DOE/OE Transmission Reliability Program

Substation Secondary Asset Health Monitoring and Management System

DOE Grant Award #DE-OE0000850

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Acknowledgement and Disclaimer

- Acknowledgment: This material is based upon work supported by the Department of Energy under Award Number DE-OE0000850.

Outline

- **Project Introduction & Objective**
- **Technical Merit & Approach**
  - Data-driven Methods: Moving Variance, Control Chart
  - Substation Linear State Estimator (SLSE) Method
- **Testing & Results**
  - Simulation Data, Field PMU Data, COMTRADE Data (Point-on-wave)
- **Major Accomplishments & Next Steps**

Project Introduction

- DOE/OE and DOE/NETL
  - Phil Overholt, Program Manager & Alicia Dalton-Tingler, Project Officer
- American Electric Power (AEP) – Sub-recipient
  - Project Manager / Alternate – Carlos Casablanca / Yanfeng Gong
- Professor Anjan Bose (Washington State University)
  - Technical Advisor
- Electric Power Group, LLC
  - Principal Investigator – Lin Zhang
  - Key Project Personnel – Ken Martin, Simon Mo, Tianyu Hu, Neeraj Nayak, Joshua Chynoweth

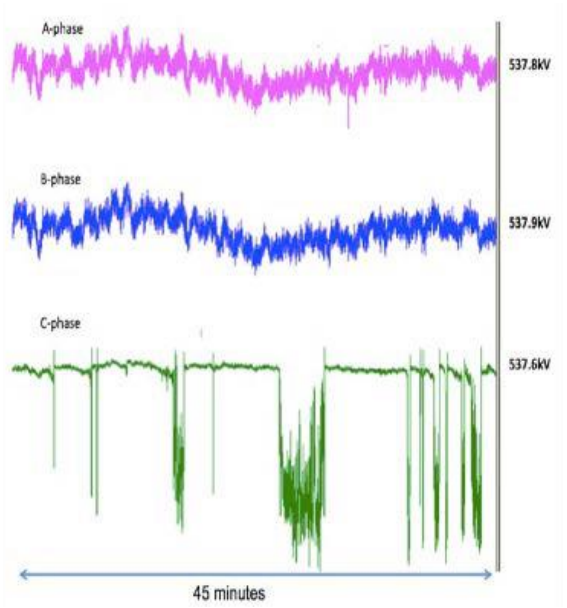
Project Objective

- Research, design, develop and demonstrate software application in substation(s) to:
  - Collect three phase measurements from substation equipment
  - Process data from PMUs, DFRs and Instrument Transformers to derive synchrophasor equivalents and run a three phase Substation Linear State Estimator (SLSE) in real-time
  - Monitor and characterize equipment data signatures
  - Detect signature anomalies
  - Alert end-users and provide equipment signatures for detailed forensic analysis
  - Enable end-users to take needed proactive actions – calibration, repairs, replacement

Technical Merit

Using Data for Proactive Actions to Prevent Failure

Example of failing CCVT in a substation



Example of CCVT voltage signals at Dominion

- Monitor the status and health of substation equipment
- Provide early warning indications for potential malfunctioning equipment
- Proactively replace and repair before equipment is damaged
- Reduce utility's forced outage of equipment
- Reduce utility's operating and maintenance costs

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Technical Approach

- Data from substation provided by utility partners
- Leverage existing synchrophasor technology
- Research new algorithms in this project
  - Data-driven Method
  - Substation Linear State Estimator (SLSE) Method
- Validate with Simulated and PMU data from Utilities
  - Central Location
  - Substation
- Adapt for general commercial use at other utilities

Moving Variance Method

- The variance is calculated one phase at a time with 3 moving windows
- Main window
  - Delayed Window
  - Variance Window – Centered data
- Square the centered data
- Moving average of Squared data
- Moving threshold is obtained based on a scaling factor

Control Chart Method

Control chart is a graph or chart with limit lines. There are basically three kinds of control lines:

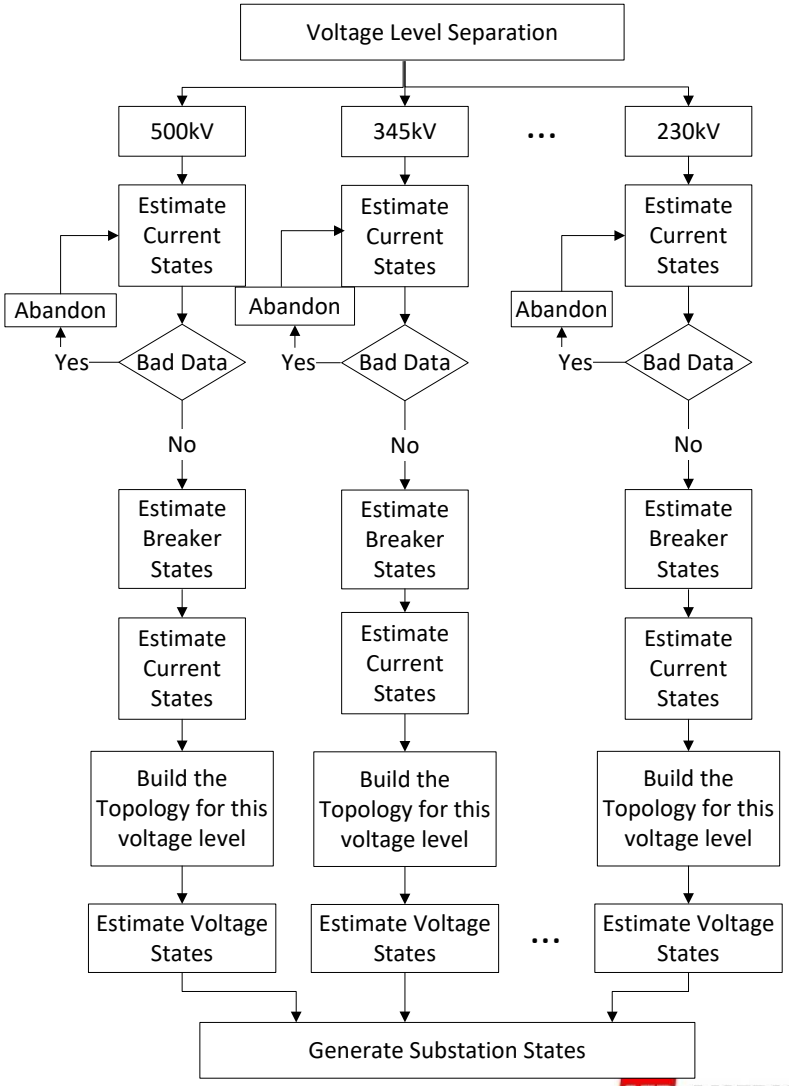
- the upper control limit (UCL),
- the central line, and
- the lower control limit (LCL).

The UCL and LCL are calculated based on a 20σ

1) Identifying the maximum and minimum values in 1-second time window.
2) Calculating 1-second the data change range=maximum-minimum.
3) Comparing the 1-second change range with upper control limit (UCL).

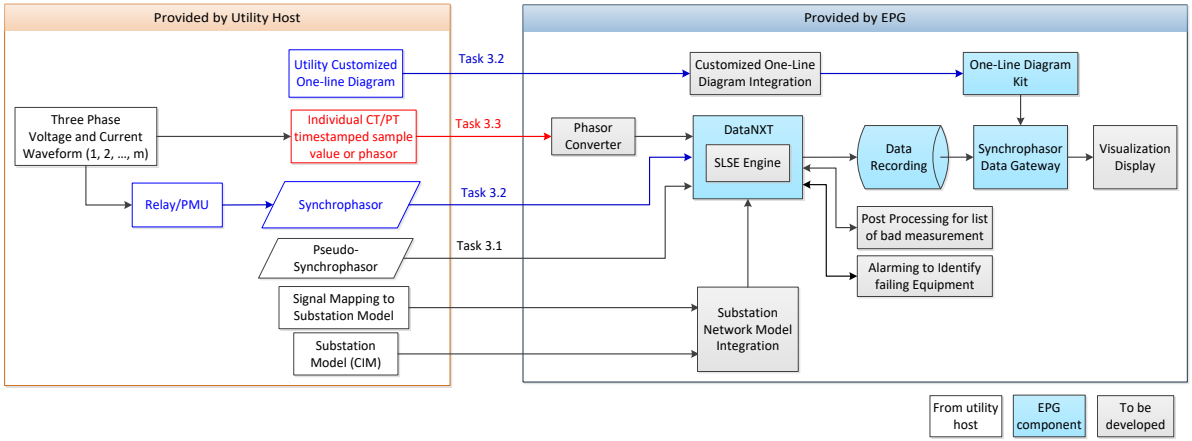
SLSE Method

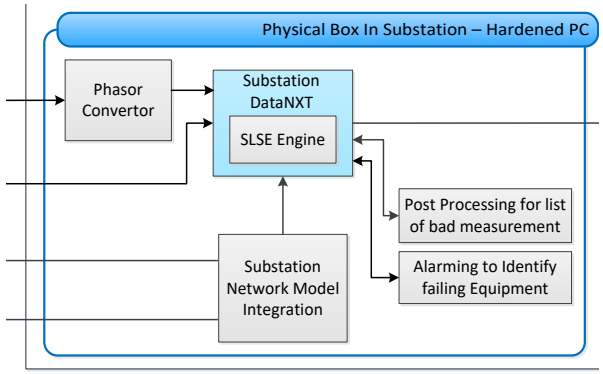
3 phase current state estimator



3 phase voltage state estimator

Deployment Options





- **Central Processing**
- **Data sent from substations to central site**
- Pros:
  - > Monitoring multiple substations
  - > Simple deployment
- Cons:
  - > Need large bandwidth

- **Local Processing at Substations**
- **Results sent to asset monitoring center**
- Pros:
  - > Less latency
  - > Less bandwidth
- Cons:
  - > Deployment not as easy

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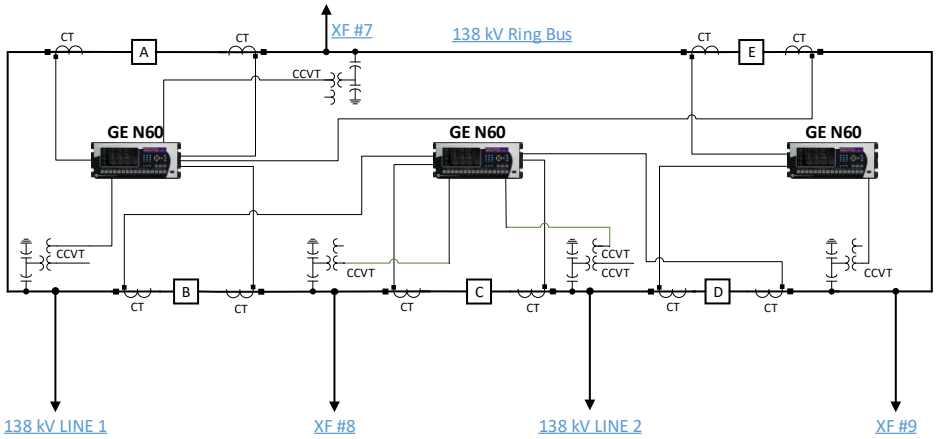
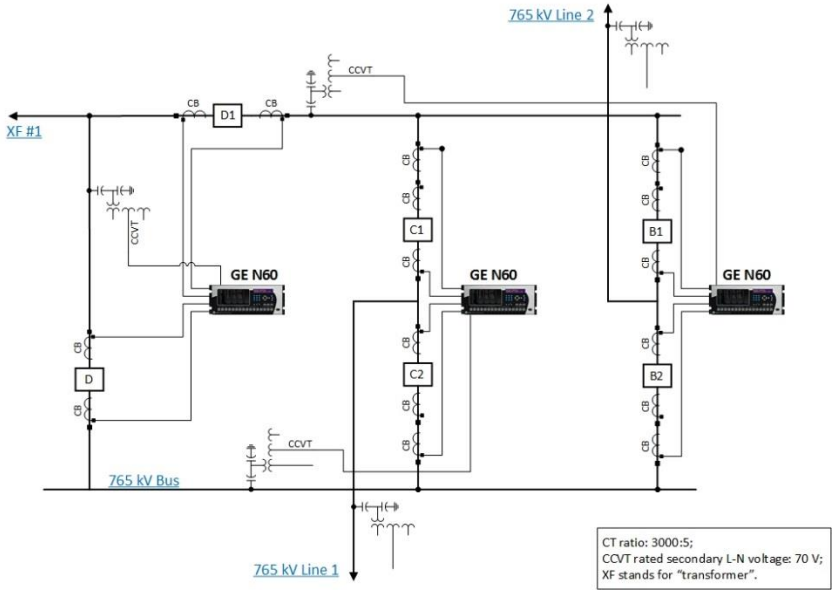
PMU Deployment at AEP

138 kV STATION PMU Connection



765 kV STATION PMU Connection



3 PMUs deployed at 138 kV Substation

3 PMUs deployed at 765 kV Substation

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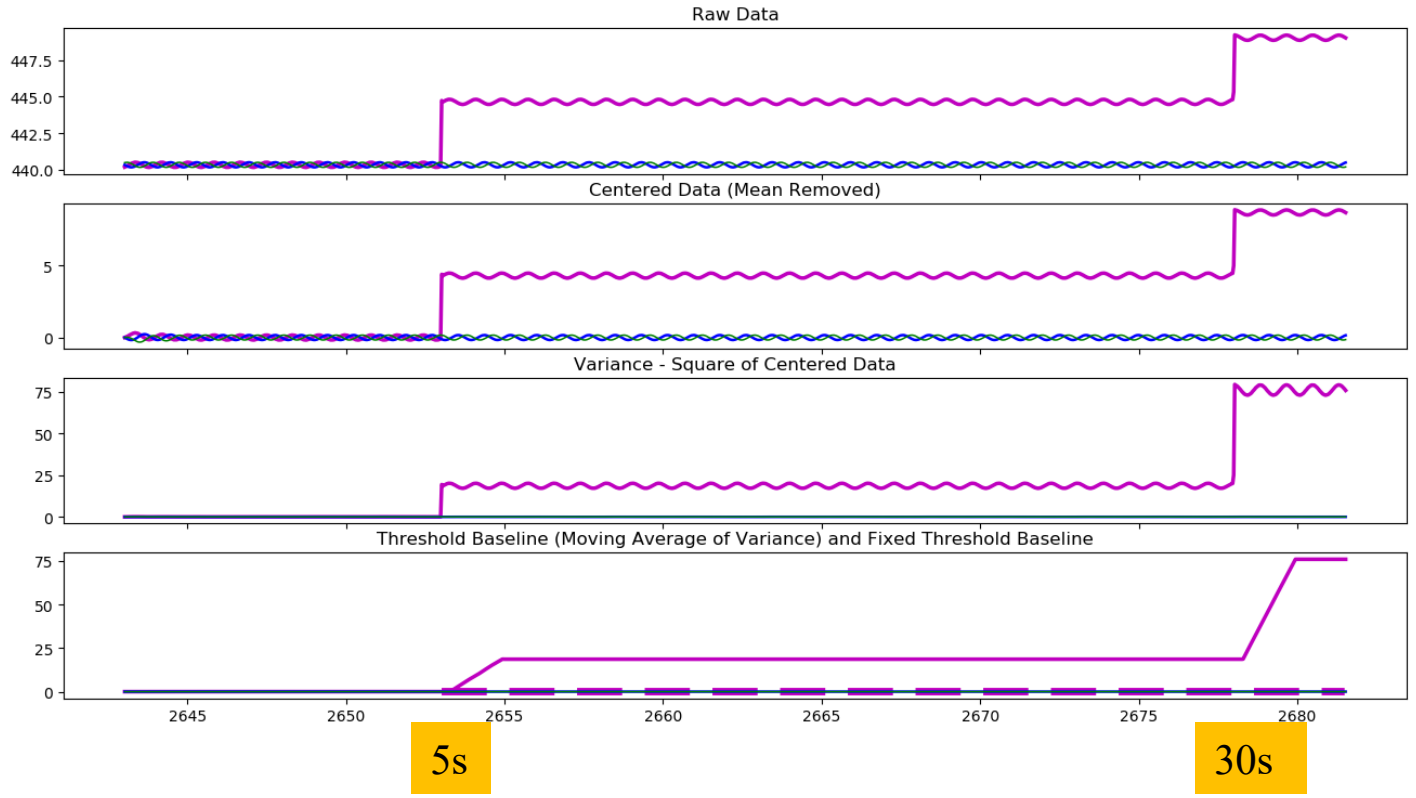
TESTING & RESULTS

AEP PSCAD Simulation Cases (60 Total)

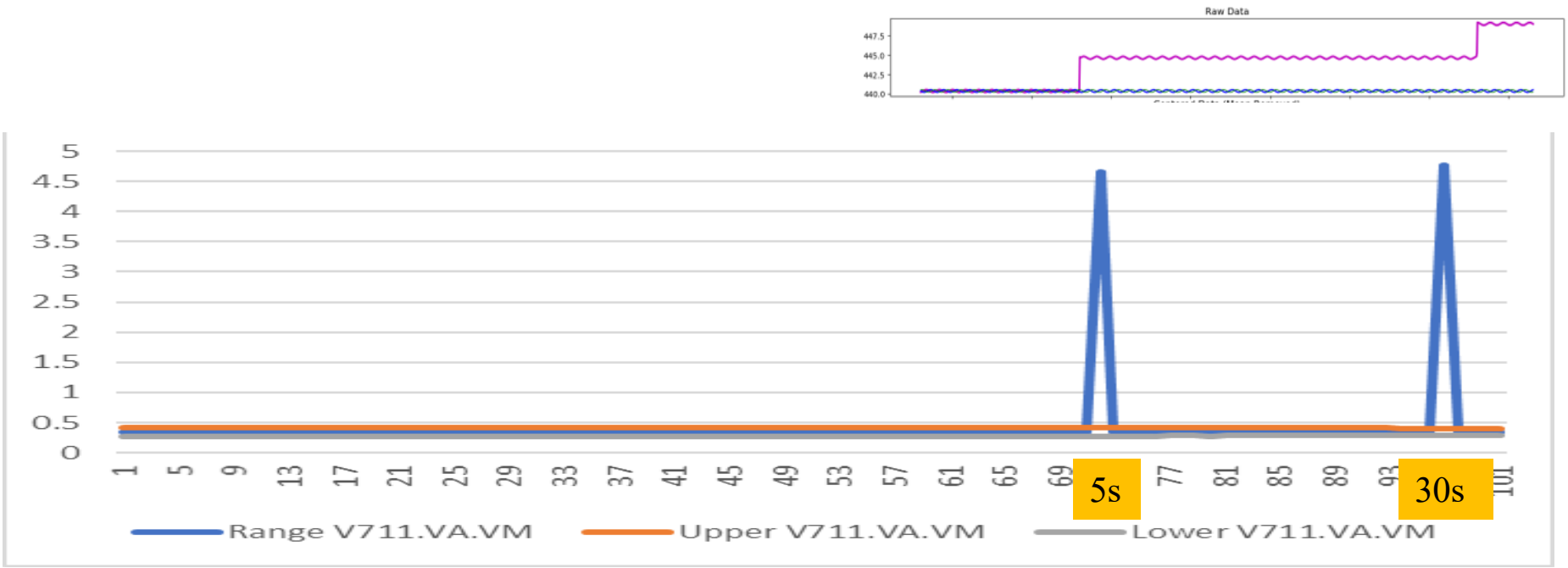
Faulted Instrument Transformer	Fault Type	No. of Scenarios
CCVT	High voltage capacitor stack failure	3
	Low voltage capacitor stack failure	3
	Ferroresonance suppression circuit (FSC) failure	2
CT	Turn-to-turn shortage within the same coil	2
	Turn-to-ground shortage	4
	Turn-to-turn shortage between different coils	6
	Ratio setting error	1
	Large burden (Loose Connections or Corroded Connections)	1
	Open CT secondary	1
	CT polarity error	1
None	External system events (bus fault and line fault)	6

Moving Variance Test - CCVT Capacitor Failure



1C - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

Control Chart Test – CCVT Capacitor Failure



1C - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

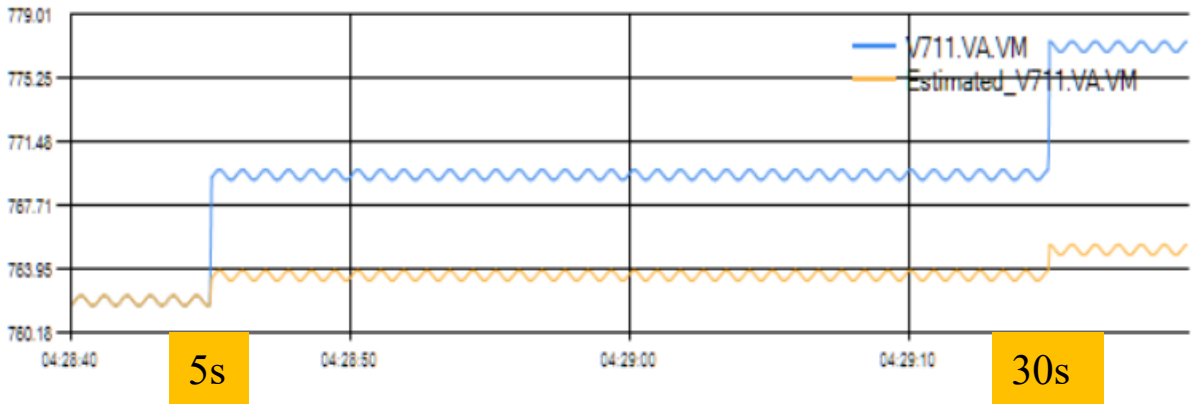
SLSE Test – CCVT Capacitor Failure

SLSE successfully detected the anomaly caused by CCVT 711 failure

1/11/2018 4:28 AM	V711.VA.VM exceed limit!

Angle Reference

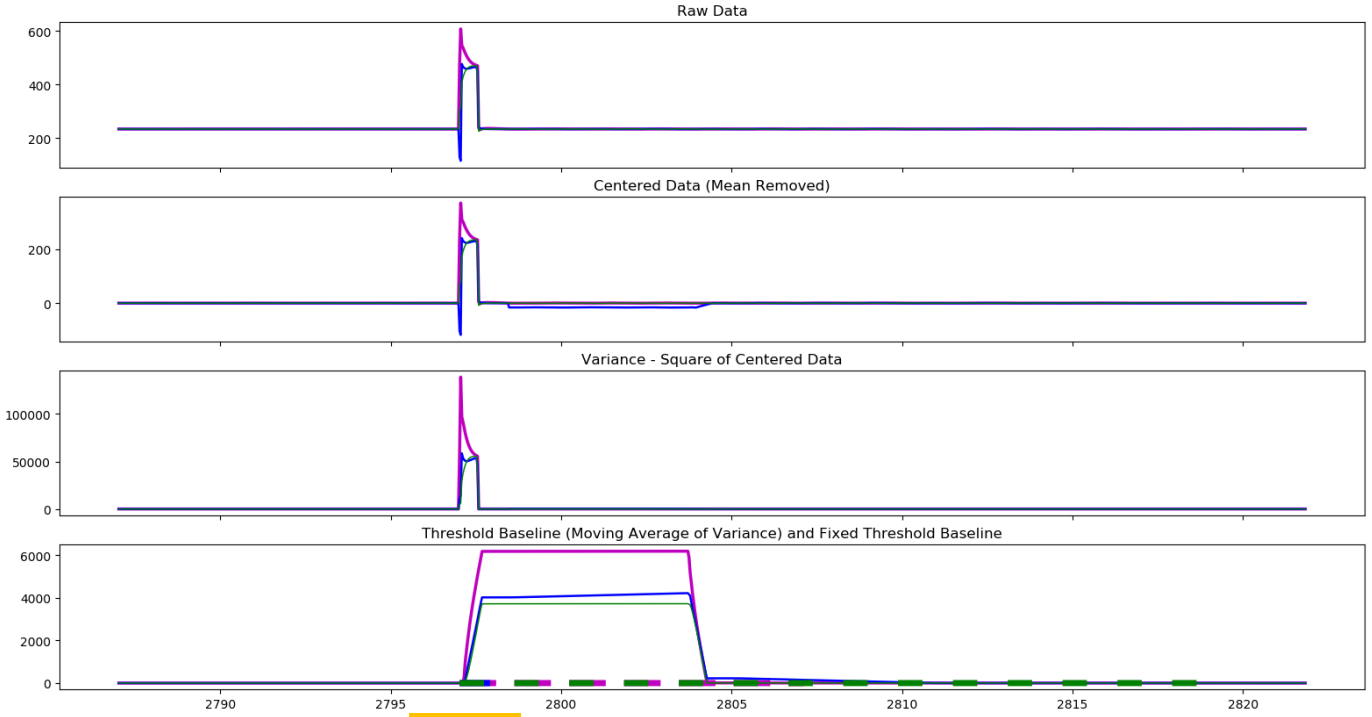
	Signal Name	Check
▶	V711.VA.VM	☑
	V711.VA.VA	☐
	V711.VB.VM	☐
	V711.VB.VA	☐
	V711.VC.VM	☐
	V711.VC.VA	☐
	V711.VP.VM	☐



1C - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

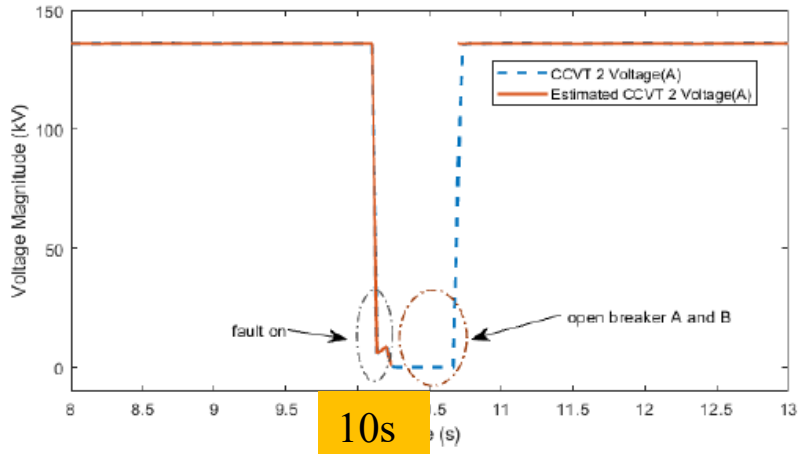
Moving Variance Test – System Fault

System Fault is flagged as an anomaly

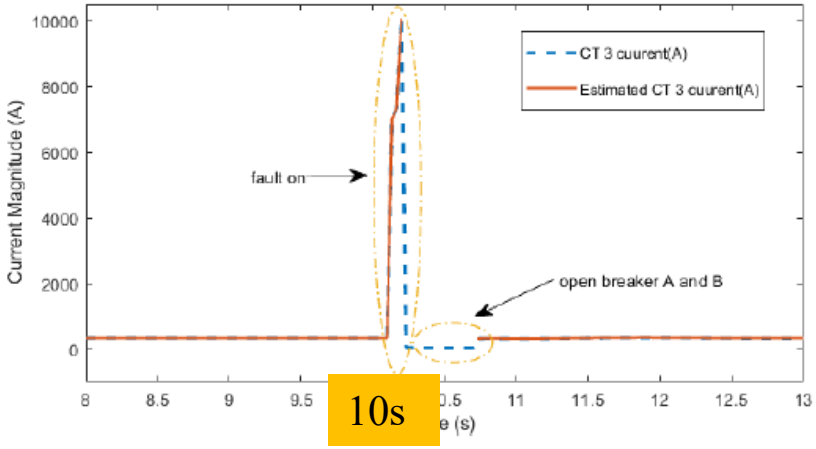


11B - A single phase-to-ground bus fault on bus 1 phase A at 10sec, fault duration is 0.06 s, open D1, C1, B1 at t = 10.05s, reclose at t=10.55s.

SLSE Test – System Fault



(a) CCVT 2 Voltage Magnitude



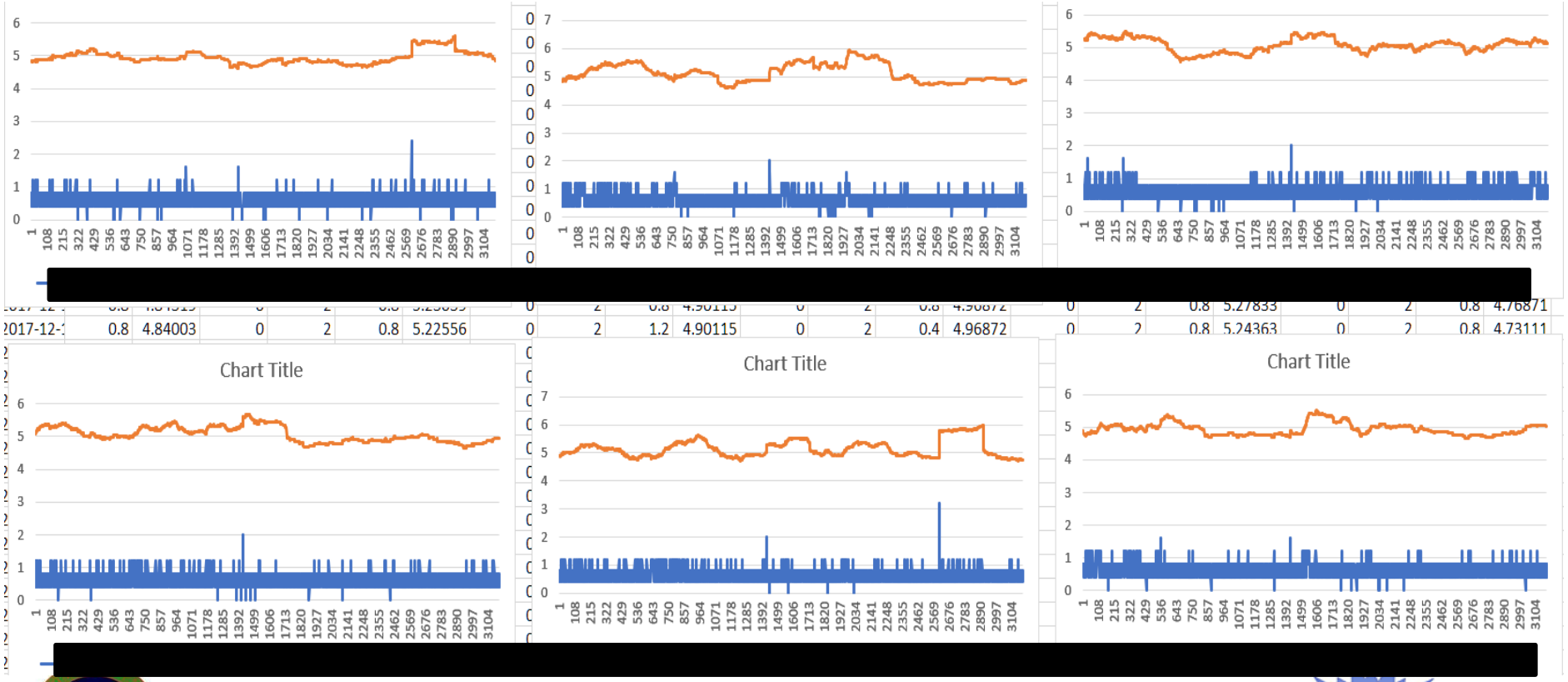
(b) CT 3 Current Magnitude

SLSE successfully follows the system fault and did not false alarm for CCVT or CT anomaly

1 Hour Field PMU Data Test – Control Chart

Normal operation data without equipment failure nor system event

- Each voltage and current signal is tested independently
- Didn't have false alarm based on the setting



[redacted]

2017-12-1	0.8	4.84003	0	2	0.8	5.22556	0	2	1.2	4.90115	0	2	0.4	4.96872	0	2	0.8	5.24363	0	2	0.8	4.73111

[redacted]

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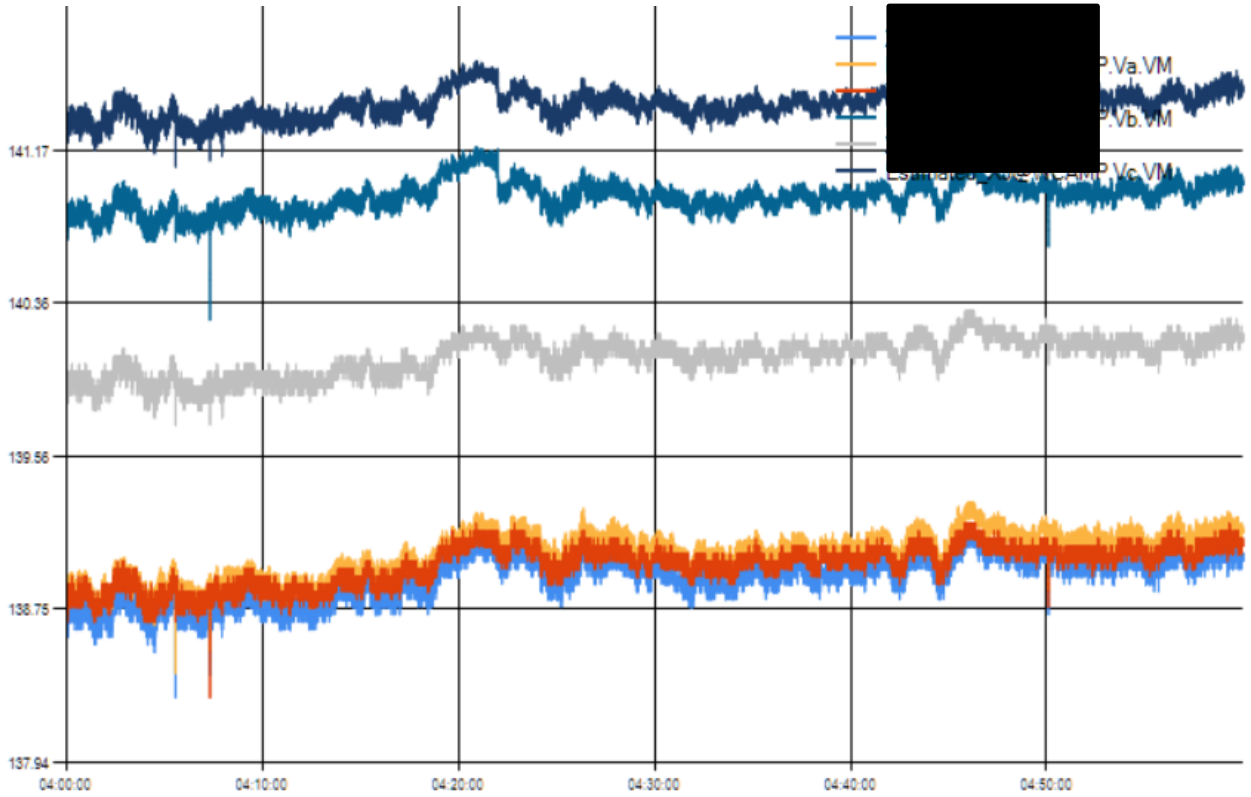
1 Hour Field PMU Data Test – SLSE

- The SLSE didn't alarm on any anomalies, which is as expected.
- The SLSE results are also very close to and following the variations of the raw signals

3 Phase voltage signals:

Signal Name	Check
[redacted]	
.VM	☑
.VA	☐
.VM	☑
.VA	☐
.VM	☑
.VA	☐
quency.FR	☐
.IM	☐
.IA	☐
.IM	☐
.IA	☐
a.VM	☐
a.VA	☐
b.VM	☐
b.VA	☐
c.VM	☐
c.VA	☐
requency.FR	☐



Key Findings from Testing

- Validated 3 methods

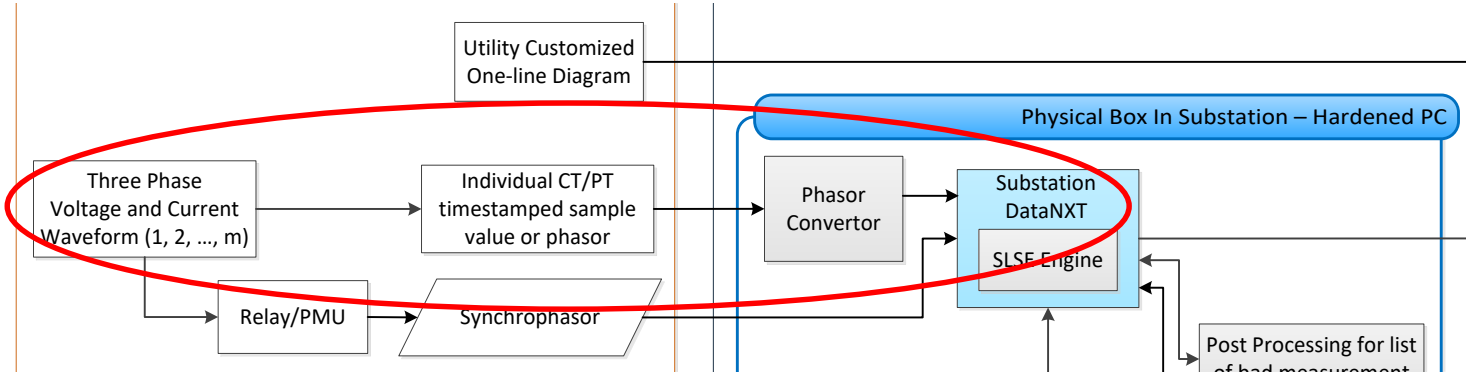
Data-driven Method (moving variance & control chart)

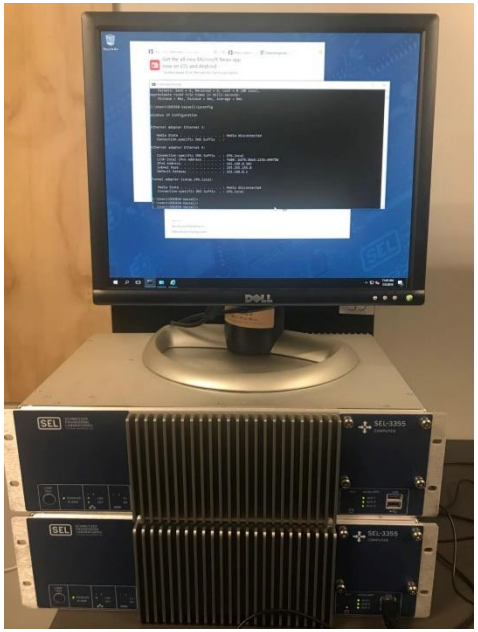
- Pro:
  - > Fast
  - > Configure Multiple windows
- Con:
  - > Biased by bad data
  - > Can not distinguish system fault

SLSE Method

- Pro:
  - > Robust with system fault and bad data
- Con:
  - > Requires model integration

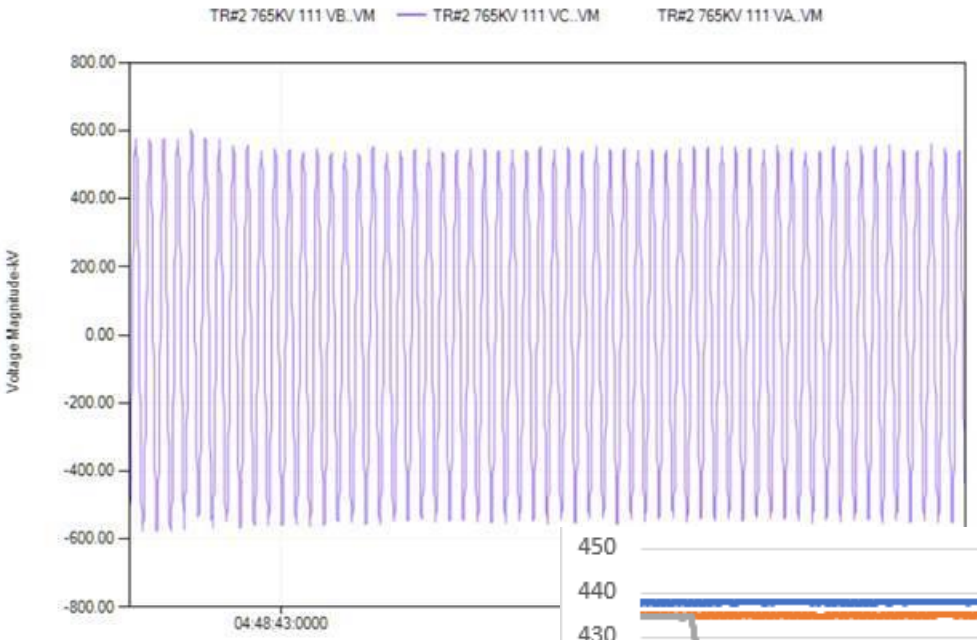
Local Processing & Substation Deployment





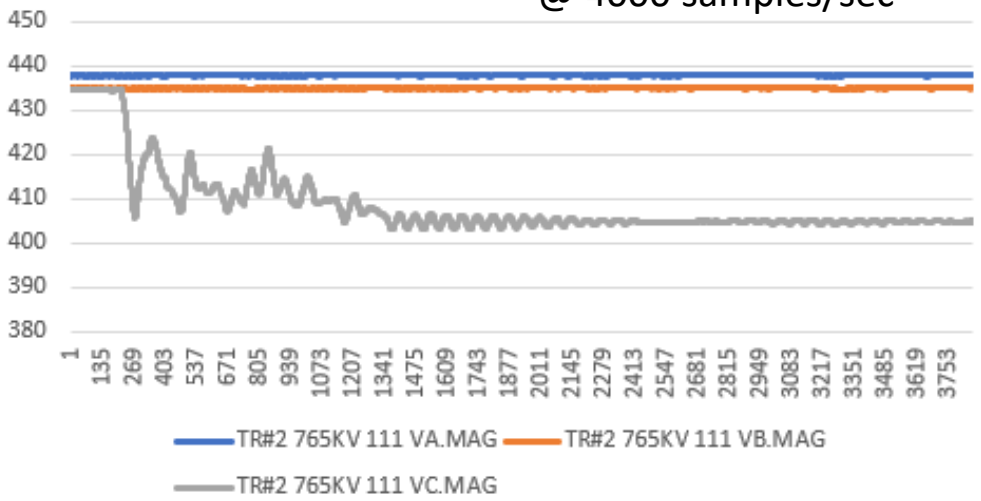
- Sampled CT, CCVT waveform data in COMTRADE format
- Trigger 1 time/hour
- 48 cycles of data, 64 samples/cycle
- Multiple COMTRADE files from multiple PMUs in one station
- Timestamp using same GPS clock as PMU

Point on Wave - Phasor Converter

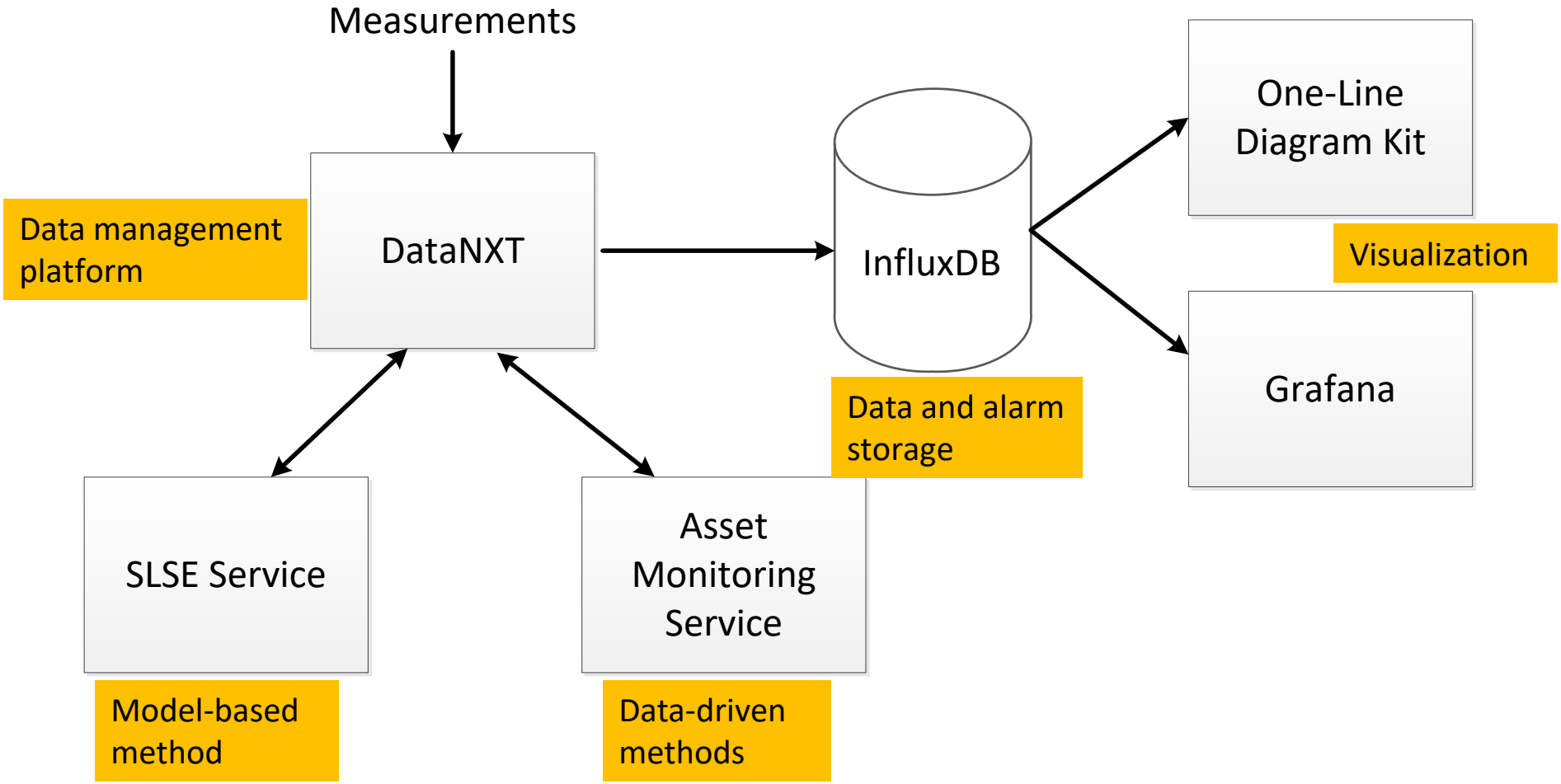


Original Sampled waveform voltage data @ 4000 samples/sec

Converted to phasor, original sample @ 4000 samples/sec



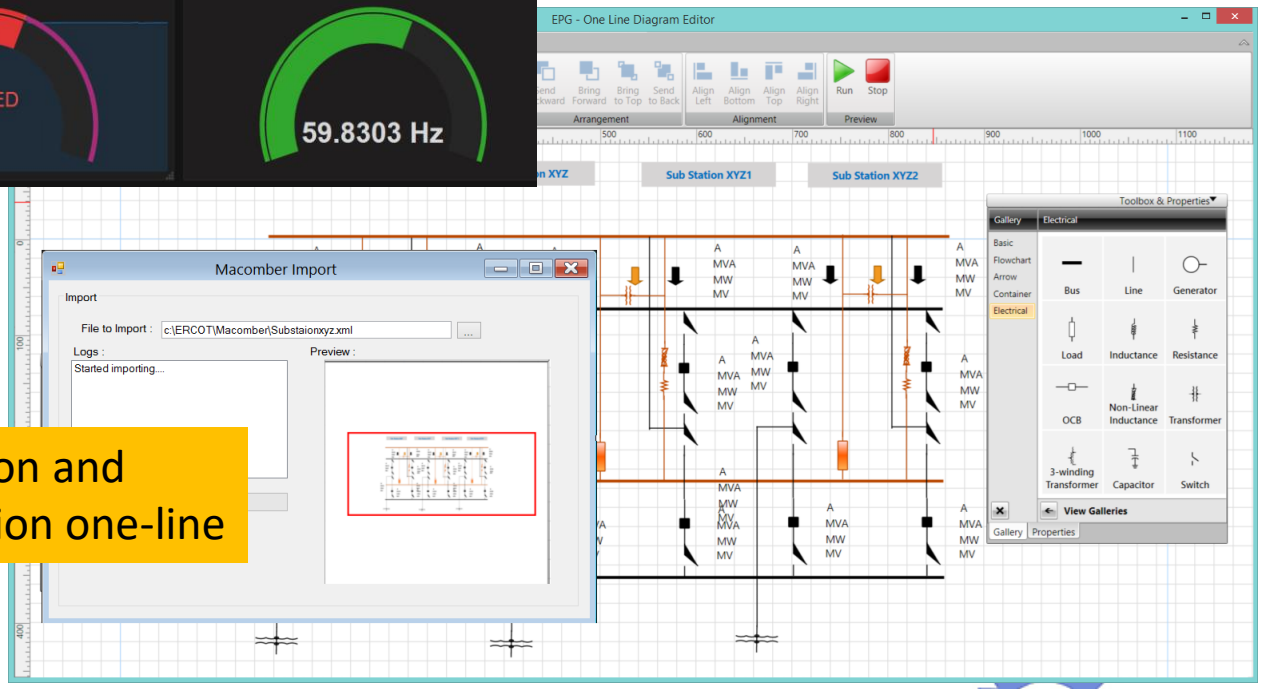
Software Package Testing at EPG & AEP



Grafana & One-line Diagram Visualization

Monitor 5 equipment

- Independent alarming
- measurement signal & status trending



Equipment location and status on substation one-line

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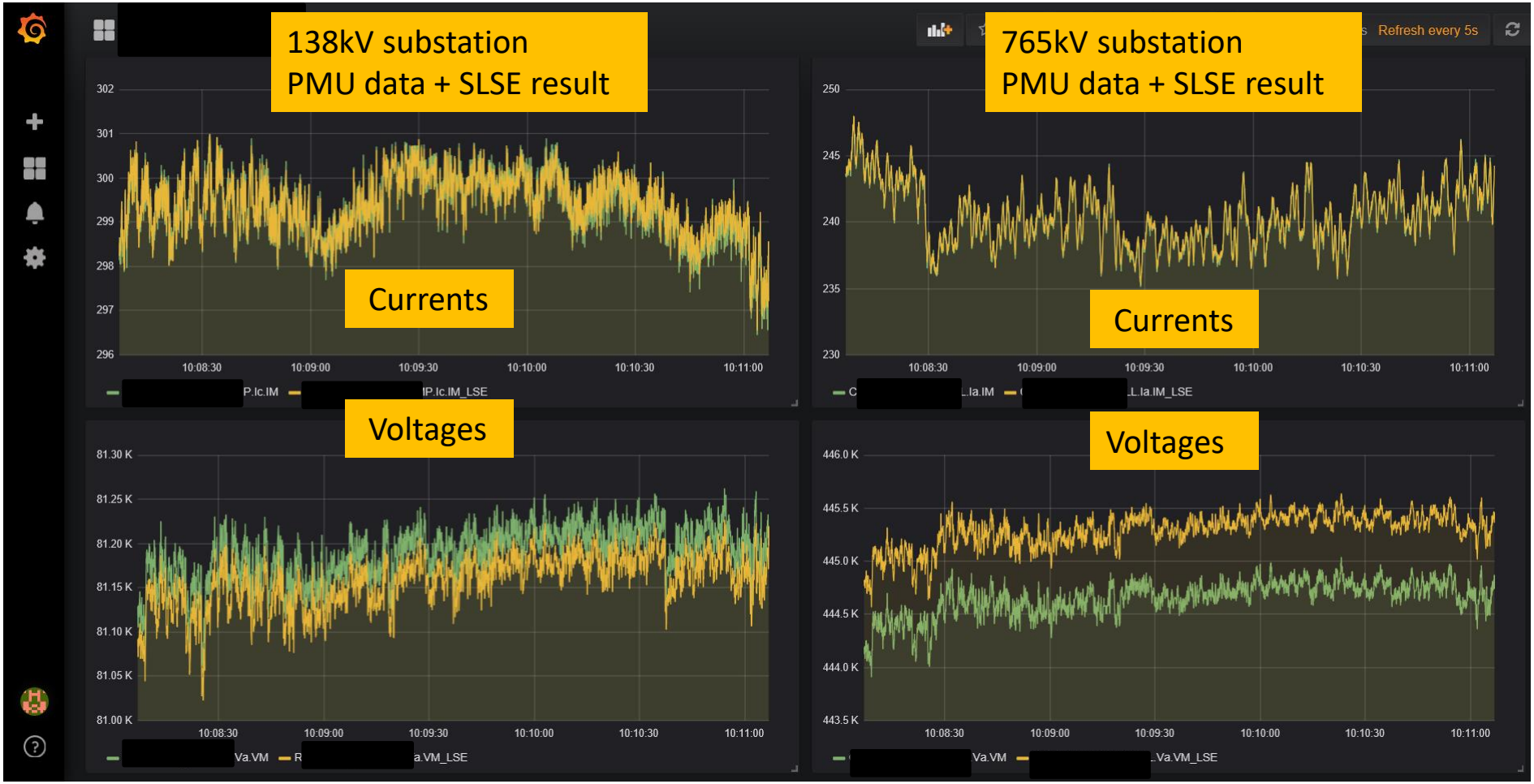
Real-time Trend – PMU and SLSE results



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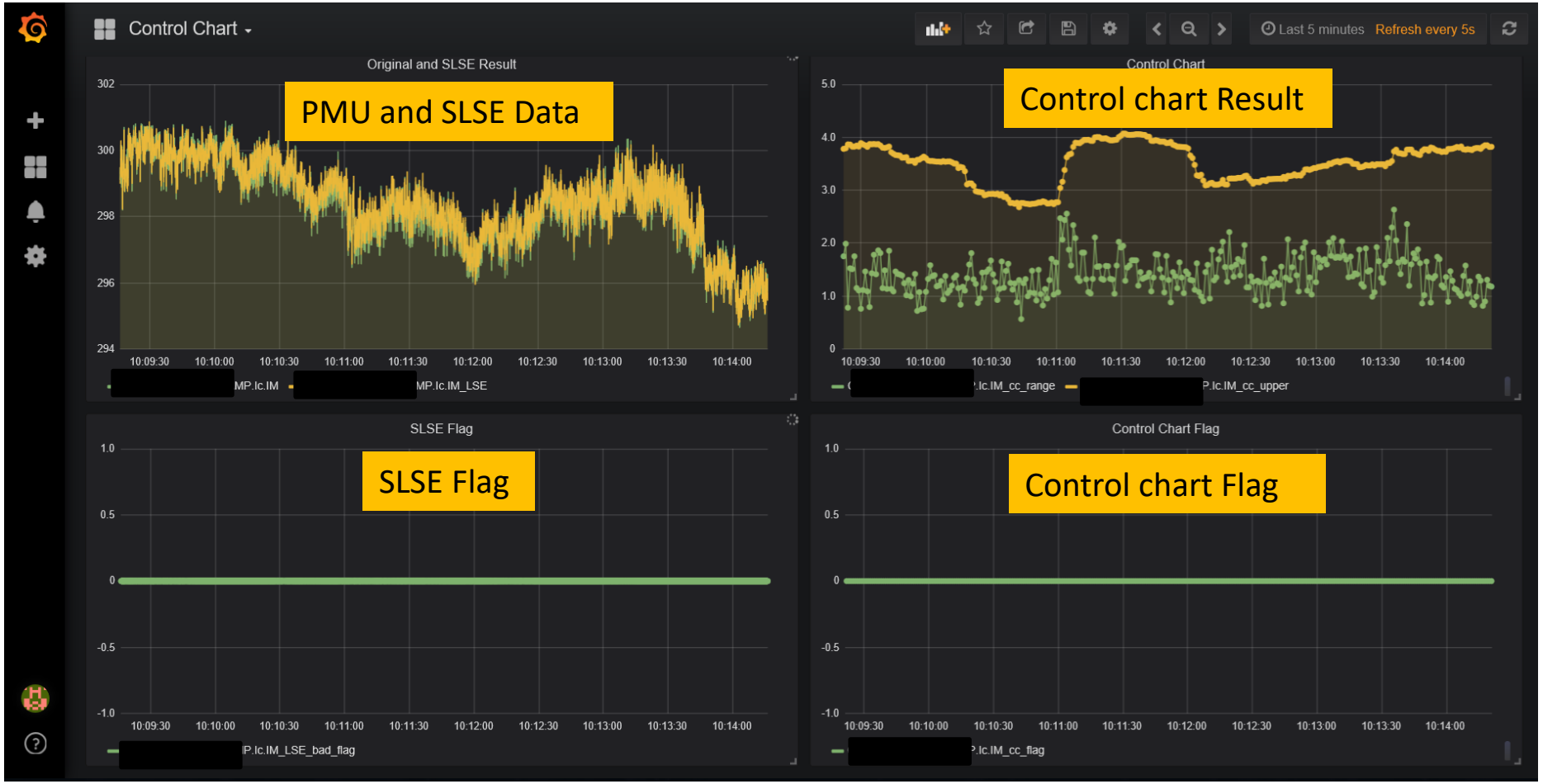
Real-time Trend – Data and Flags



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Major Accomplishments & Next Steps

Completed

- Completed research & scoping study, and system functional design
- Developed two data-driven methods and the model-based SLSE method for anomaly detection
- Simulated 60 cases that include equipment failure and system events
- Tested methods using simulated data and historical field PMU data
- Deployed 6 new PMUs at two demonstration substations
- Completed software development and released to AEP
- Published two papers and presented project work at multiple conferences

Next Steps

- FAT under way at EPG & Integration under way at AEP (Ongoing)
- Project demo for AEP internal users (Planned)
- Ship two hardened PC to AEP for field deployment in substations (Planned)

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Thank You!