U.S. DEPARTMENT of ENERGY

NASPI North American SynchroPhasor Initiative

APRIL 14, 2026

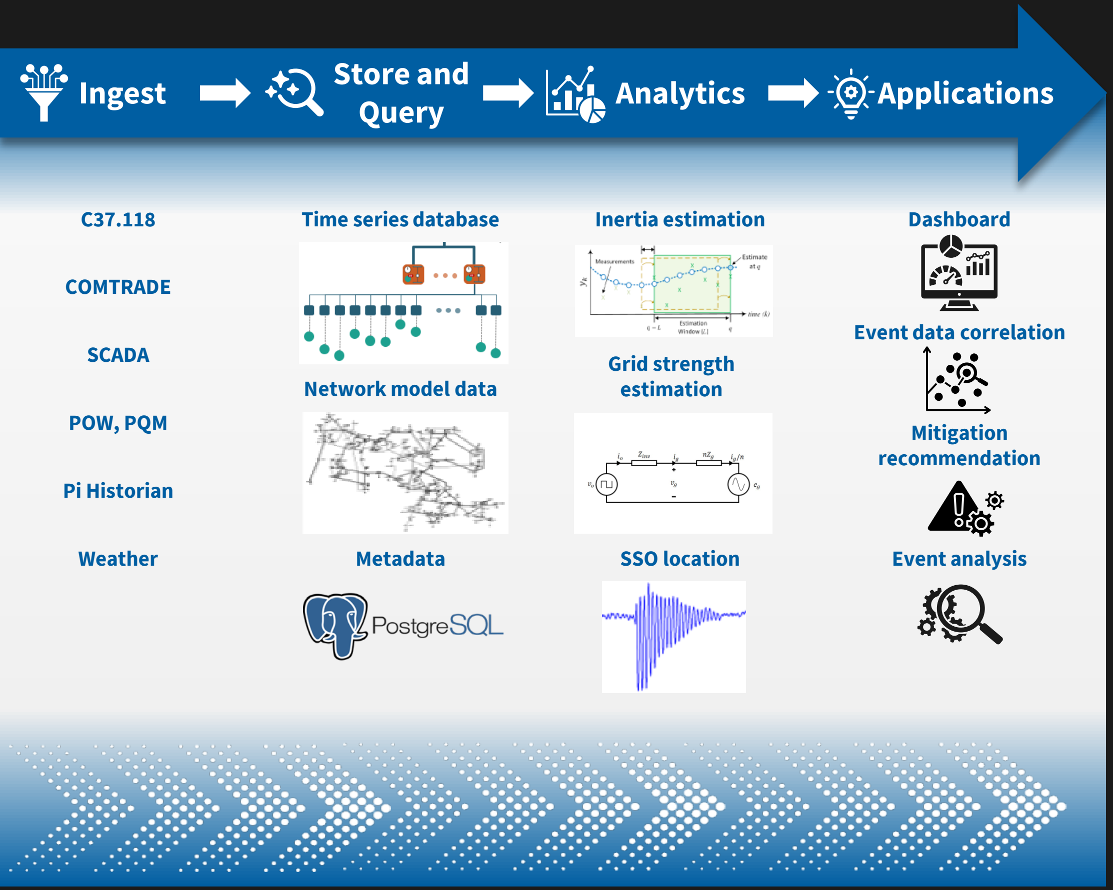
Grid Operator Analytics and Assessment Tools for Inverter-Based Resources Dominated Grid (GOAAT-IBR)

conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Required DOE Disclosures

Acknowledgment: "This material is based upon work supported by the U.S. Department of Energy's Office of Critical Minerals and Energy innovation (CMEI) under the Integrated Energy Systems Office (IESO) Award Number DE-EE0011375."

Grid Operator Analytics and Assessment Tools for Inverter-Based Resources Dominated Grid (GOAAT-IBR)



Key Technical Goals:

- Interactive dashboard visualizing system health in real time, e.g., grid inertia, IBR related sub-synchronous oscillations, and grid strength.
- Disturbance event correlation and curated datasets for post-event analysis.
- Real-time mitigation recommendation.
- Automated event analysis and report generation.

Key Technical Approaches:

- Cloud-based time-series platform for ingesting diverse sensor streams and performing analytics.
- Rigorous lab sensor hardware-in-the-loop prototyping and validation.
- Field demonstration on Entergy's system.

Unique Perspectives:

- Practical, scalable, innovative real-time solutions with a clear path to commercialization.
- A diverse project team.
- Leveraging extensive existing PMU data from Entergy's system.

Budget:

- Total budget: $5,280,184.
  - Federal funds: $3,826,341.
  - Cost-share: $1,453,843.

conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Overall Project Plan (BP-1, BP-2, BP-3)

BP-1 objective

1. Complete development of all software modules.
2. Determine whether data analytics algorithms meet expected performance using simulated or historical data.
3. Set up 43 live sensor streams in the RTDS lab.
4. Set up PingThings platform and cloud environment in the test lab.
5. Plan field sensor deployment.

BP-2 objective

1. Complete the GOAAT prototype that operates with real-time simulation and lab hardware sensors (meeting performance targets).
2. Develop a detailed plan for the BP-3 demonstration and deploy any additional hardware sensors at the demonstration utility.
3. Deploy field sensors.

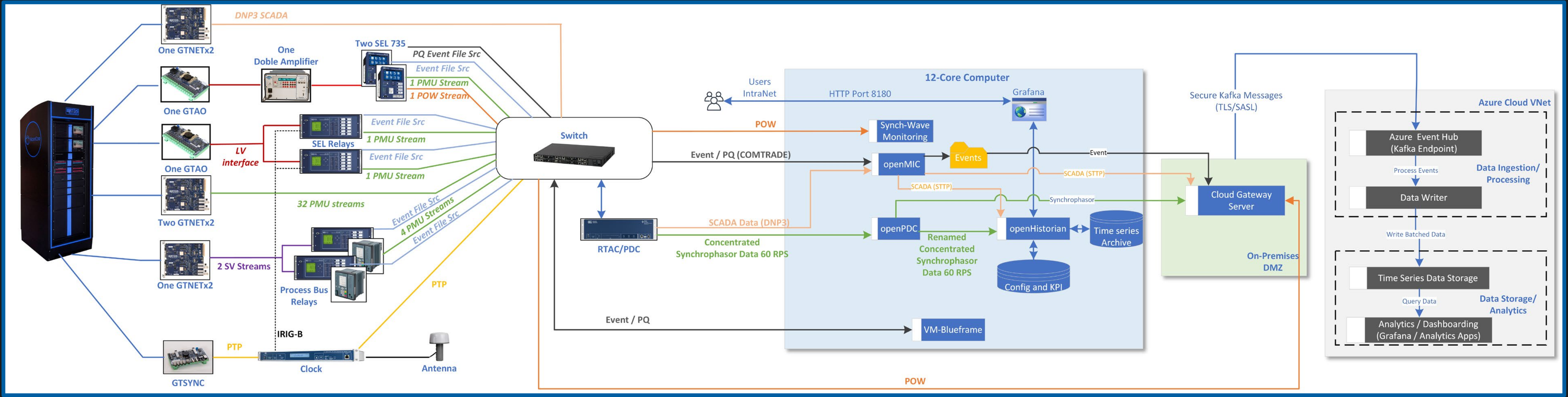
BP-3 objective

1. Deploy GOAAT at the demonstration utility.
2. Operate GOAAT with live sensor streams.
3. Demonstrate that GOAAT meets all performance targets.
4. Complete a techno-economic analysis for commercialization.

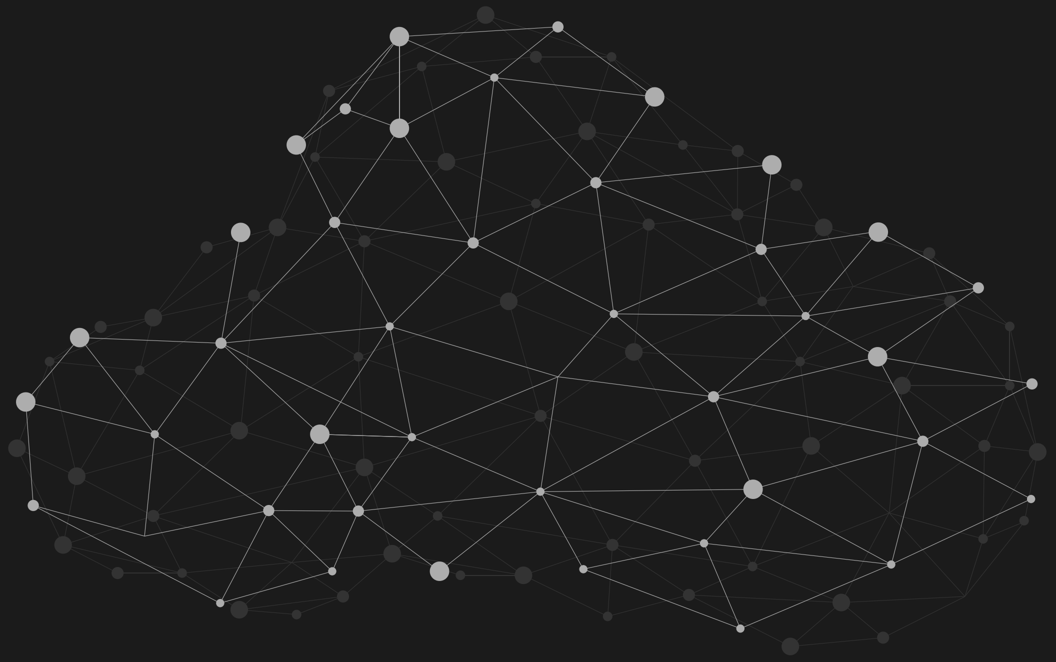
Sensor Hardware Lab Setup

Sensor hardware-in-the-loop simulation of the IEEE 14-bus system:

- One generator and three synchronous condensers
- Three IBR plants modeled (one black-box GTSOC model and two generic models).

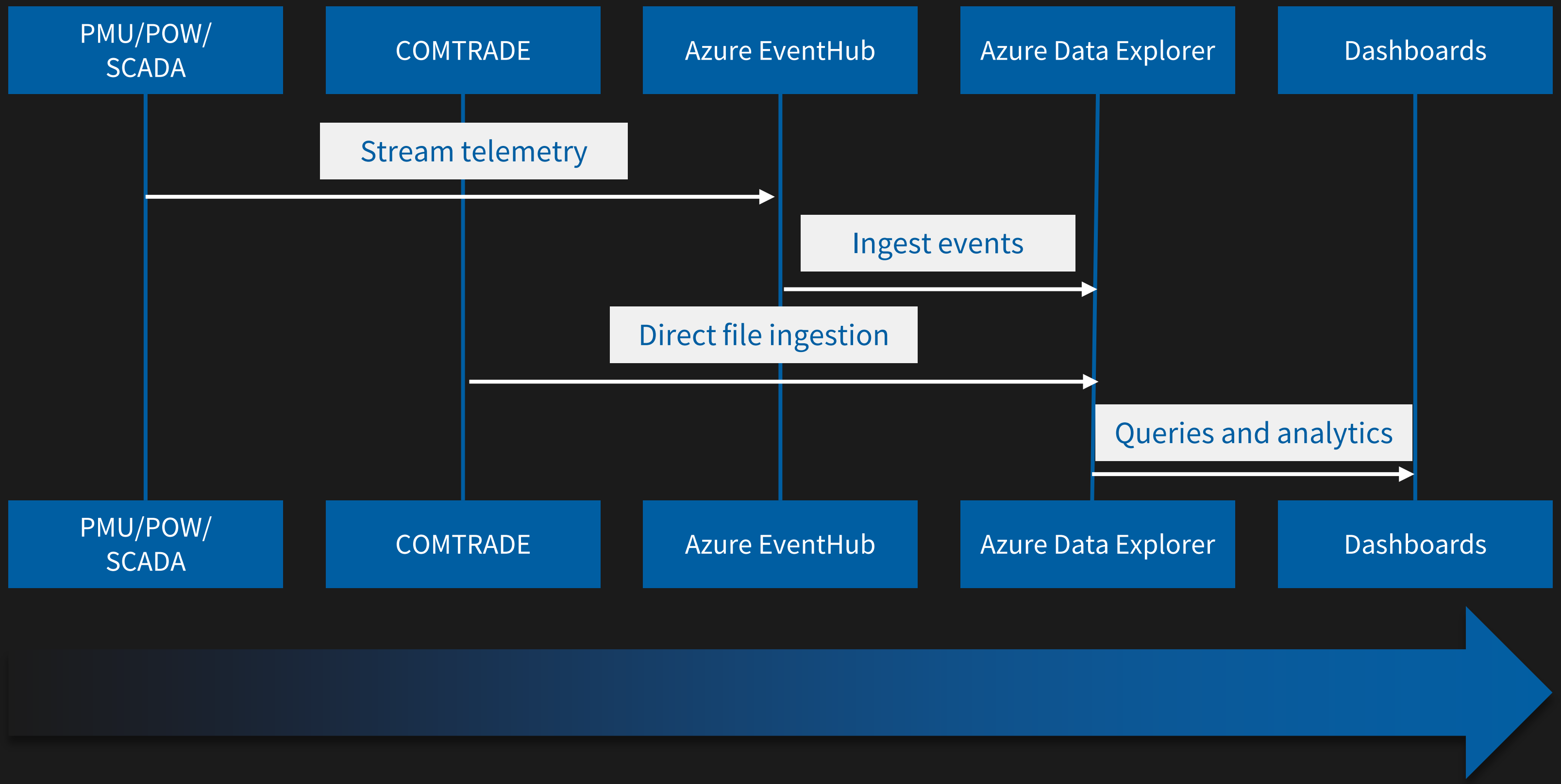


Cloud-native Data Platform



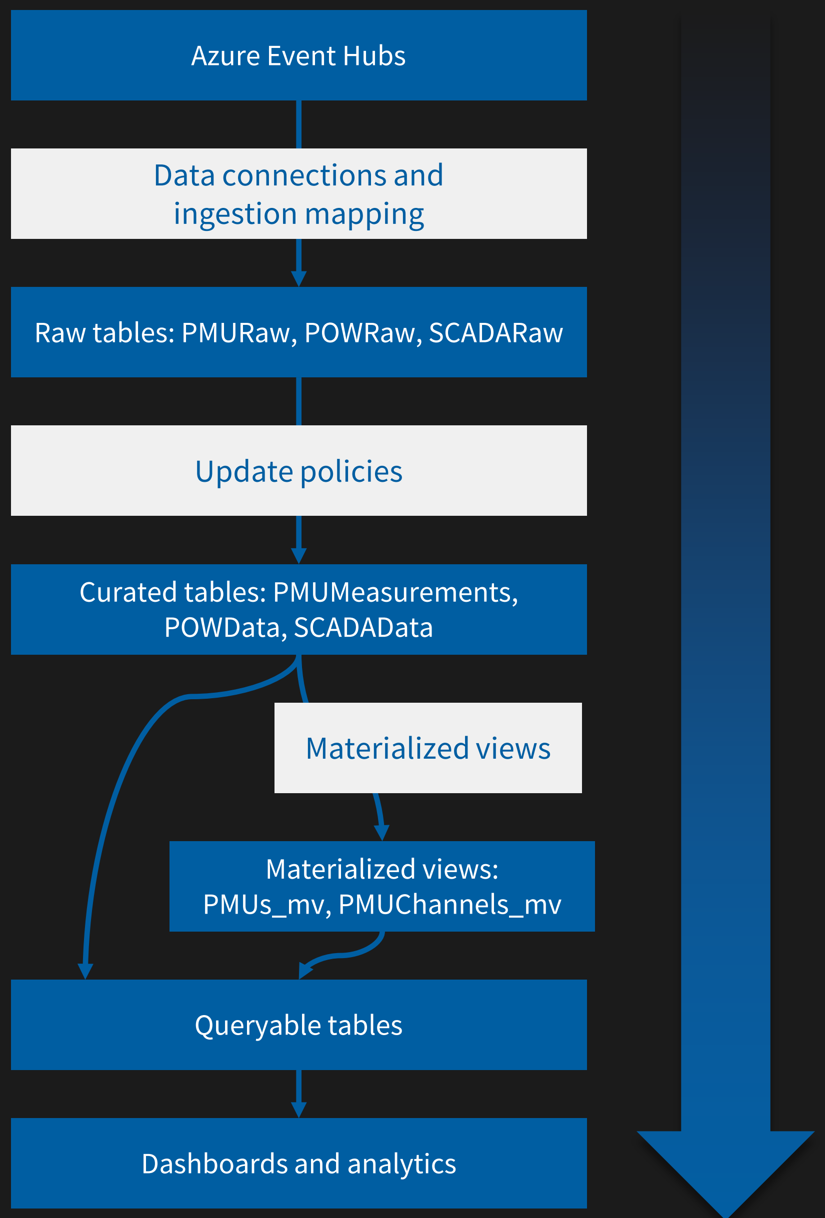
conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Data Flow

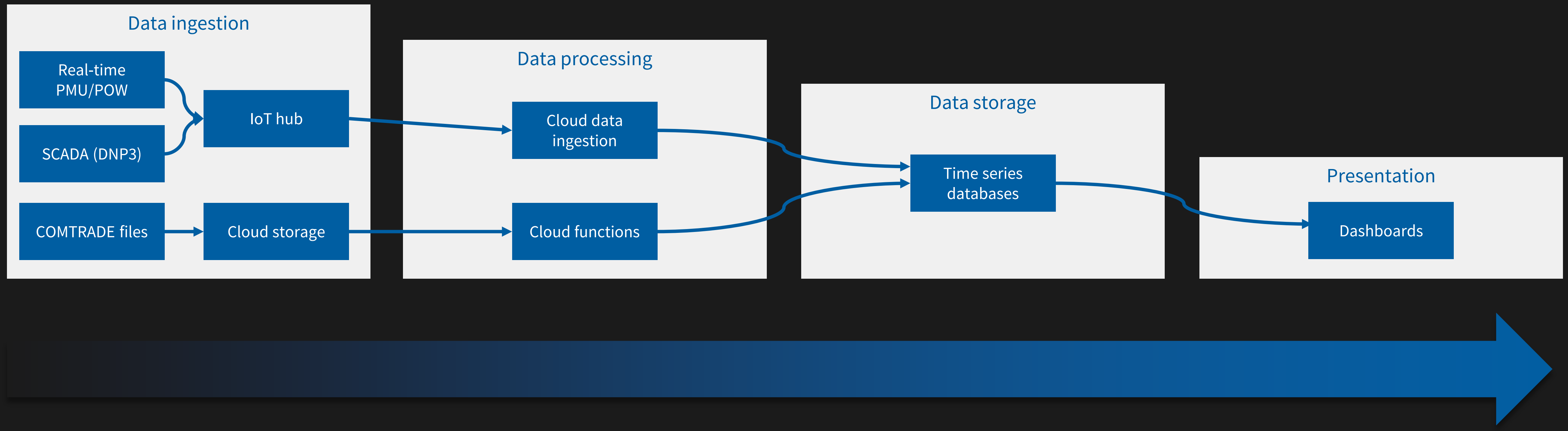


PMU/POW/ SCADA
COMTRADE
Azure EventHub
Azure Data Explorer
Dashboards
Stream telemetry
Ingest events
Direct file ingestion
Queries and analytics
PMU/POW/ SCADA
COMTRADE
Azure EventHub
Azure Data Explorer
Dashboards

IoT Data Processing in the Cloud



Data Ingestion and Processing



Cloud Estimates – PMU Data Assumptions

Data volume assumptions

Based on current system configuration (39 PMUs at 60 fps):

Metric	Value
Data per PMU per second	1.61 KB × 60 frames per second = 96.6 KB/sec
Data per PMU per day	8.35 GB/day
Total data per day (39 PMUs)	325.6 GB/day
Total data per month	~9.77 TB/month
Events per day	39 × 60 × 86,400 = 202.2M events/day

Cloud Costs Estimates – Costs by Service

Note: Costs vary based on actual data volumes, retention policies, and Azure pricing changes. Use the Azure Pricing Calculator for precise estimates.

PMU event hub data

Component	Calculation	Daily Cost	Monthly Cost
Throughput units	4 TUs × $0.03/hour × 24h	$2.88	$86
Event ingress	202.2M events × $0.028/M	$5.66	$170
Data ingress	325.6 GB × $0.10/GB	$32.56	$977
PMU Event Hub Total		**$41.10**	**$1,233**

Other services

Service	SKU	Monthly Cost
PostgreSQL	B_Standard_B1ms	~$25
App service	B1	~$13
Storage account	Standard LRS	~$5
Functions	Consumption	~$0 (pay per use)
ACR	Basic	~$5
Other Total		**~$48**

POW event hub device data

Component	Daily Cost	Monthly Cost
POW data (1 device)	~$5	~$150

ADX time series database

Component	Calculation	Monthly Cost
Compute (E4ads_v5, 2 nodes)	$24/day × 30	$720
Storage (9.77 TB ingested)	~$0.10/GB	~$977
ADX Total		**~$1,700**

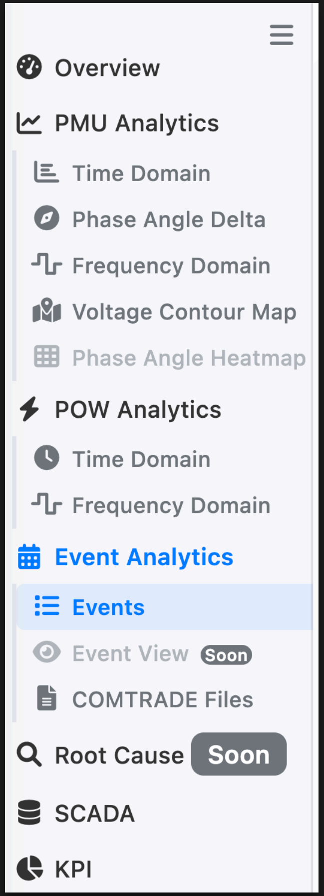
Total estimated monthly cost

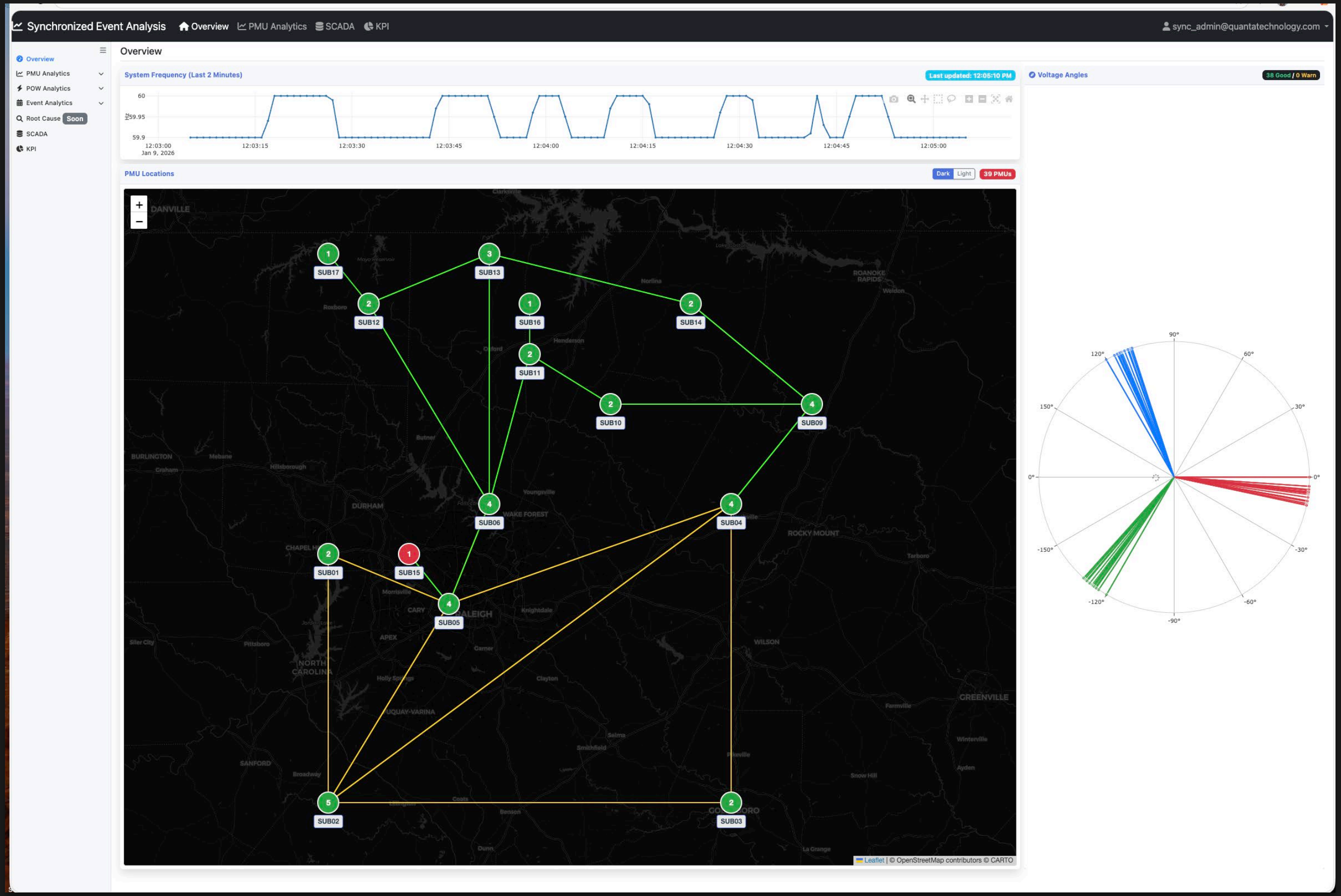
Category	Monthly Cost
Event hub (PMU + POW)	~$1,383
ADX (compute + storage)	~$1,700
Other Services	~$48
Grand Total	**~$3,131/month**

Data Analytics UI / UX

Graphical, Geospatial, and Tabular Visualizations

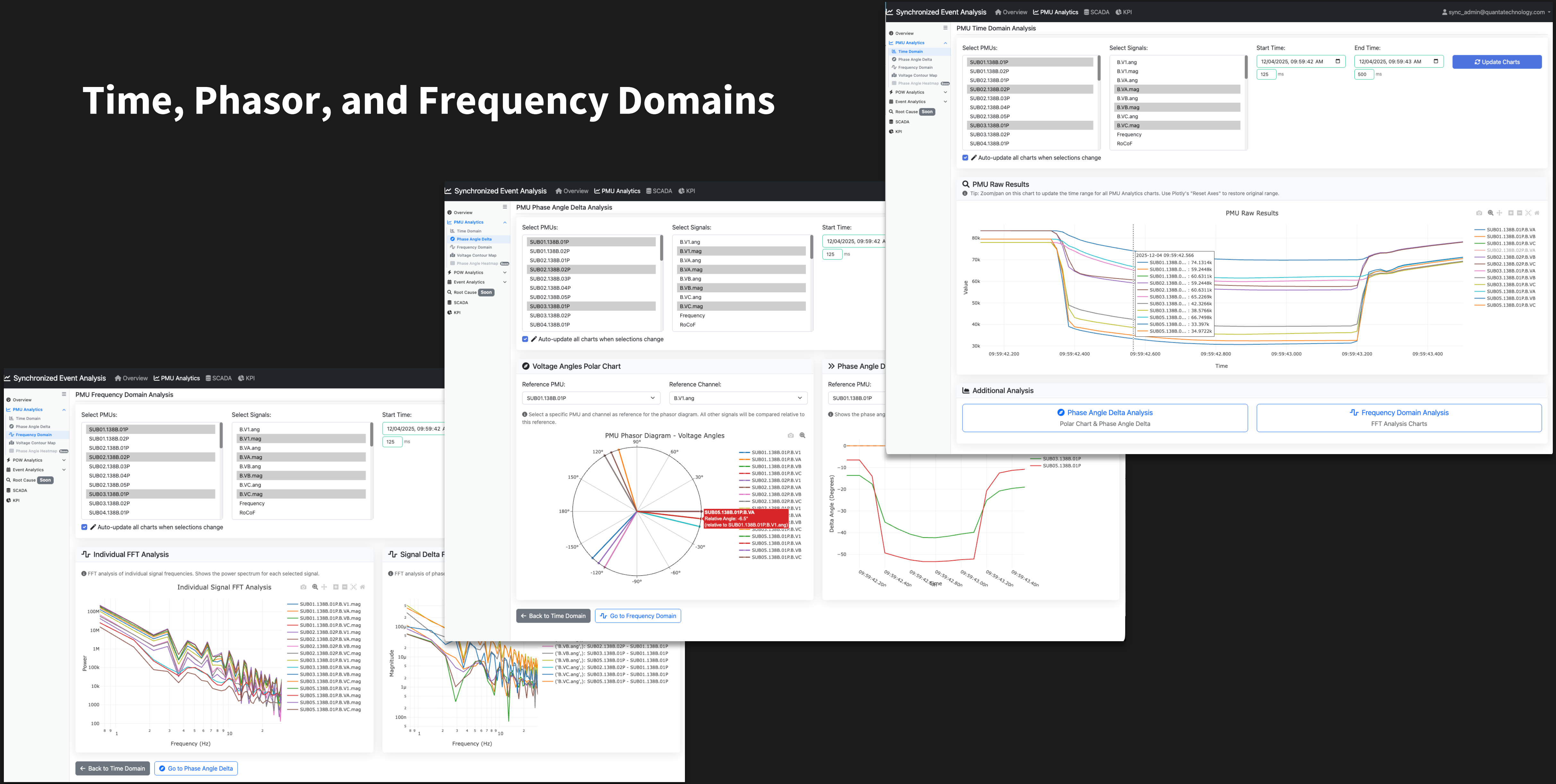
A cloud-based web application for analyzing PMU (phasor measurement unit), SCADA, PoW, and COMTRADE data stored in Azure Data Explorer (Kusto) time-series databases.





conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Time, Phasor, and Frequency Domains



conEdison

entergy

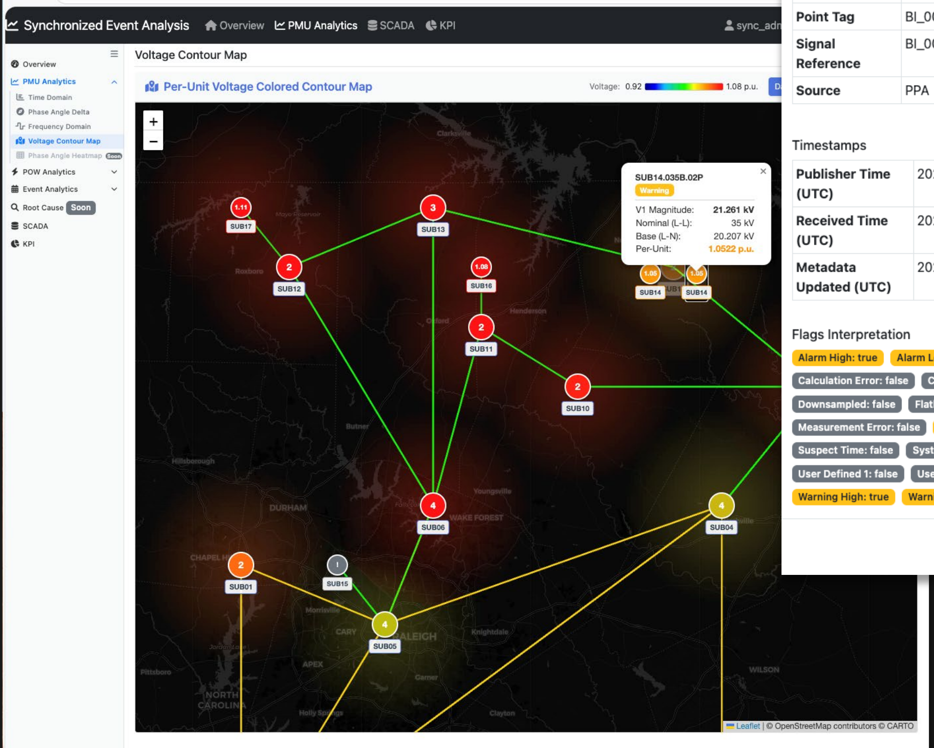
FPL

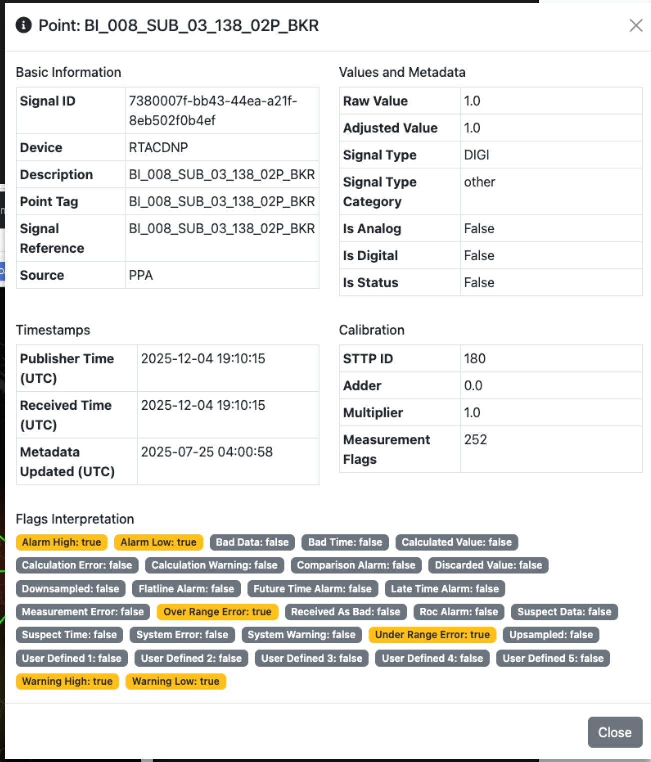
DANOVO ENERGY SOLUTIONS
A QUANTA SERVICES COMPANY

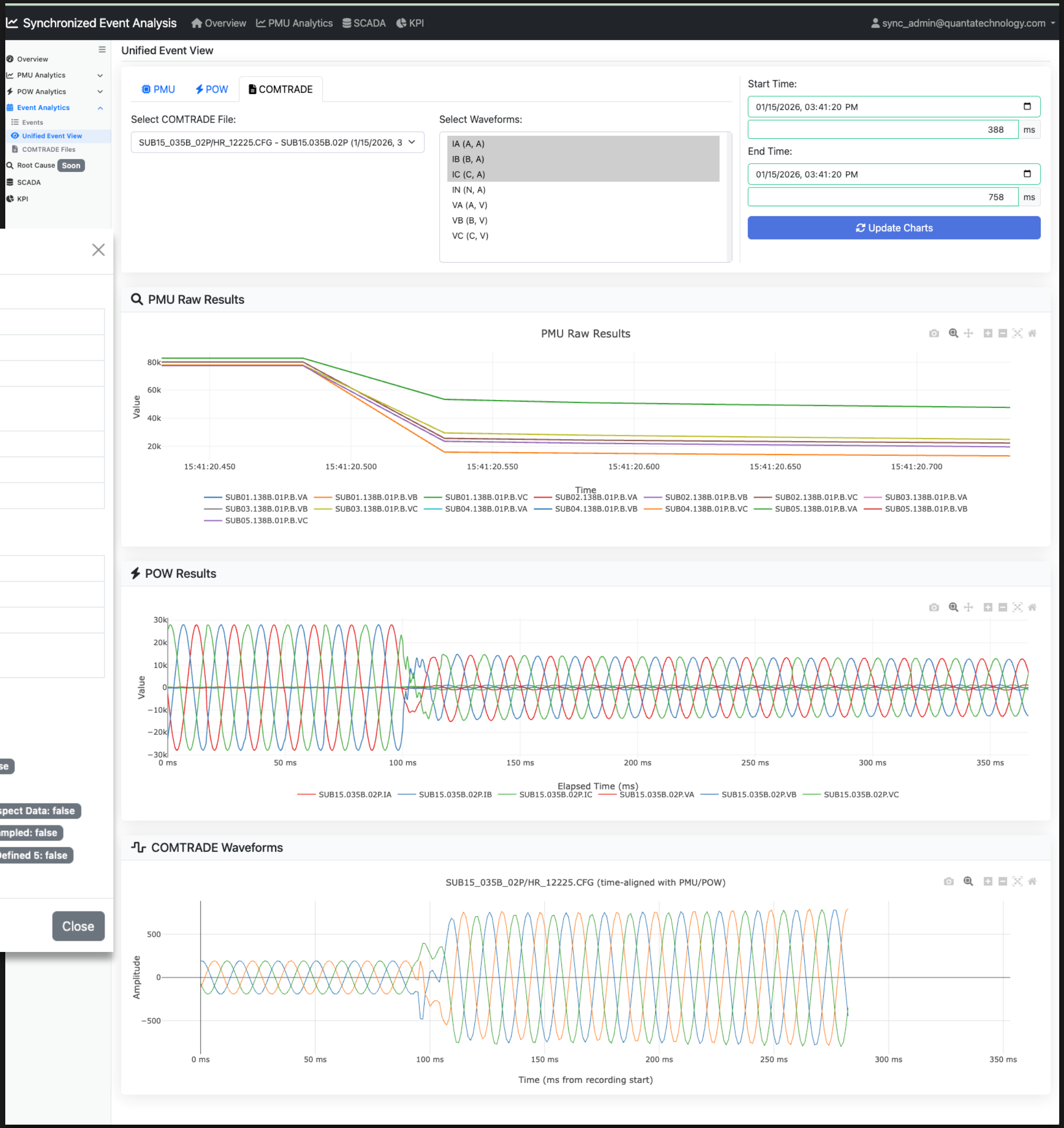
SRP

Sandia National Laboratories

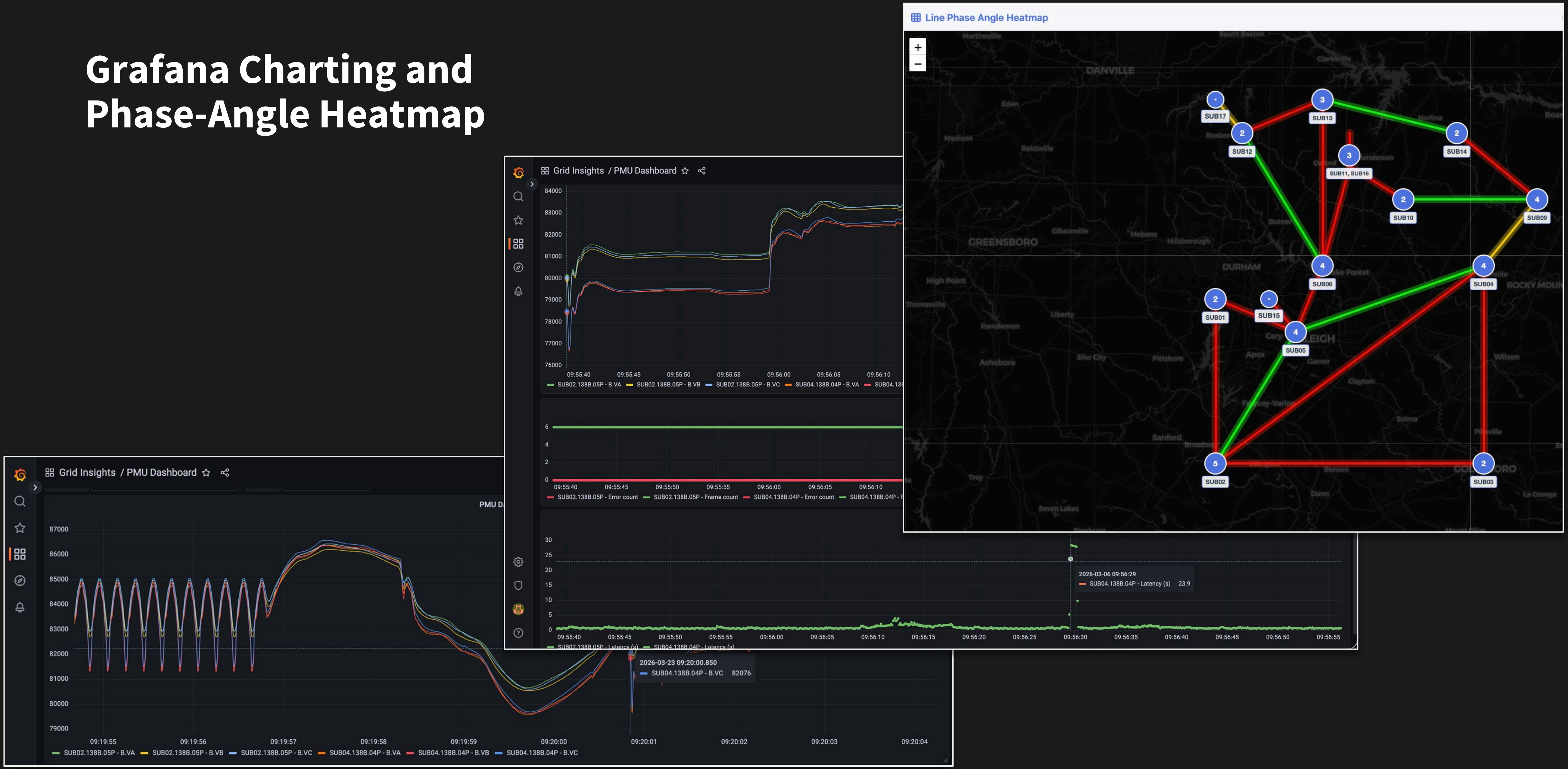
Unified Event View, SCADA, and Voltage Contour Maps







Grafana Charting and Phase-Angle Heatmap



conEdison
entergy
FPL
DANOVO ENERGY SOLUTIONS
A QUANTA SERVICES COMPANY
SRP
Sandia National Laboratories

Data vs. Information

Source: Mike Legatt, "Visualization, Situational Awareness, and Cyber-Physical Resilience in Real-Time Electric Power Operations," HTF55 Technical Presentation on Cyber Physical Assessment for Grid Resilience, 2025.

Situational Awareness?

Source: Mike Legatt, "Visualization, Situational Awareness, and Cyber-Physical Resilience in Real-Time Electric Power Operations," HTF55 Technical Presentation on Cyber Physical Assessment for Grid Resilience, 2025.

HOP instead of HPI

HPI — Human Performance Improvement is a structured approach focused on:

- Reducing human error
- Emphasizing procedures, checklists, and compliance controls
- Performing root-cause analysis after events
- Applying individual performance tools (self-checking, peer checks, three-way communication).

HOP — Human and Organizational Performance is a newer evolution that recognizes:

- Humans are not the problem — they are the solution in complex systems
- Errors are symptoms of system design, not just individual mistakes
- Focus on learning, adaptability, and real-world operational conditions
- Design systems that remain resilient under real-time operational pressure.

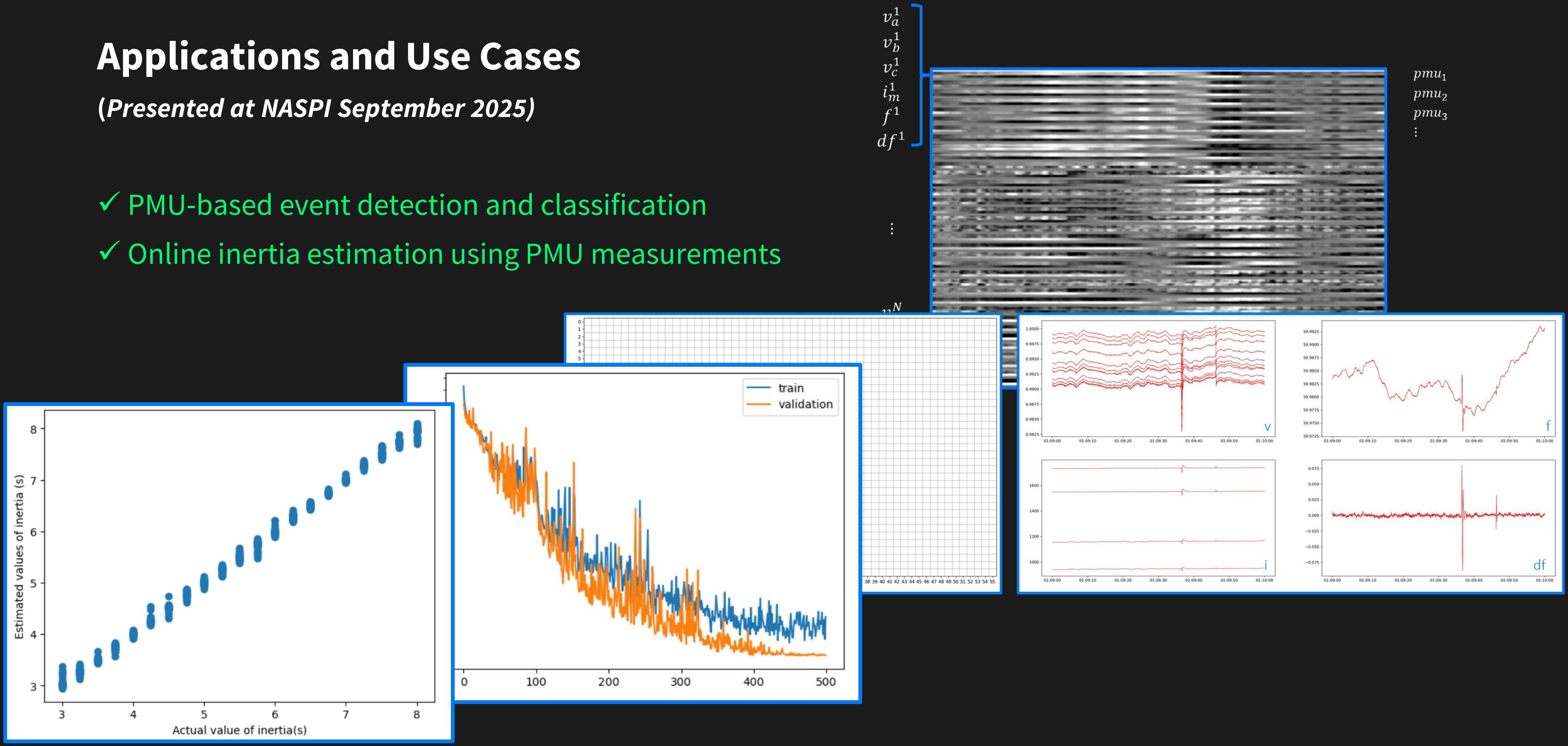
Data Analytics

Applications and Use Cases

(Presented at NASPI September 2025)

✓ PMU-based event detection and classification

✓ Online inertia estimation using PMU measurements



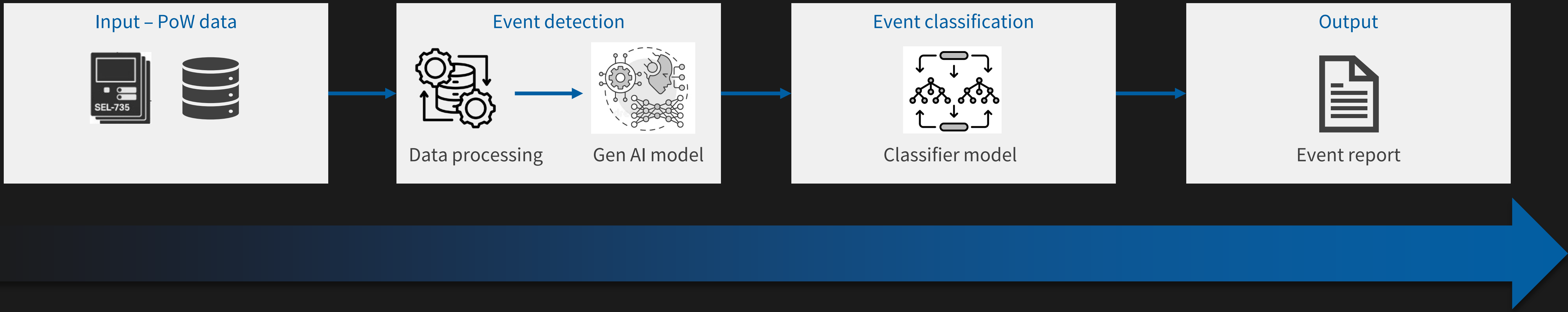
Applications and Use Cases

- ✓ Sub-synchronous oscillation (SSO) detection and source location

- ✓ PoW-based event detection and classification
- ✓ Online grid strength estimation (IBR aware)
- ✓ Deep event analysis and automated reporting

- ✓ PMU-based event detection and classification
- ✓ Online inertia estimation

PoW-based Event Detection and Classification

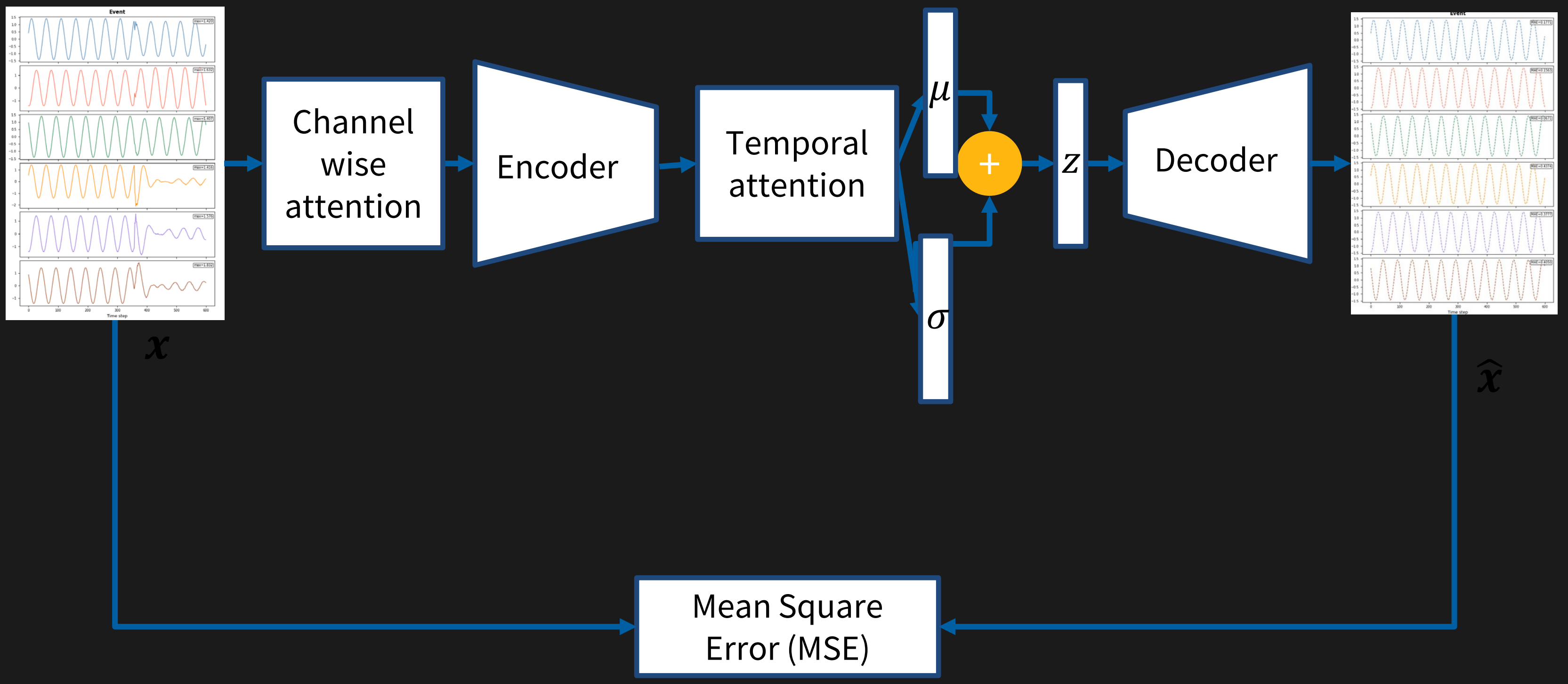


The proposed framework is a **two-stage framework:**

1. **Event detection:** Generative AI-based convolutional autoencoder.
2. **Event classification:** Random Forest classifier.

PoW-based Event Detection and Classification

Model details



Input

- PoW waveform data represented as time-series signals.

Model

- Encoder extracts features and generates **latent representations.**
- Latent vector ***z*** is used by the decoder to **reconstruct the input waveform.**

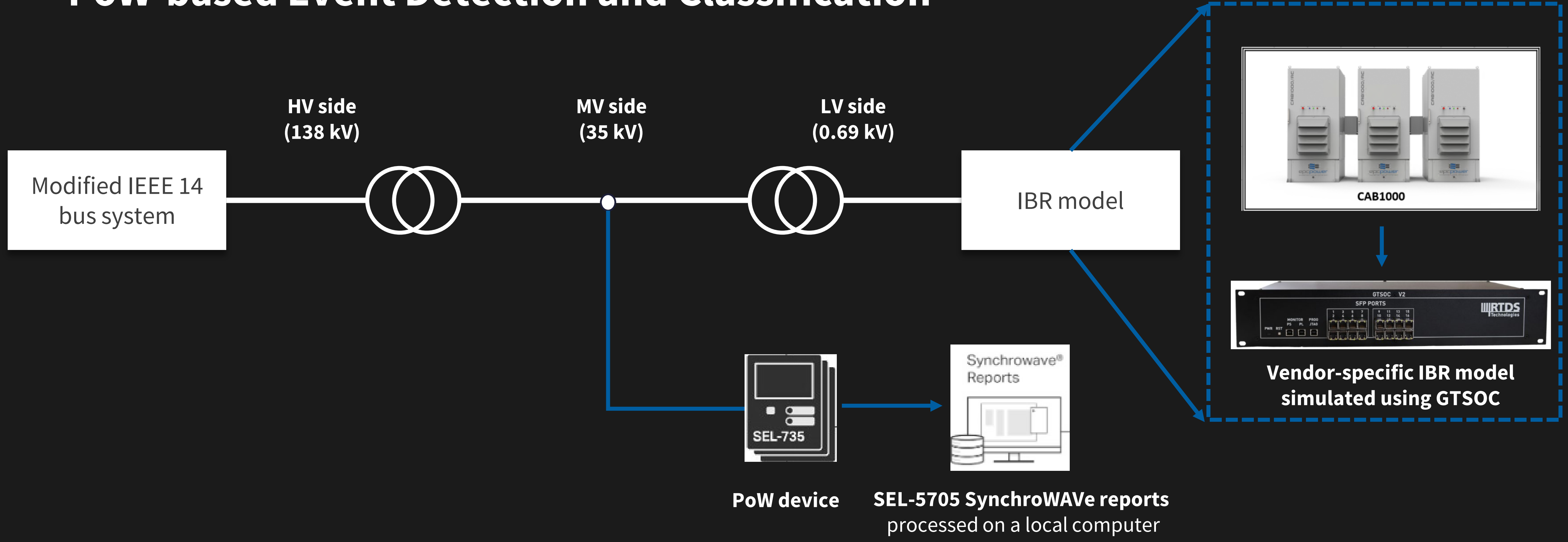
Output

- Reconstructed waveform is used to identify abnormal PoW events.

Evaluation

- Reconstruction error, quantified using mean squared error (MSE), is used for event detection.

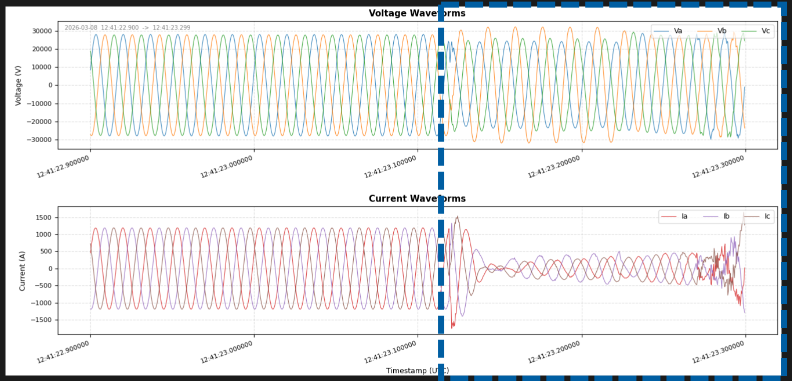
PoW-based Event Detection and Classification



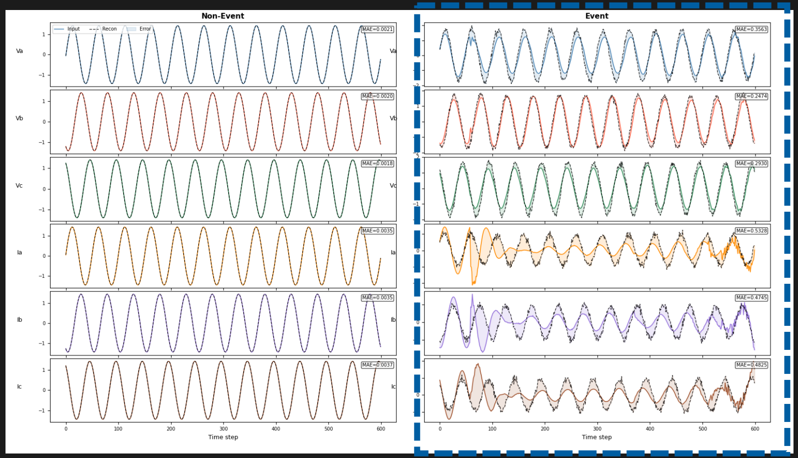
- **Simulation platform:** RTDS.
- **Test system:** Modified IEEE 14-bus network with three IBRs, including two vendor-specific models.
- The vendor model is realized in RTDS via GTSOC.
- The SEL-735 PoW device is located at the 35 kV bus.

PoW-based Event Detection and Classification

Event in time domain

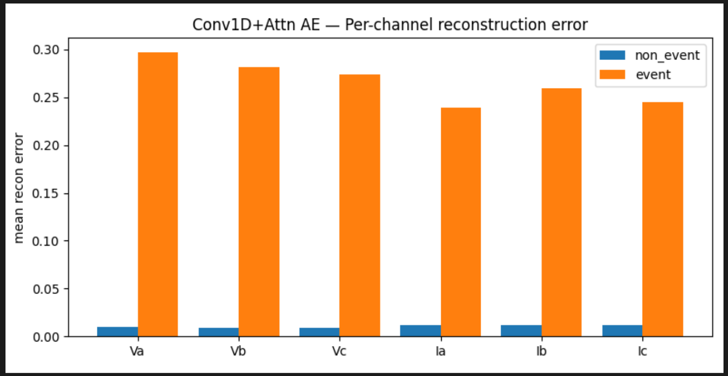


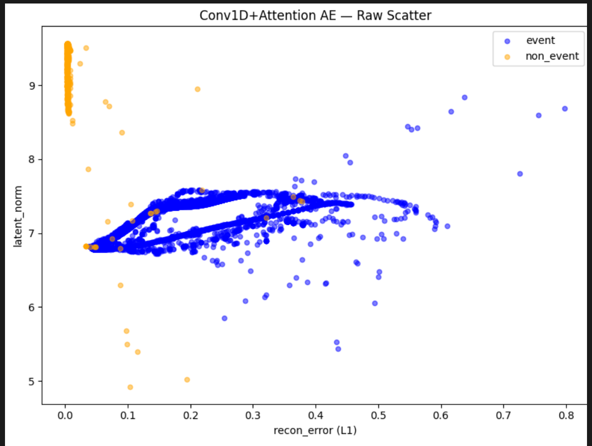
Event window



Input and reconstructed waveform

Event overview

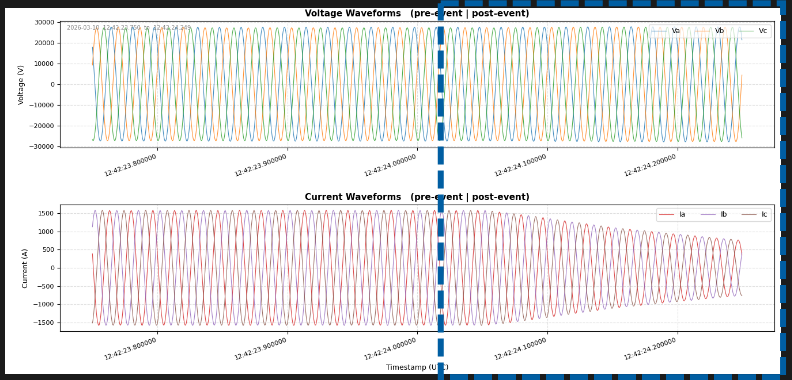




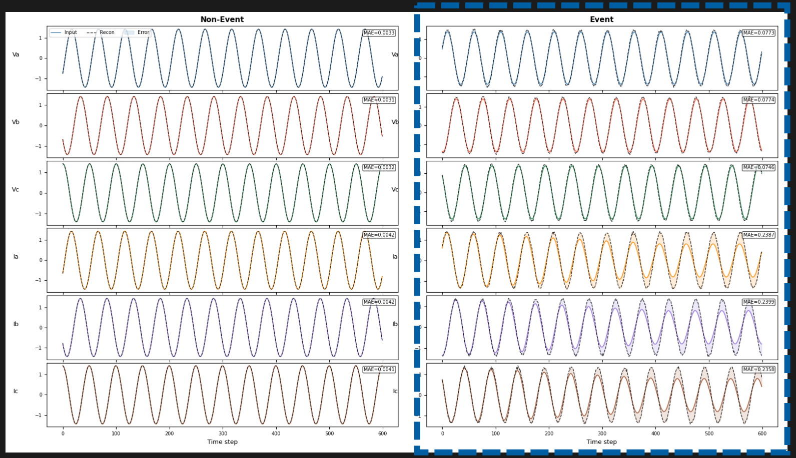
The event exhibits approximately 25x higher reconstruction error across all six channels compared to normal operation.

PoW-based Event Detection and Classification

Event in time domain

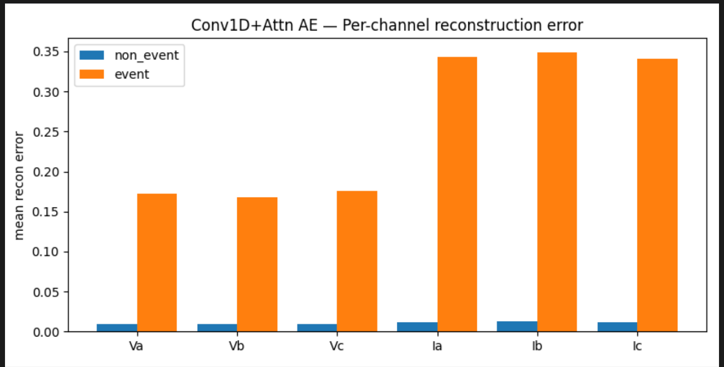


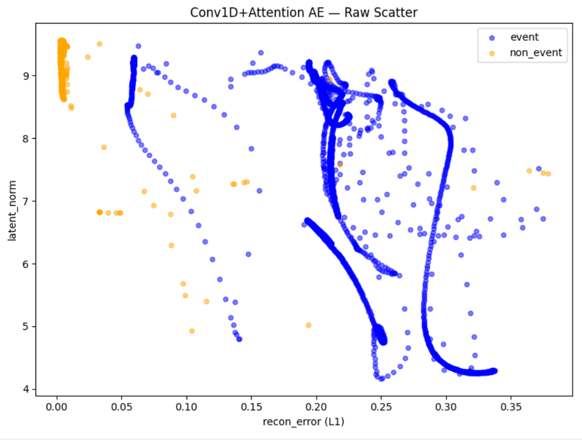
Event window



Input and reconstructed waveform

Event overview

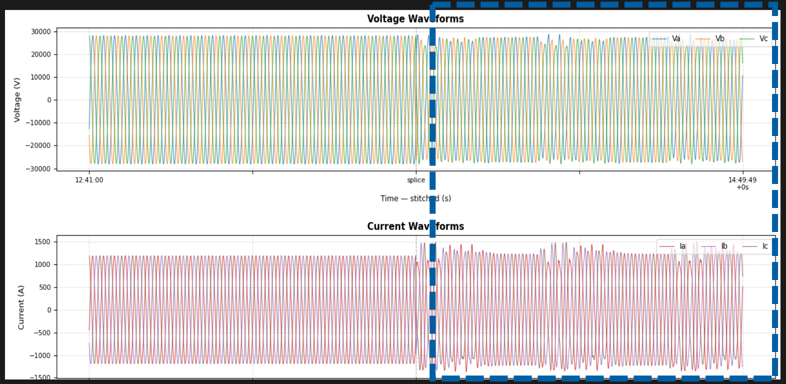




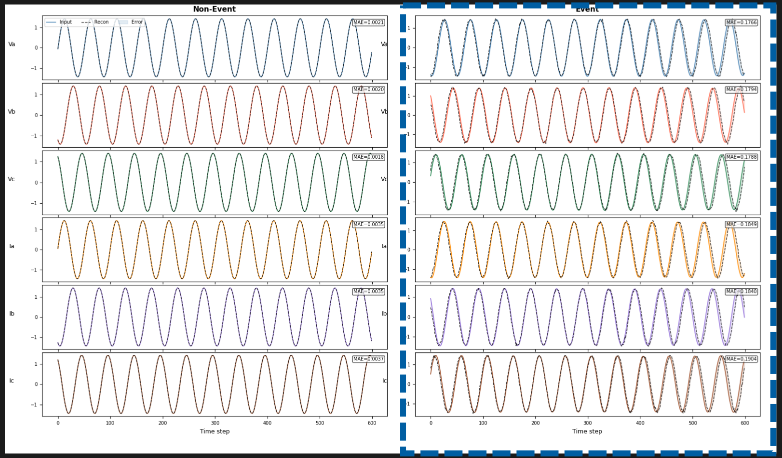
High reconstruction error is observed in current channels as expected.

PoW-based Event Detection and Classification

Event in time domain

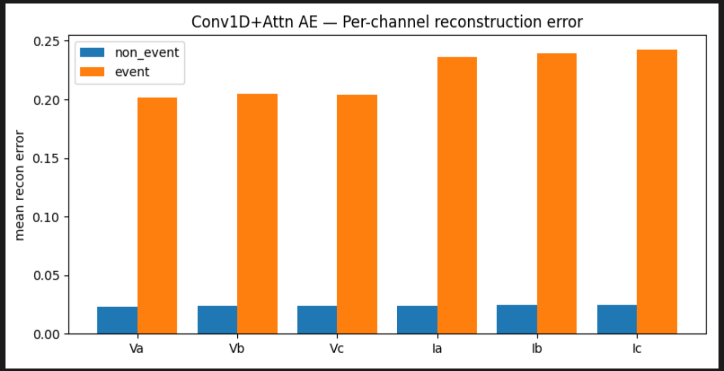


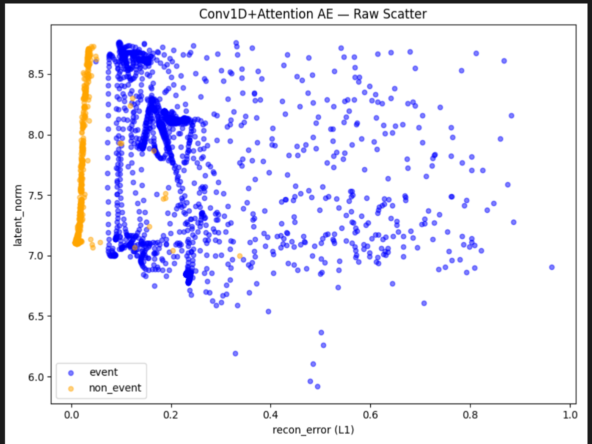
Event window



Input and reconstructed waveform

Event overview



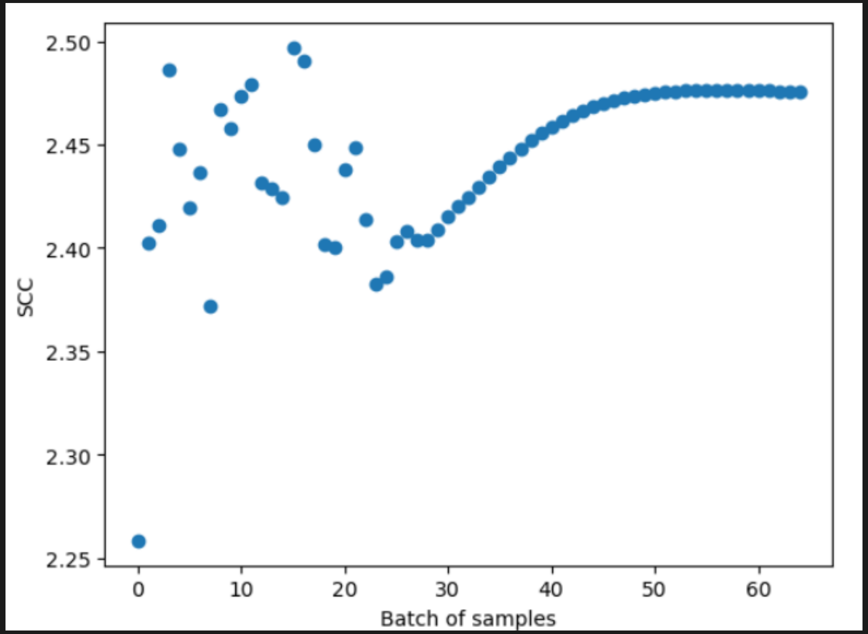


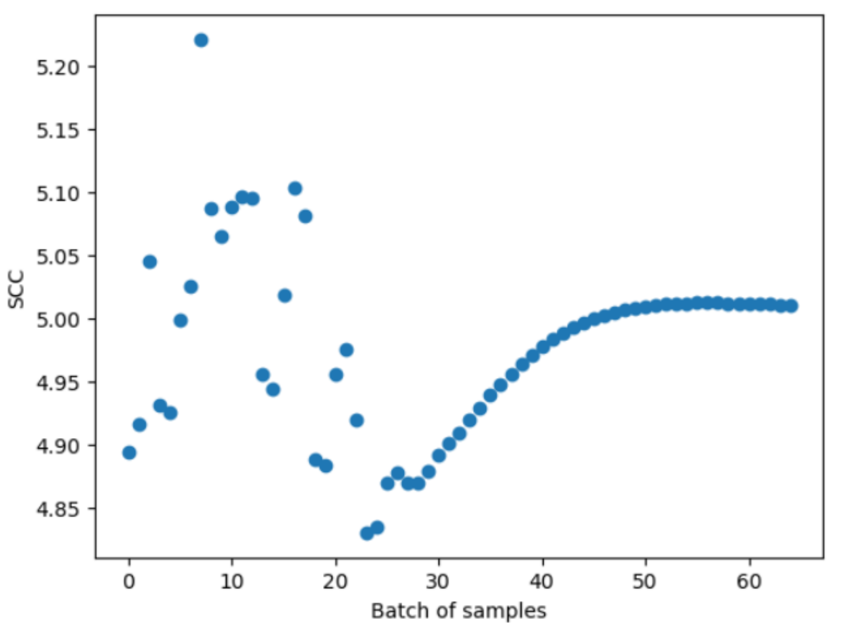
Distinguishable error is seen across all six channels.

conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Online Grid Strength Estimation

Grid strength estimation results across buses, where each dot represents the estimated SCC at a given bus for a specific second.





- Voltage and current measurements are collected at multiple buses in the IEEE-24 Bus Simulink test system.
- A least-squares approach is applied every 60 samples (~ 1 s) to solve the governing equation and estimate short-circuit capacity (SCC) in per unit.

Solving $\begin{bmatrix} V_1 \\ V_2 \\ V_n \end{bmatrix} = \begin{bmatrix} -I_1 & 1 \\ -I_2 & 1 \\ -In & 1 \end{bmatrix} \begin{bmatrix} Z_{th} \\ E_{th} \end{bmatrix}$ where SCC$=\frac{|(mean(V))^2|}{|Z_{th}|}$

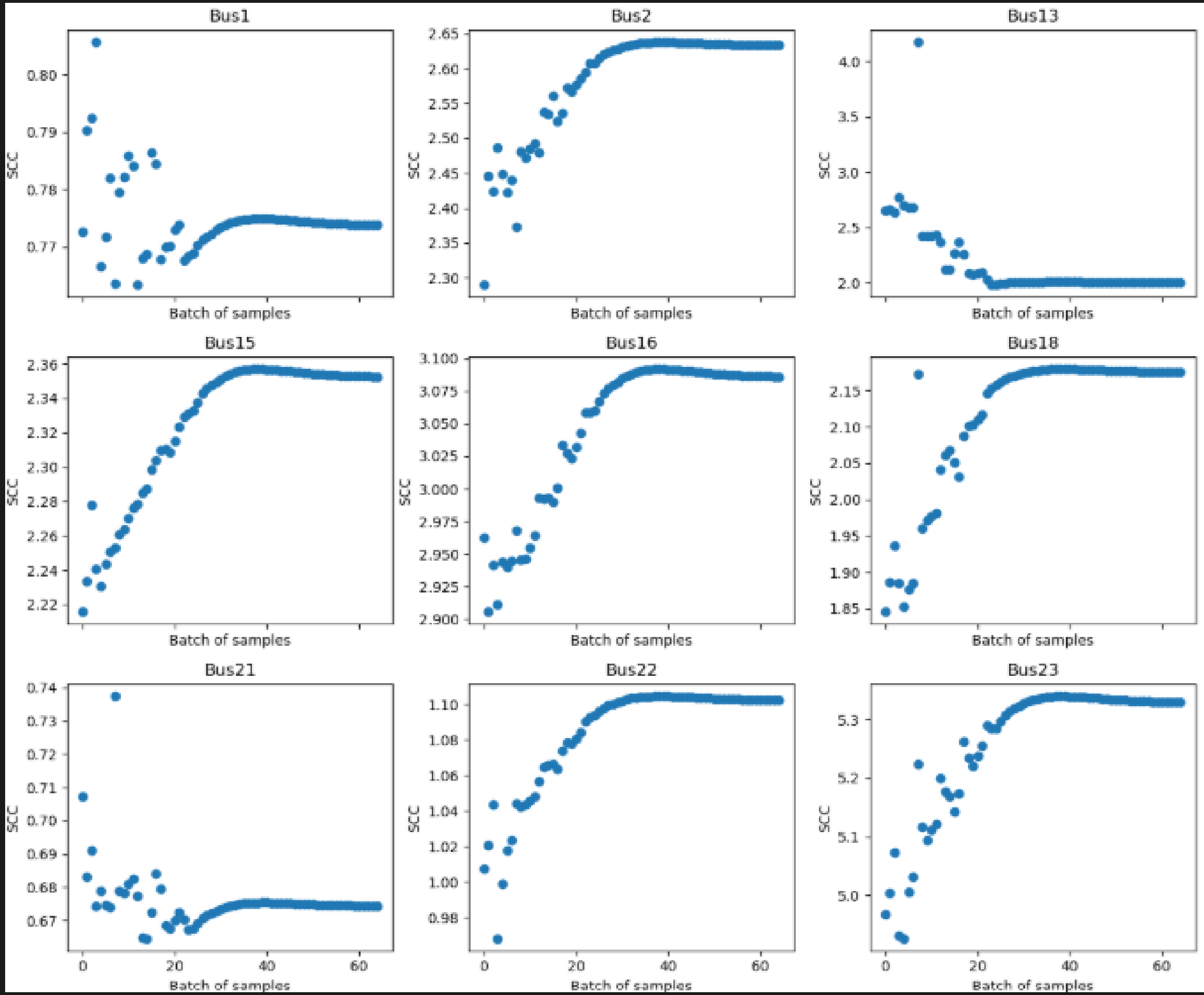
Online Grid Strength Estimation

The Thevenin-equivalent-based technique works well in a conventional power systems but degrades in accuracy for IBR-dominated grids.

Bus	Algorithm-based	Simulated/Actual	Absolute Error (%)
1	0.785	0.789	0.53
2	2.61	2.81	7.12
13	4.02	3.95	1.77
15	2.35	2.52	6.75
16	3.06	3.05	0.33
23	5.28	5.49	3.83

In IBR-rich systems, grid strength is no longer solely an impedance-based property; it becomes a closed-loop interaction between network impedance and inverter controls.

Dynamic state-estimation techniques may offer a more viable solution

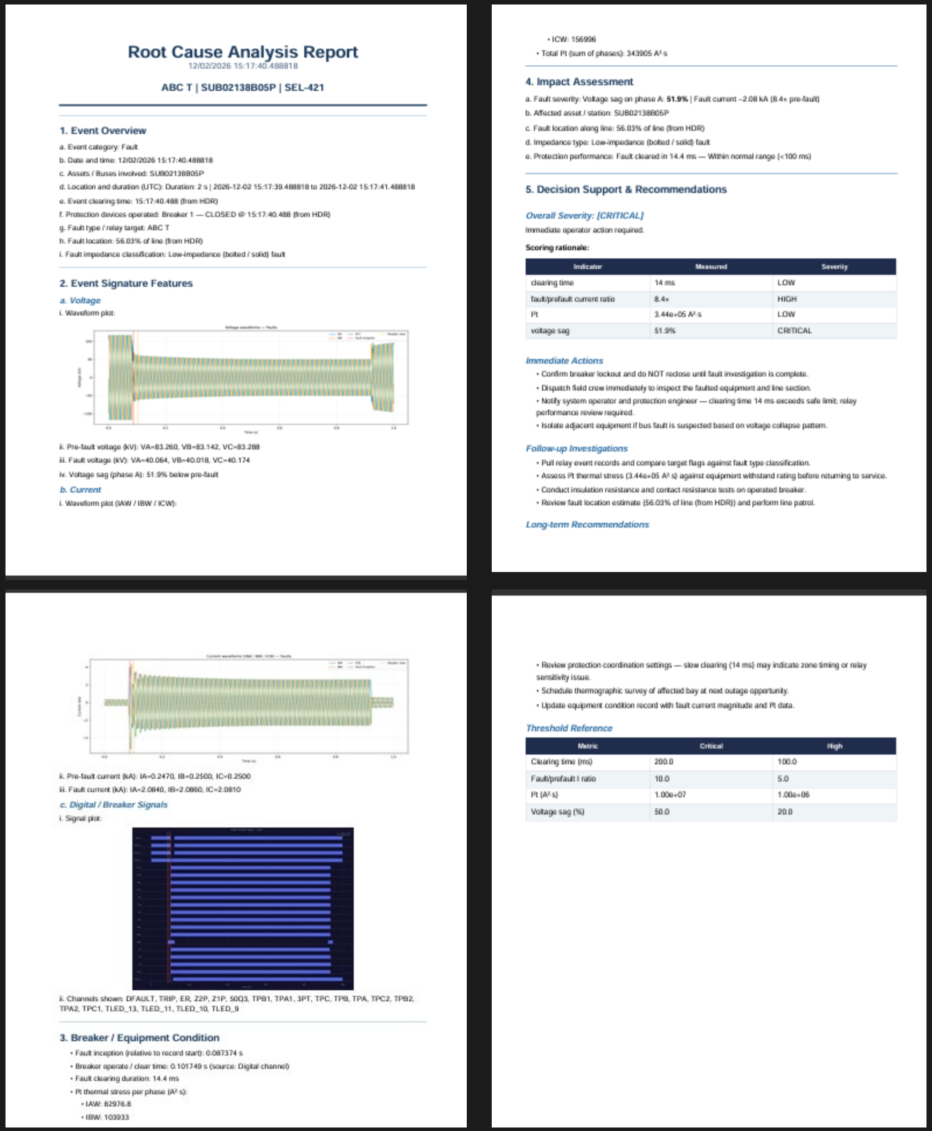


conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Deep Event Analysis and Reporting

- Each event is analyzed using an automated Python module to generate an event analysis report.
- **Covers five event categories:** faults, Frequency disturbances, voltage disturbances, transients and oscillations.
- Structured report generated for each event:
  - Event overview
  - Signature features
  - Impact assessment
  - Decision support.

Sample Fault Event Report



Root Cause Analysis Report

12/02/2026 15:17:40.488818

ABC T | SUB02138B05P | SEL-421

1. Event Overview

a. Event category: Fault
b. Date and time: 12/02/2026 15:17:40.488818
c. Assets / Buses involved: SUB02138B05P
d. Location and duration (UTC): Duration: 2 s | 2026-12-02 15:17:39.488818 to 2026-12-02 15:17:41.488818
e. Event clearing time: 15:17:40.488 (from HDR)
f. Protection devices operated: Breaker 1 — CLOSED @ 15:17:40.488 (from HDR)
g. Fault type / relay target: ABC T
h. Fault location: 56.03% of line (from HDR)
i. Fault impedance classification: Low-impedance (bolted / solid) fault

2. Event Signature Features

a. Voltage

i. Waveform plot:

ii. Pre-fault voltage (kV): VA=83.260, VB=83.142, VC=83.288
iii. Fault voltage (kV): VA=40.064, VB=40.018, VC=40.174
iv. Voltage sag (phase A): 51.9% below pre-fault

b. Current

i. Waveform plot (IAW / IBW / ICW):

ii. Pre-fault current (kA): IA=0.2470, IB=0.2500, IC=0.2500
iii. Fault current (kA): IA=2.0840, IB=2.0860, IC=2.0810

c. Digital / Breaker Signals

i. Signal plot:

ii. Channels shown: DFAULT, TRIP, ER, Z2P, Z1P, 50Q3, TPB1, TPA1, 3PT, TPC, TPB, TPA, TPC2, TPB2, TPA2, TPC1, TLED_13, TLED_11, TLED_10, TLED_9

3. Breaker / Equipment Condition

- Fault inception (relative to record start): 0.087374 s
- Breaker operate / clear time: 0.101749 s (source: Digital channel)
- Fault clearing duration: 14.4 ms
- I^2t thermal stress per phase ($A^2 \cdot s$):
  - IAW: 82976.8
  - IBW: 103933
  - ICW: 156996
- Total I^2t (sum of phases): 343905 $A^2 \cdot s$

4. Impact Assessment

a. Fault severity: Voltage sag on phase A: **51.9%** | Fault current ~2.08 kA (8.4× pre-fault)
b. Affected asset / station: SUB02138B05P
c. Fault location along line: 56.03% of line (from HDR)
d. Impedance type: Low-impedance (bolted / solid) fault
e. Protection performance: Fault cleared in 14.4 ms — Within normal range (<100 ms)

5. Decision Support & Recommendations

Overall Severity: [CRITICAL]

Immediate operator action required.

Scoring rationale:

Indicator	Measured	Severity
clearing time	14 ms	LOW
fault/prefault current ratio	8.4×	HIGH
I^2t	3.44e+05 $A^2 \cdot s$	LOW
voltage sag	51.9%	CRITICAL

Immediate Actions

- Confirm breaker lockout and do NOT reclose until fault investigation is complete.
- Dispatch field crew immediately to inspect the faulted equipment and line section.
- Notify system operator and protection engineer — clearing time 14 ms exceeds safe limit; relay performance review required.
- Isolate adjacent equipment if bus fault is suspected based on voltage collapse pattern.

Follow-up Investigations

- Pull relay event records and compare target flags against fault type classification.
- Assess I^2t thermal stress (3.44e+05 $A^2 \cdot s$) against equipment withstand rating before returning to service.
- Conduct insulation resistance and contact resistance tests on operated breaker.
- Review fault location estimate (56.03% of line (from HDR)) and perform line patrol.

Long-term Recommendations

- Review protection coordination settings — slow clearing (14 ms) may indicate zone timing or relay sensitivity issue.
- Schedule thermographic survey of affected bay at next outage opportunity.
- Update equipment condition record with fault current magnitude and I^2t data.

Threshold Reference

Metric	Critical	High
Clearing time (ms)	200.0	100.0
Fault/prefault I ratio	10.0	5.0
I^2t ($A^2 \cdot s$)	1.00e+07	1.00e+06
Voltage sag (%)	50.0	20.0

Event Analysis Validation

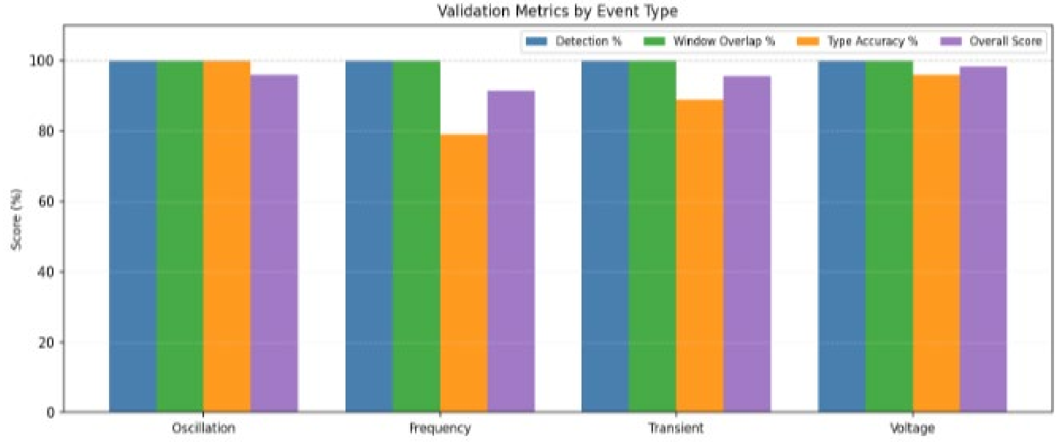
- The event analysis pipeline is validated against hardware-in-the-loop (HIL) testbed ground truth.
- Ground truth is defined from known simulation parameters used to trigger events.
- For each event category, an overall event score (out of 100) is computed based on event-wise features validation.
    - Oscillations are scored based on frequency, location, time window, and event type.
- Average validation score: **95.4/100** across all event types.

RCA Validation Report

Automated comparison of RCA outputs against simulation ground truth

Executive Summary

Event Type	Truth Events	Detected	Detection %	Window Overlap %	Type Accuracy %	Freq Error (Hz)	Overall Score
Oscillation	100	100	100.0%	100.0%	100.0%	0.318	96.0
Frequency	100	100	100.0%	100.0%	79.0%	N/A	91.6
Transient	100	100	100.0%	100.0%	89.0%	N/A	95.6
Voltage	100	100	100.0%	100.0%	96.0%	N/A	98.4



conEdison entergy FPL DANOVO ENERGY SOLUTIONS A QUANTA SERVICES COMPANY SRP Sandia National Laboratories

Key Takeaways and Next Steps

1 Cloud streamed data with a web front end turns distributed PMU, PoW, SCADA, and COMTRADE data into a single searchable, time-synchronized archive–supporting both real-time operational insights and forensic post-event analysis.

2 PoW data securely illustrates system and IBR abnormal or changing operating conditions and provides strong signatures for event classification.

3 Thevenin-based grid strength estimation degrades in IBR-rich systems because the network is no longer linear time-invariant (LTI).

4 Next steps:

Grid strength estimation in IBR-rich systems requires new dynamic analysis techniques.

SSO detection and source location are being worked on.

The final report of Iberian blackout: *Enhance dynamic monitoring and operational oscillation detection (both inter-area and forced).*

Thank you!

Questions?

Chris Carpenter
Executive Advisor,
Monitoring, Protection, Automation, and Control
Danovo Energy Solutions
CCarpenter@danovoenergy.com
(919) 737-3685

Farrokh Aminifar
Principal Advisor,
Monitoring, Protection, Automation, and Control
Danovo Energy Solutions
FAminifar@danovoenergy.com
(919) 451-0856