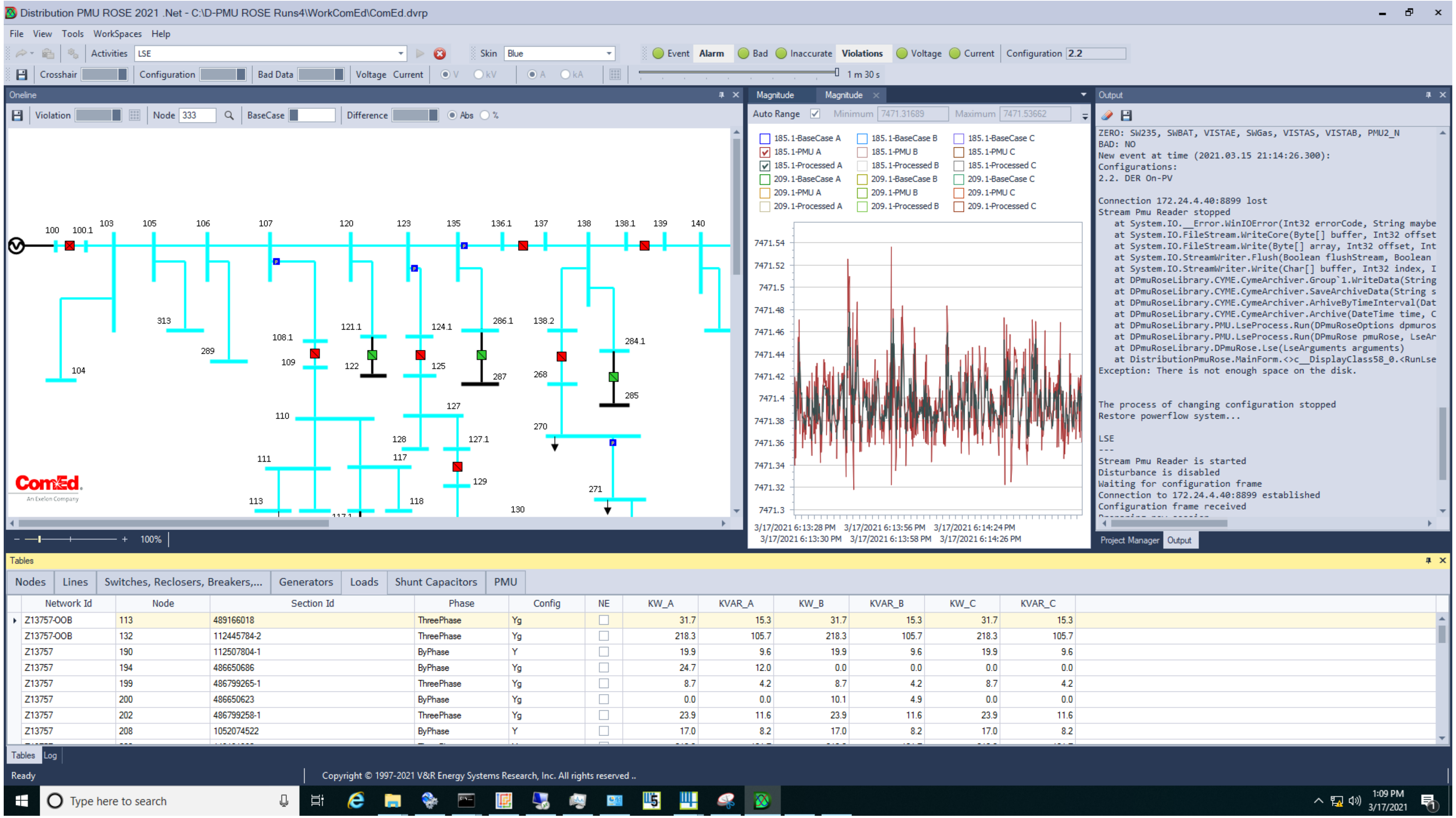
Hybrid State Estimation
- Partnership with Northeastern University to develop Graph-Learning-Assisted State Estimation method by utilizing the diverse set of existing data sources (SCADA, AMI, PMU, smart inverter, weather data) to improve system-wide situational awareness

Cyber Resilience Project
- In partnership with VT, GE Corp Research, use block-chain-based distributed control architecture to coordinate multiple hybrid solar PV plants to provide grid reliability and resilience services to cyberattacks

ABSCoRES*
- Partnership with Lehigh University, MIT, ANL and Siemens, to develop coherent asset and risk management framework in power systems with application of the method utilized by banking scoring and rating
- This is ARPA-e supported project

NOTE: *Participating in an advisory role with no budget commitment from ComEd

DLSE Version 2021



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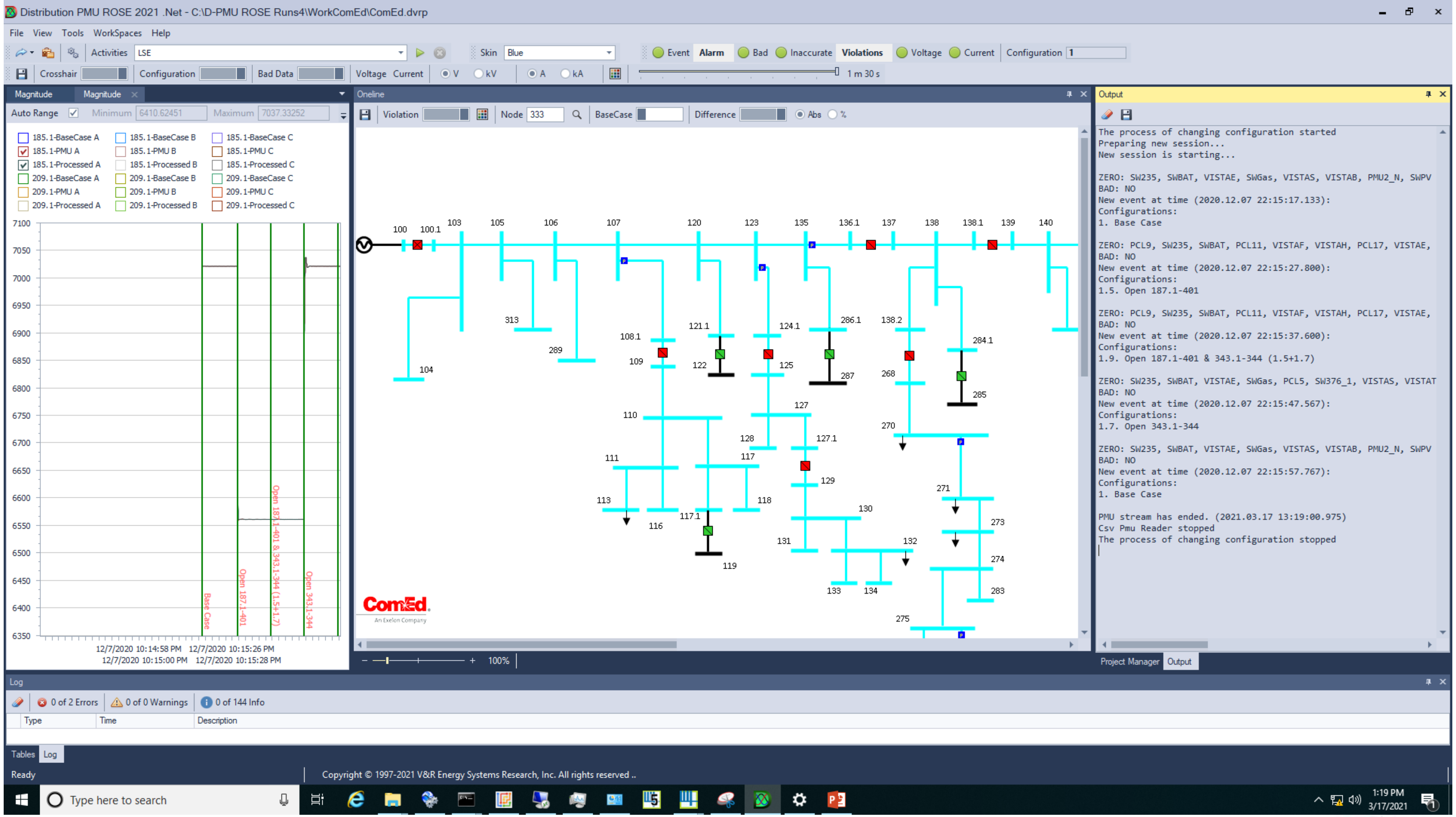
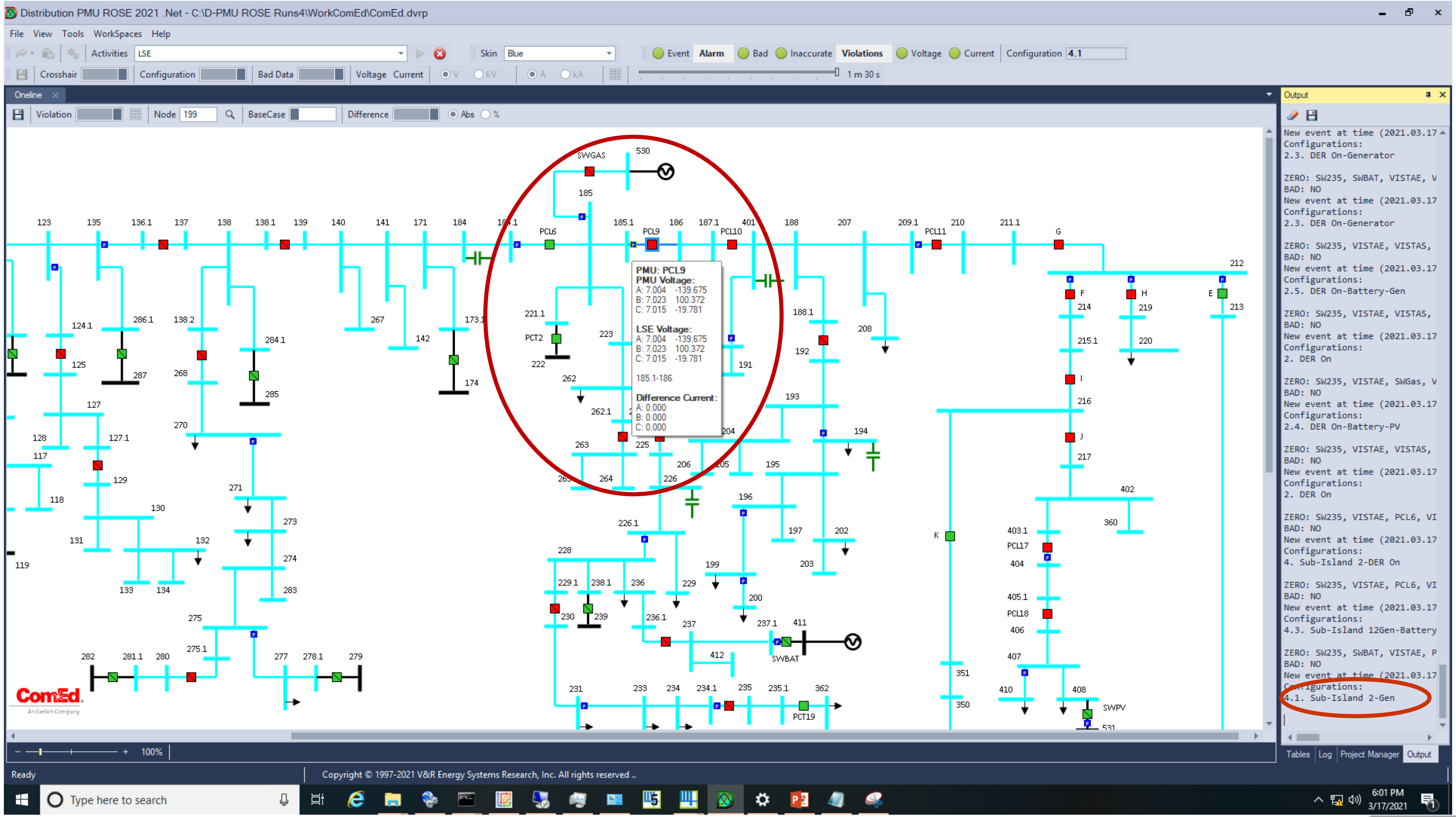
Topology Change Identification



DLSE Islanding

- DLSE detects the topology and the estimates accurately.



D-LSE Result – Estimated vs. Raw Data Visualization

- Yellow – raw PMU values
- Light Blue – estimated values after the LSE (filtering and weighted least square method)
- Estimated values of voltages and currents (for all phases) are also shown on single line diagram by placing mouse pointer over a node/branch

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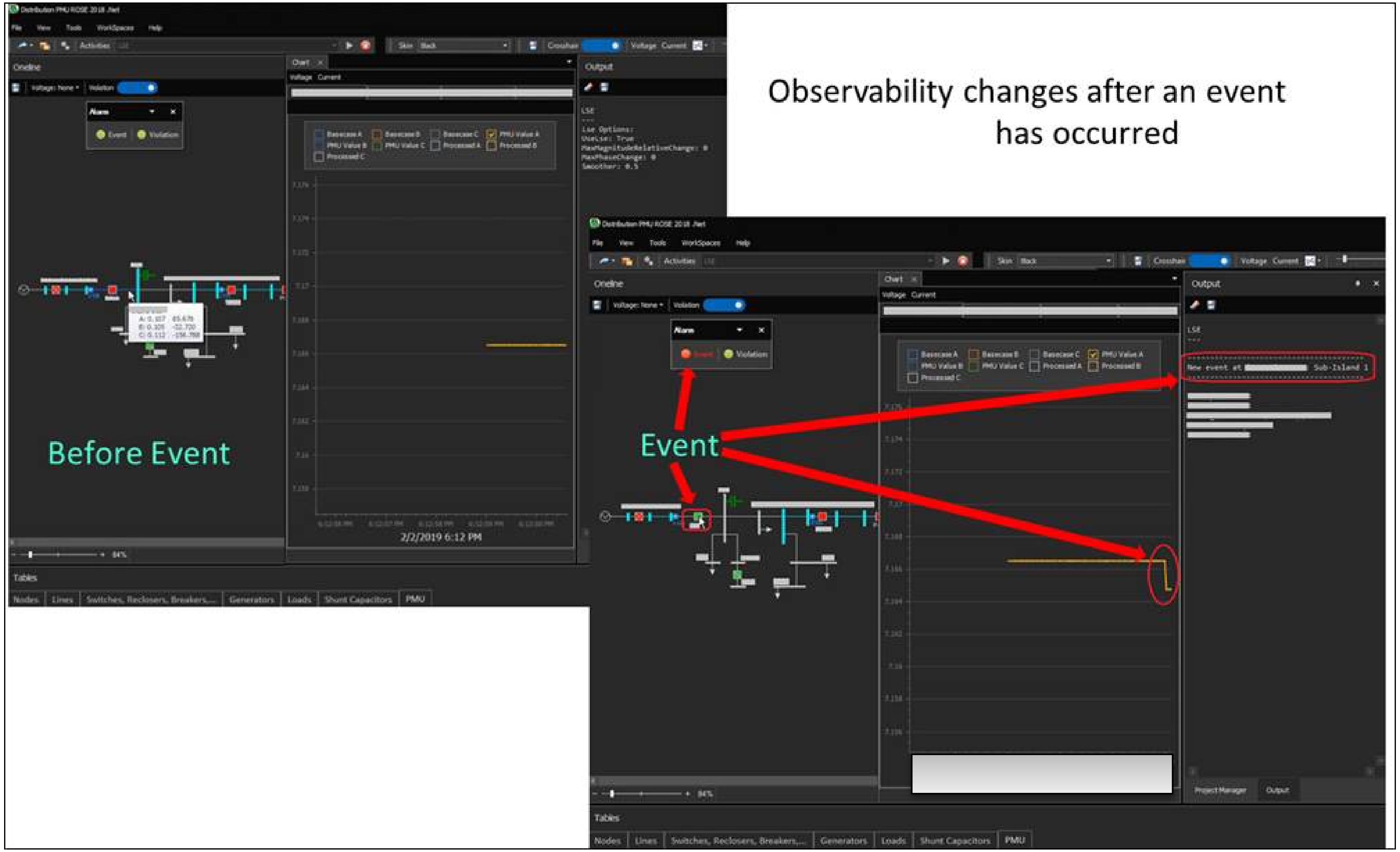
Detecting and Alarming on Switching Events



Paul Pabst, P.E.
Manager, Project Execution
Smart Grid & Technology

Kevin Chen, P.E.
Manager, Grid Strategy & Analytics
Smart Grid & Technology

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