Substation Secondary Asset Health Monitoring and Management System
-- Project Update

DOE Grant Award #DE-OE0000850

NASPI Meeting

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Project Introduction

- DOE/OE and DOE/NETL
  - Phil Overholt, Program Manager and 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 Investigators – Kevin Chen, Lin Zhang
  - Key Project Personnel – Ken Martin, Simon Mo, Tingyang Zhang, Neeraj Nayak, Joshua Chynoweth

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Background

- Billions of dollars on transmission and distribution assets
- Key substation assets include transformers, circuit breakers, instrument transformers (CTs, PTs, CCVTs) and Intelligent Electronic Device (Relays, PMU, DFRs)
- Synchrophasor measurement systems have been widely installed in the North American power grids over the last decade
- Data from such assets can be used for asset health monitoring and take proactive steps to prevent equipment failure
- Proper functioning of substation assets is critical for power system operations, reliability and personnel safety

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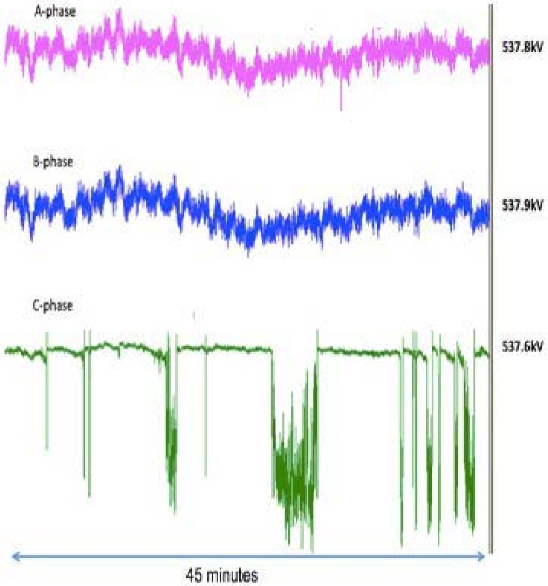
Technical Merit

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 replacement and repair before equipment is damaged
- Reduce utility's forced outage of equipment
- Reduce utility's operating and maintenance costs

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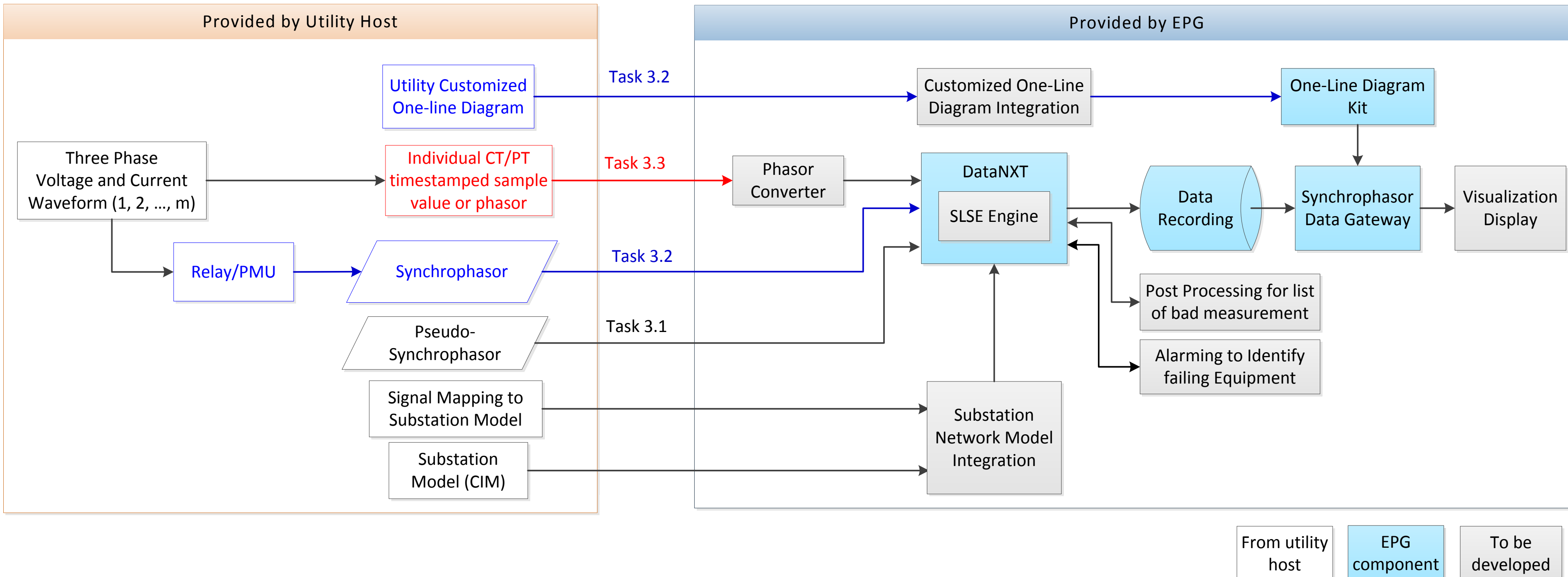
Technical Approach

- Central Processing: Data sent from substations to central site



- Data from substation will be provided by utility partners
- Leverage existing synchrophasor technology
- Research new algorithms in this project
- Validate at cost share partner substation locations
- Adapt for general commercial use at other utilities

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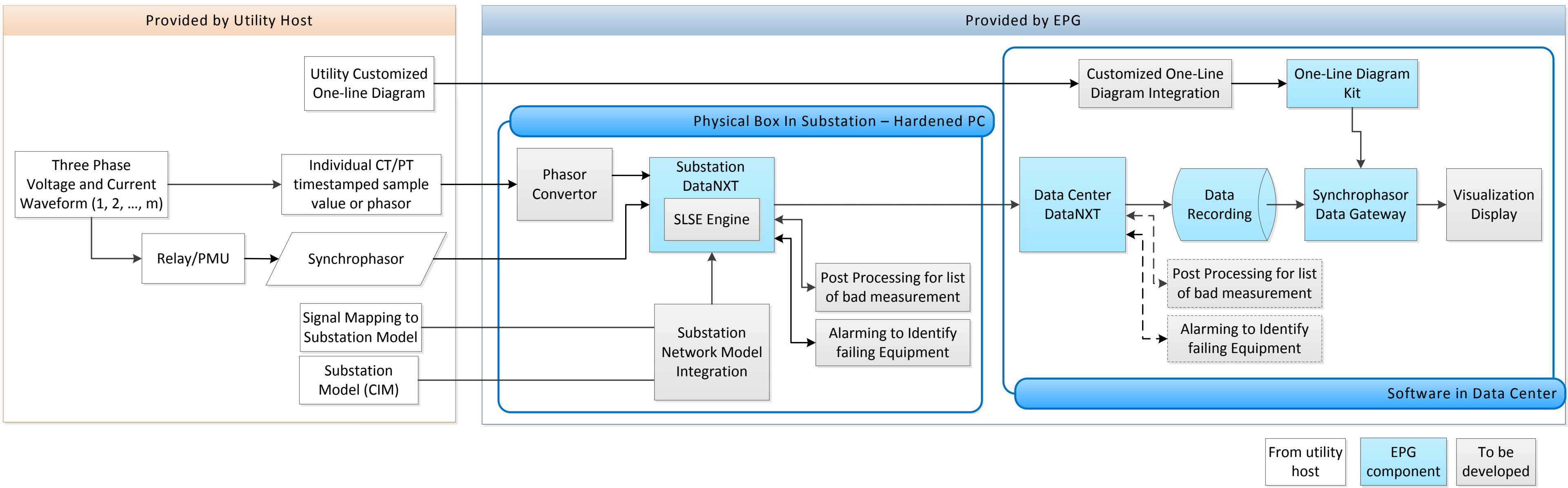
Technical Approach (Continued)

- Local Processing at substations: Results sent to asset monitoring center



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Research and System Design

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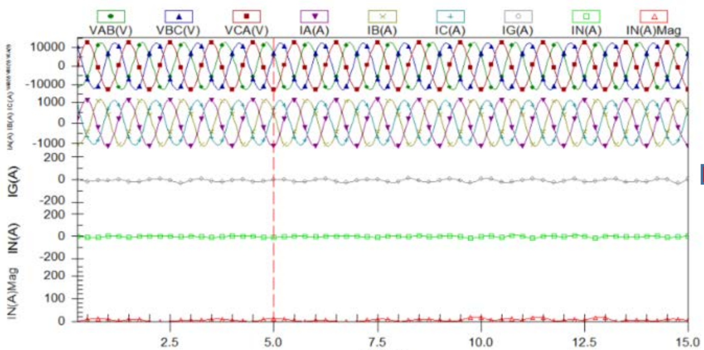
Research and Scoping Study – Equipment Failure Modes

Cause of Failure / Failure Modes		
CT	**PT**	**CVT/CCVT**

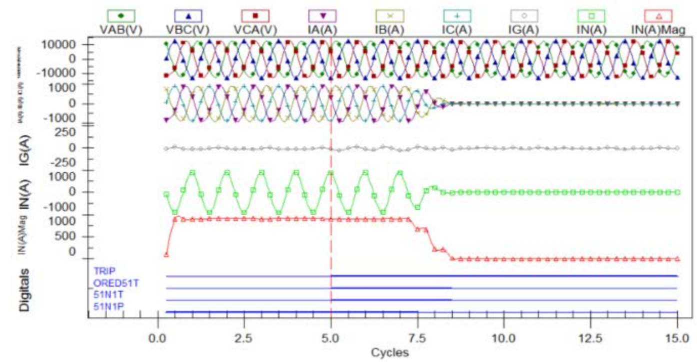
•Loose Connections or Corroded Connections
•Shorting of Winding Turns
•Turns to Ground Shorting
•Open CT secondary
•Insulation
    •Erosion of insulation, Insulation Failure
    •Voids in Insulation – Increased moisture content, Partial Discharge – increased dielectric losses
    •Aging of CT and wiring insulation, Oil Leaks
    •High Insulation power factor of internal insulation
•Magnetic core saturation
	•Ferroresonance
	    •Switching Transients
	    •PT Saturation
	•Insulation Failure
	    •High Stress Voltage Difference across some of the windings
	    •Shorting of Adjacent Windings due to insulation failure
	    •Deterioration of Insulations
	•Transient Overvoltage's & Lightning surges
	•Loose Connections
		•Failure of one or more capacitor elements in HV stack – Overvoltage and Stress on each capacitor
		•Failure of one or more capacitor elements in LV grounding stack – decrease in secondary voltage
		•Failure of intermediate voltage transformer or series reactor – change in phase angle and/or voltage
		•Failure of Ferroresonance suppression circuit – waveform distortion, changes in phase angle and/or voltage
		•Multiple element failure can cause explosion – Staff Safety Issues
		•Failure of filter circuit or spark gaps used for harmonics & transient voltage reduction – causes increased stress on components
		•External Flashover, failure of other components – expansion membrane, gasket seal
		•Low oil conditioned due to oil leak – capacitor failure

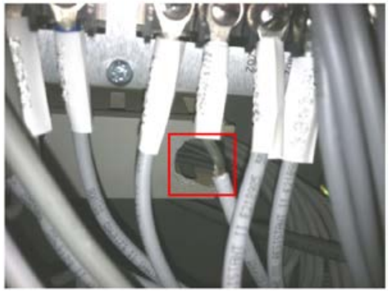
Signature Examples – CT



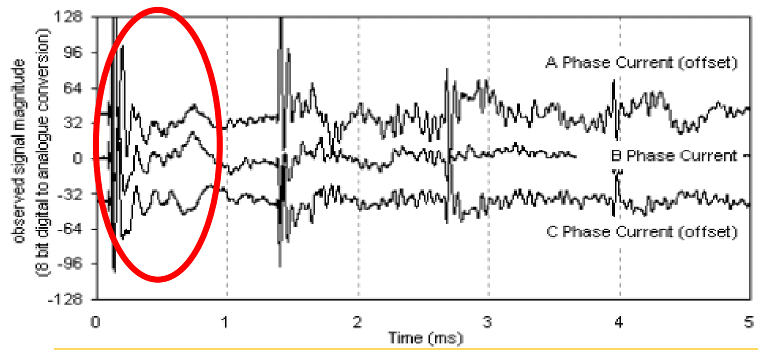
Normal Operation – No failure

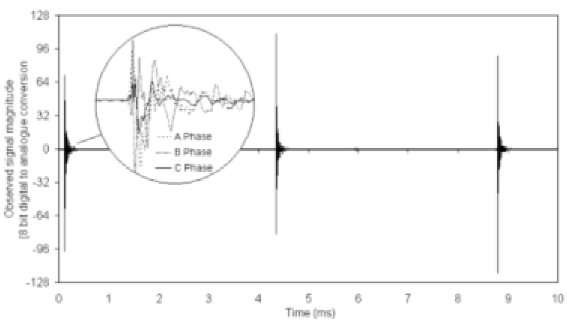
Reference: [G]





Open Circuit in CT secondary due to Wiring damage





High frequency transients observed 8 minutes before CT failure (partial discharge in insulation)

Reference: [F]

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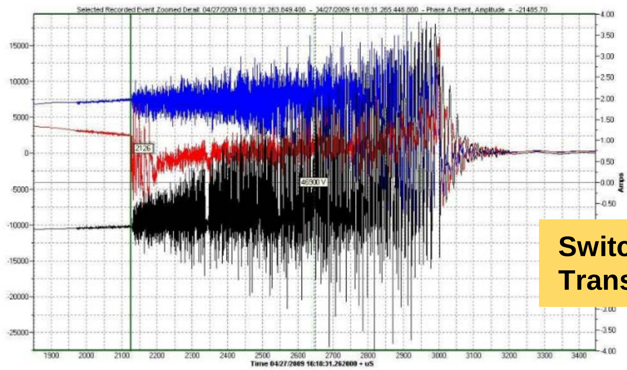
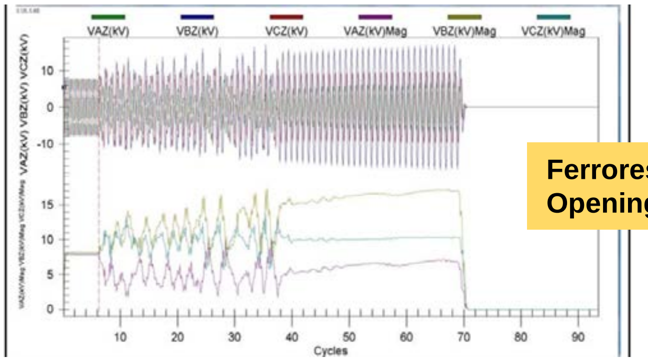
Signature Examples - PT



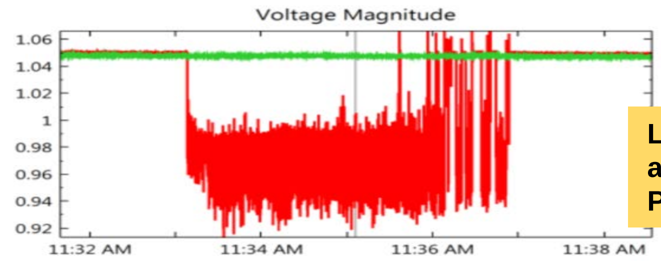
Switching Transients

Reference: [A]

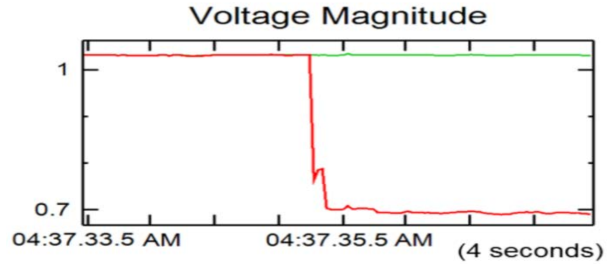


Ferroresonance – Opening Breaker

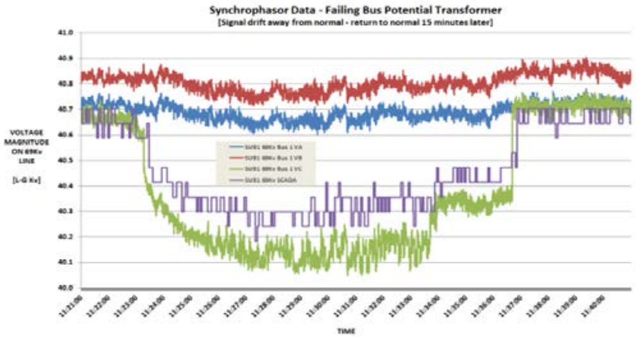
Reference: [C]



Loose Connection at PT feeding the PMU



Blown fuse on One Phase of PT



Internal Primary Winding Issue

Reference: [A]

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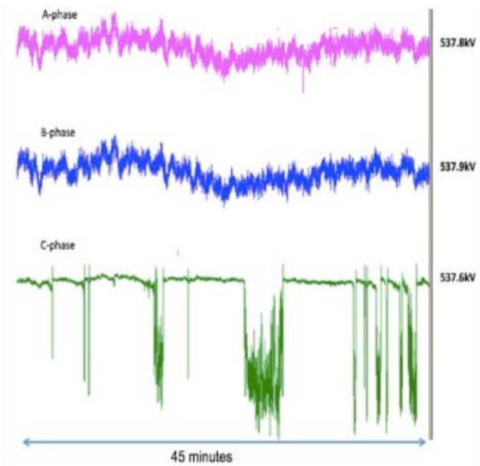
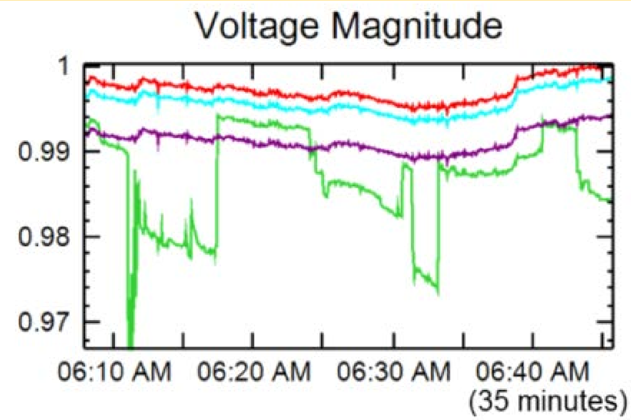
Signature Examples - CCVT

Capacitor Failure in C phase



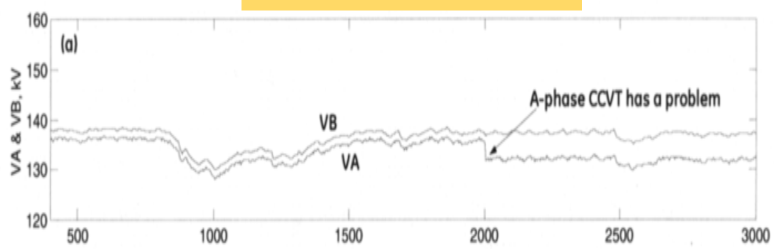
Reference: [A]

Loose Fuse Connections in CCVT Safety Switch



Reference: [A]

A - Phase CCVT Issue



Reference: [B]

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Available Inputs and Desired Output

Available Input - Data

- Raw PMU Data
- LSE Data
- Redundant Measurements
- Other Phases
- DFR Data*

Desired Output – Flag Asset Fail

- Minimal false positive
- Minimal false negative
- Maximize prediction time
- Within Computing Constraints

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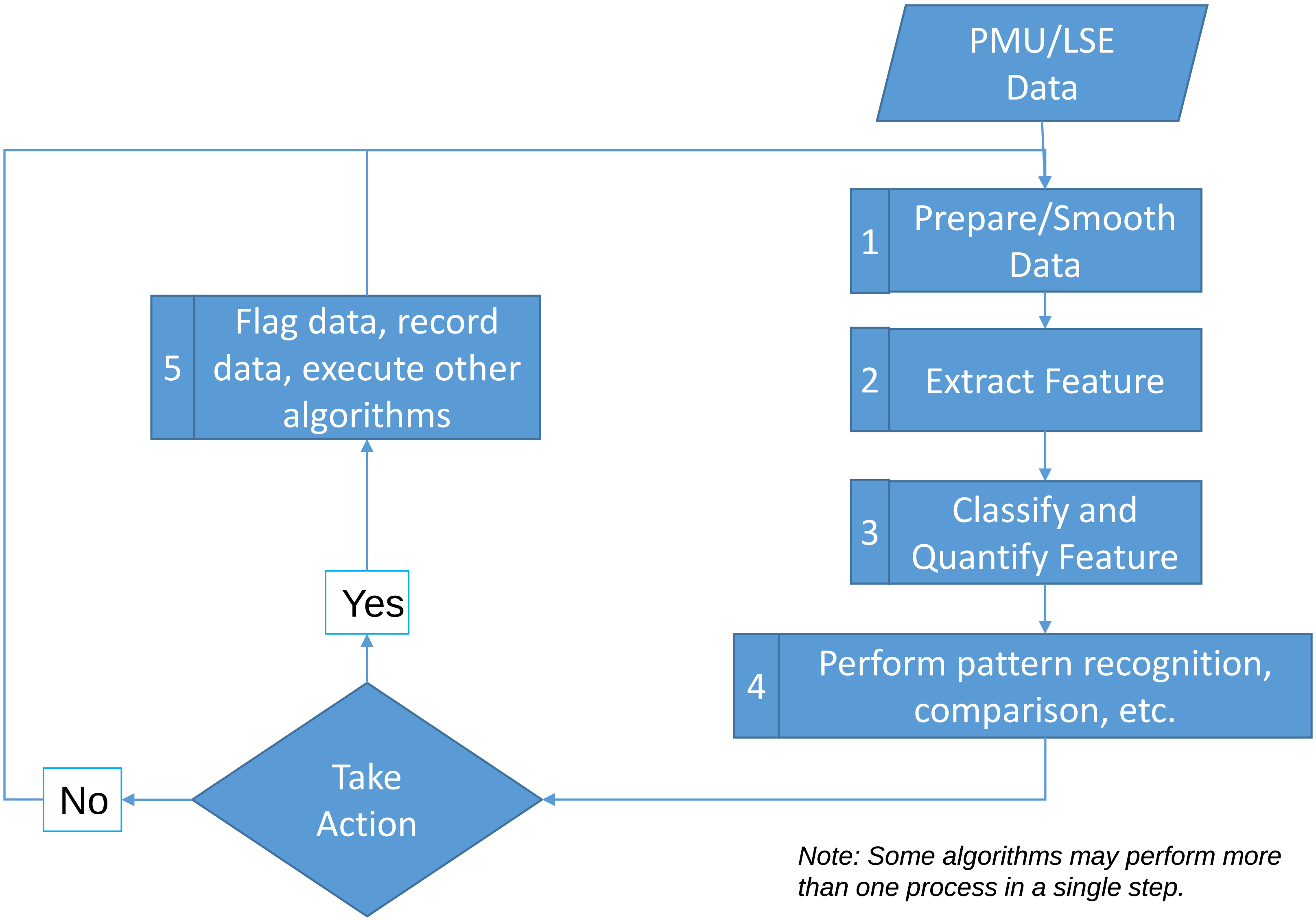
5 Processes of Data-driven Method

- Detect and React to Anomalies



Note: Some algorithms may perform more than one process in a single step.

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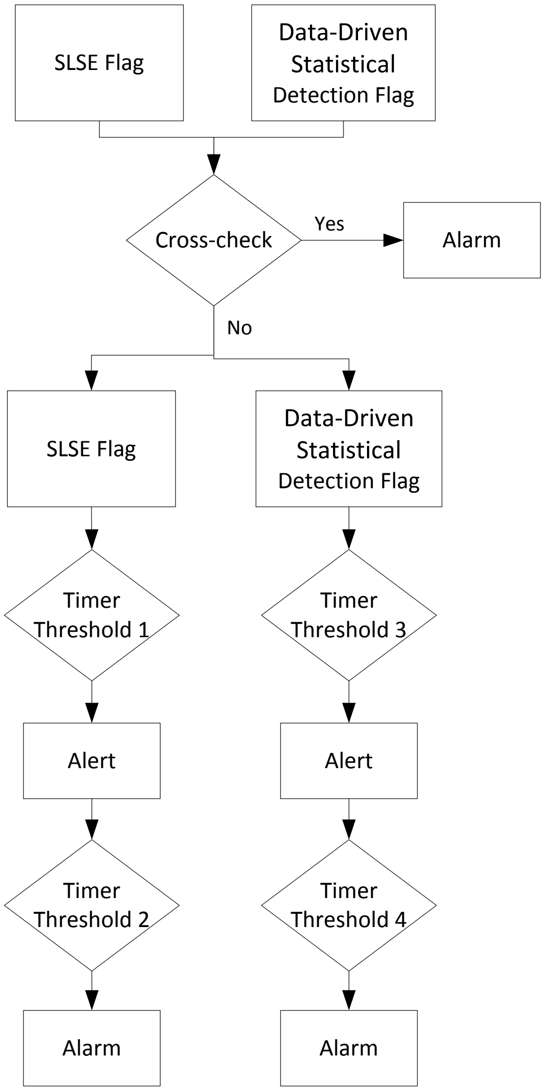
Anomaly Alarming

- SLSE and data-driven statistical detection flags are cross checked for consistency

- Two different user-defined timers are used to track these flags



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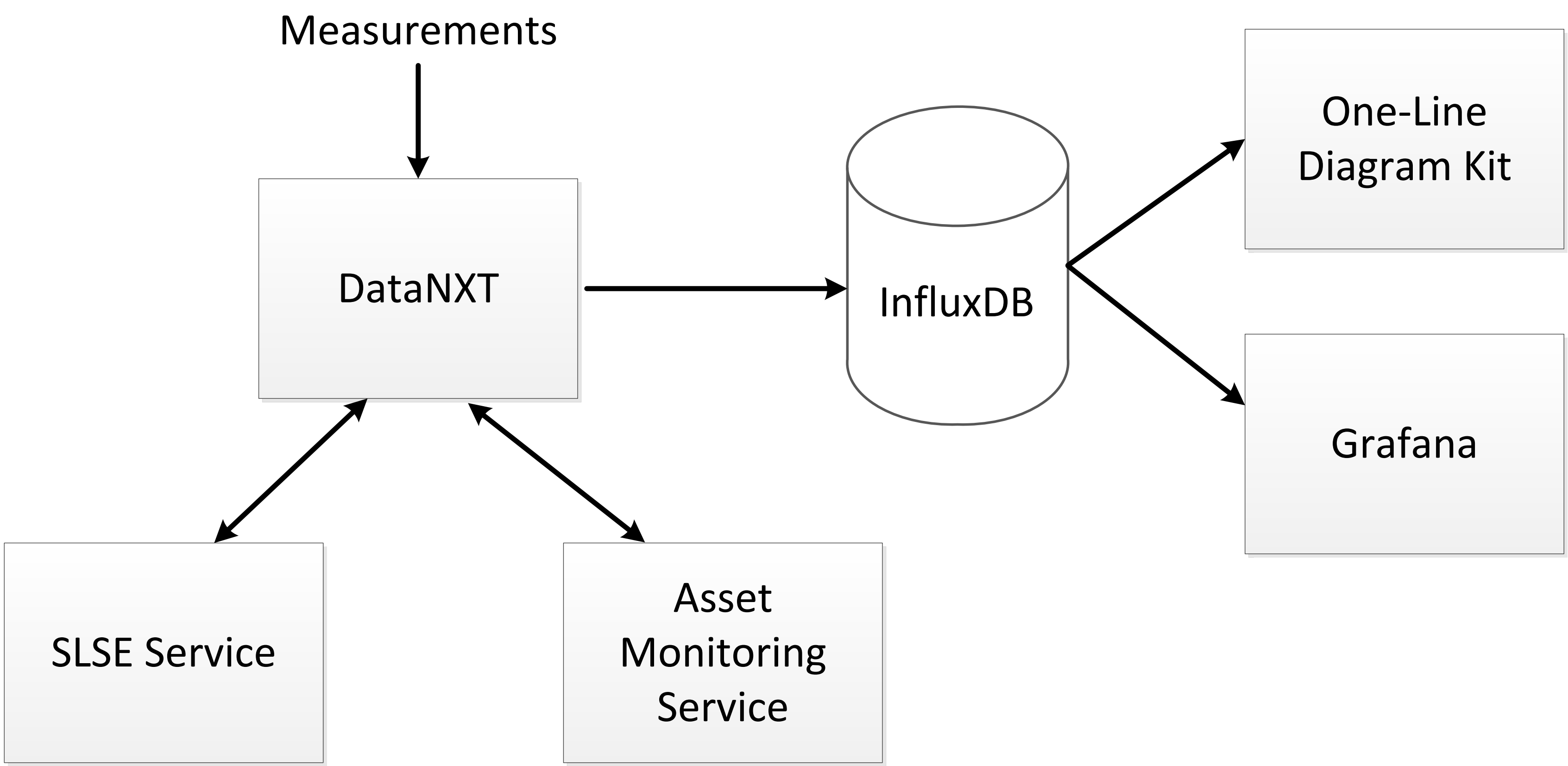
System Services Design



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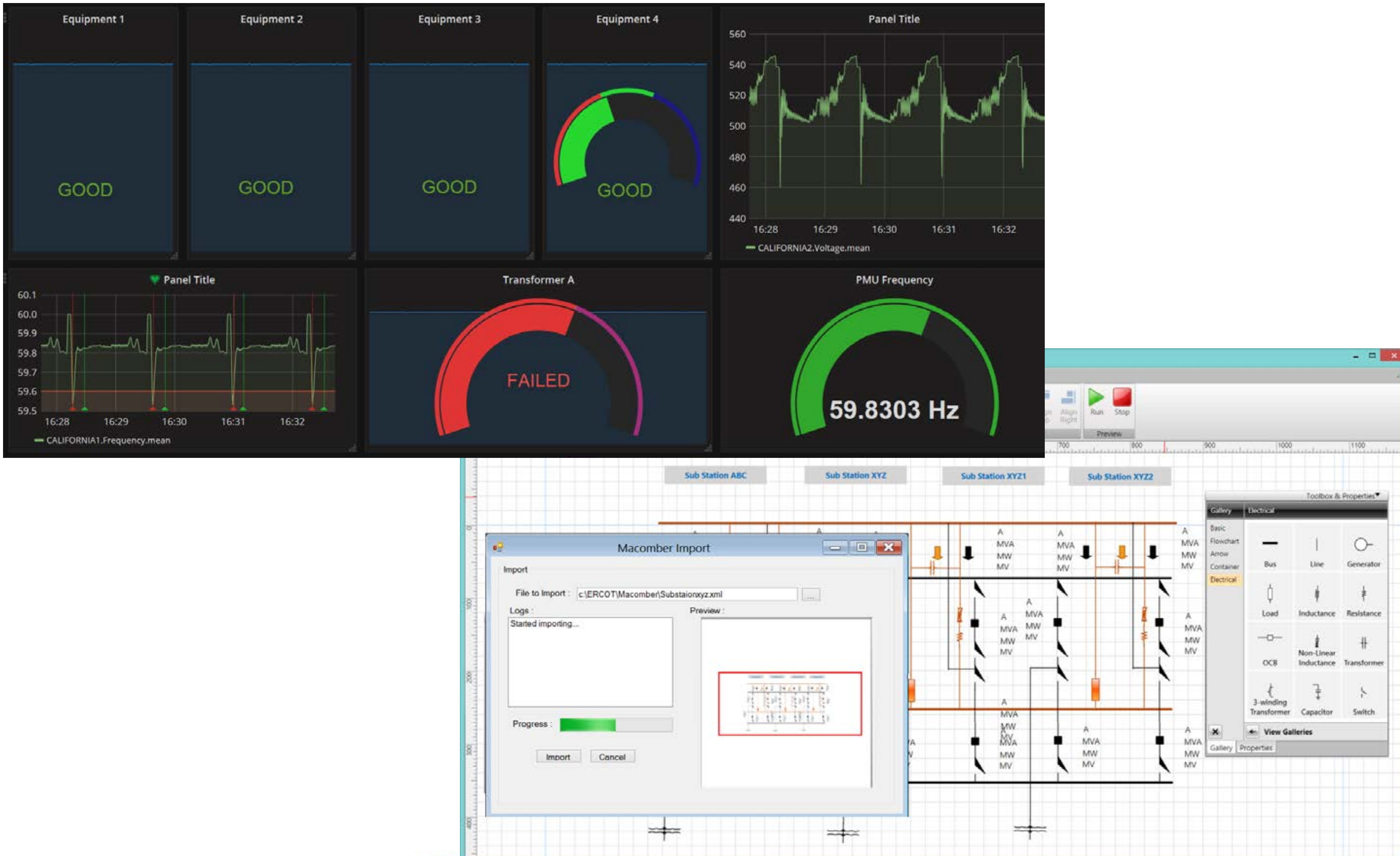
Grafana and One-line Diagram Visualization



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Preliminary Simulation Studies

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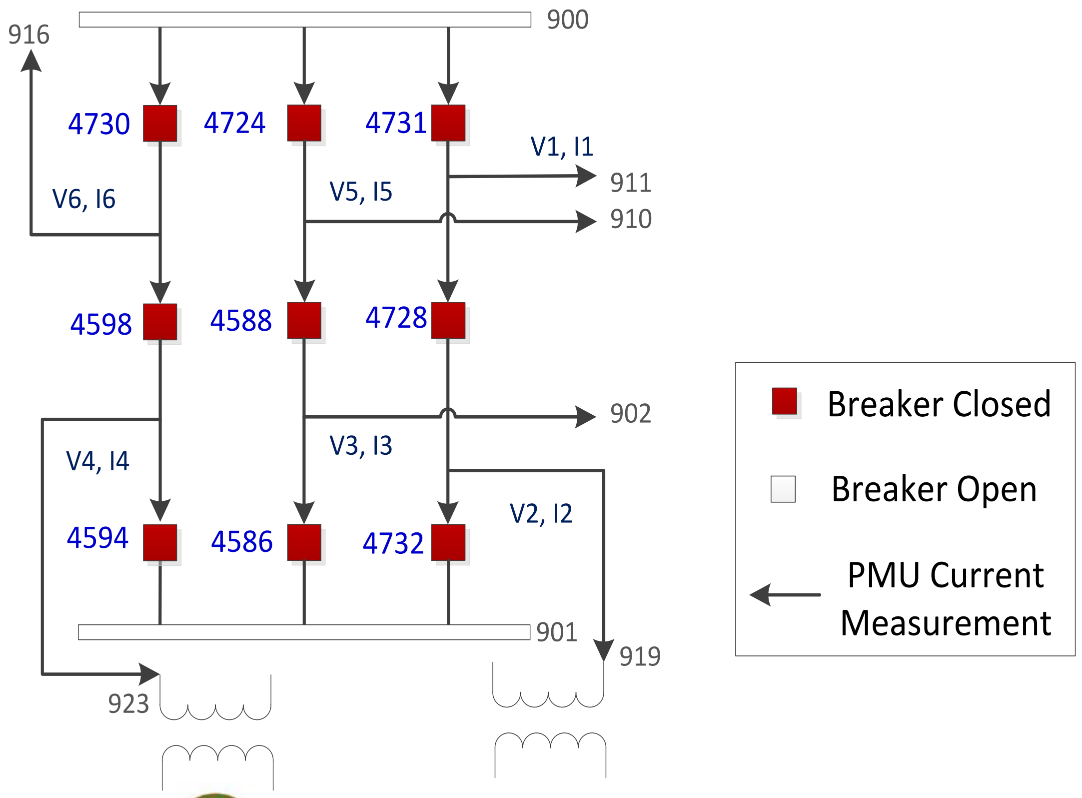
Preliminary Case Studies

- A typical breaker-and-a-half schema 500 kV substation configuration:
  - Full observability of current injection and flow
  - Breaker currents are as measurement inputs, as well as bus and line voltages



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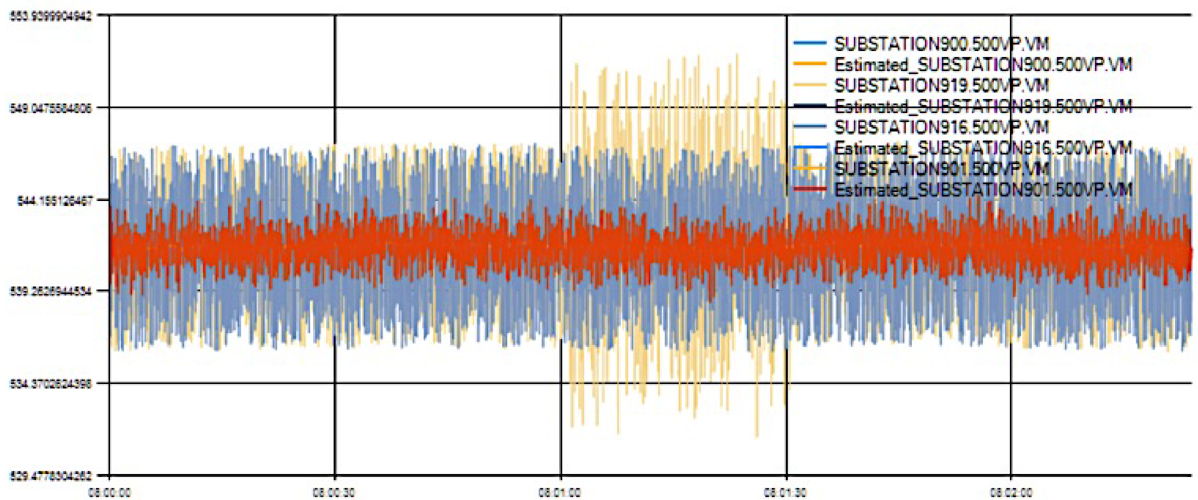
Case 1: Normal Operation

- A 1% noise to the original signal is added as anomaly to the raw measurement V2 voltage magnitude:

Comparison of raw and estimated VM for V2



Substation equipment status alarm:

1/1/2017 8:00 AM	SUBSTATION_500_919 is exceeding limit!	Alarm
1/1/2017 8:00 AM	SUBSTATION_500_919 is exceeding limit!	Alarm
1/1/2017 8:01 AM	SUBSTATION_500_919 is exceeding limit!	Alarm
1/1/2017 8:01 AM	SUBSTATION_500_919 is exceeding limit!	Alarm

The alarm points to the PT feeding the voltage signal.

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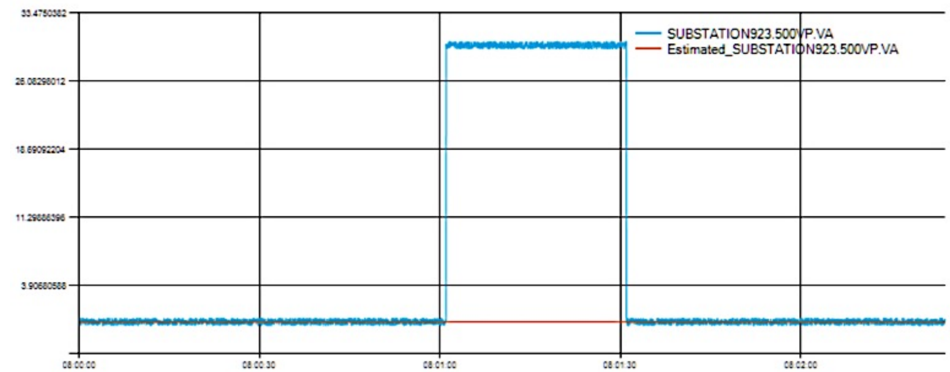
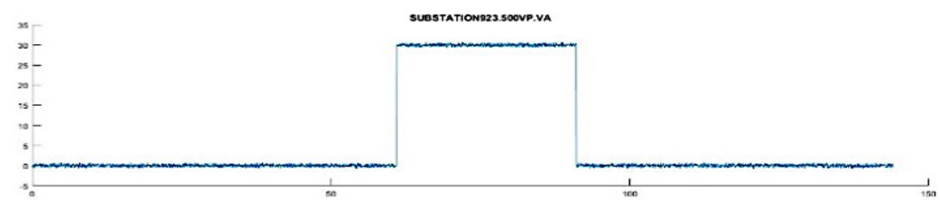
Case 2: Split Bus Operation – Angle

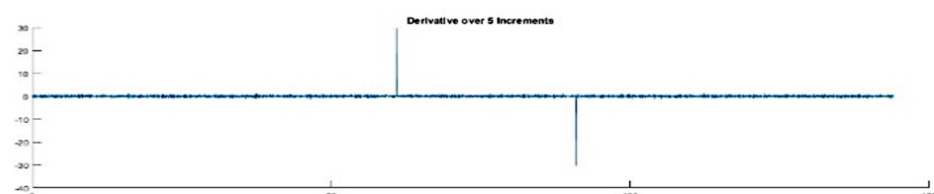
- Breaker 4598, 4588 and 4728 are open.
- A 30 degree offset to the original signal is added as anomaly to the raw measurement V4 voltage angle:

Comparison of raw and estimated voltage angles for V4:



Raw voltage angle data and its derivative over 5 time increments:





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AEP PMU Deployment and PSCAD Simulation Studies

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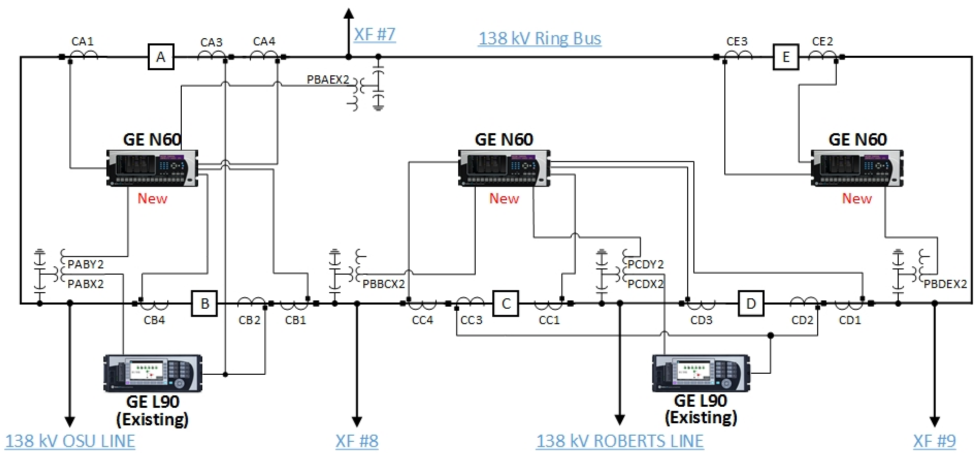
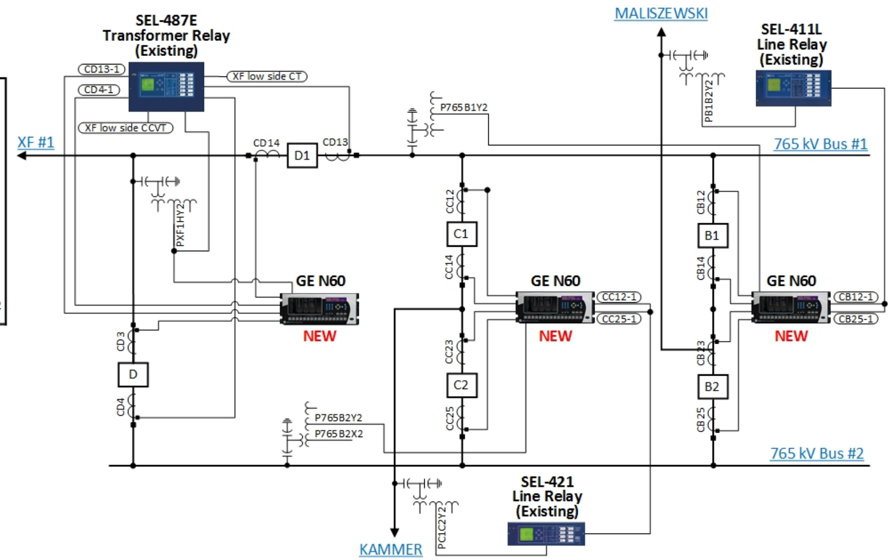
AEP PMU Deployment

WEST CAMPUS STATION PMU Connection



VASSELL STATION 765 kV Bus PMU Connection



- 3 new PMUs deployed at West Campus
- 3 PMUs planned at Vassell by Sept 2018
- Mainly to get breaker current signals

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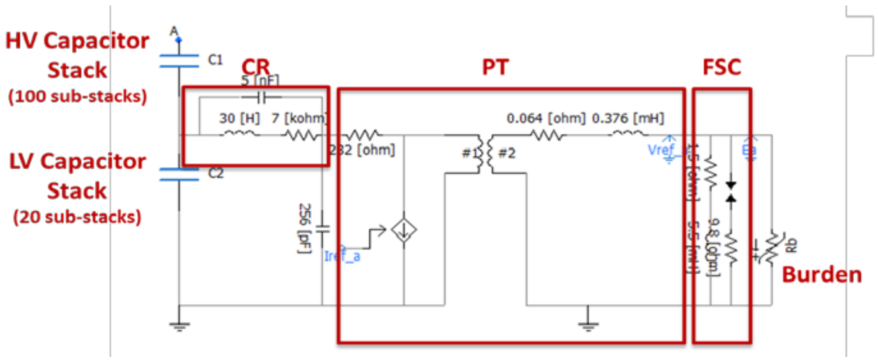
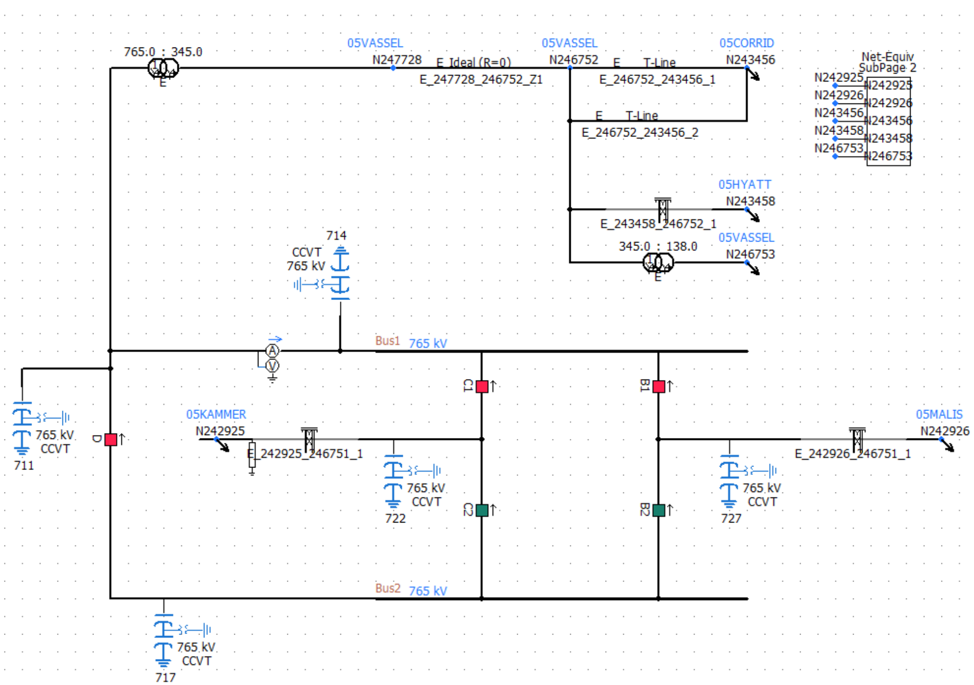
AEP PSCAD Simulation Cases—CCVT Scenarios





- Vassell Set 1: CCVT 8 Scenarios
- West Campus Set 1: CCVT 10 Scenarios

1. **Failure modes**
   - Failure of one or more capacitor elements in HV stack (capacitor stack shortage)
     - One capacitor fails (short circuit) in phase A
     - Five capacitors fail in phase B
     - One capacitor fails first, 2nd capacitor fails after 30sec, in phase C
   - Failure of one or more capacitor elements in LV grounding stack (capacitor stack shortage)
     - One capacitor fails (short circuit) in phase A
     - Five capacitors fail in phase B
     - One capacitor fails first, 2nd capacitor fails after 30sec, in phase C
   - Failure of Ferro-resonance suppression circuit (or simulation of transients without any Ferro-resonance circuit)
     - Simulation of temporarily short circuit CCVT secondary, with FSC; clearing around 7 cycles
     - Simulation of temporarily short circuit CCVT secondary, without FSC; clearing around 7 cycles

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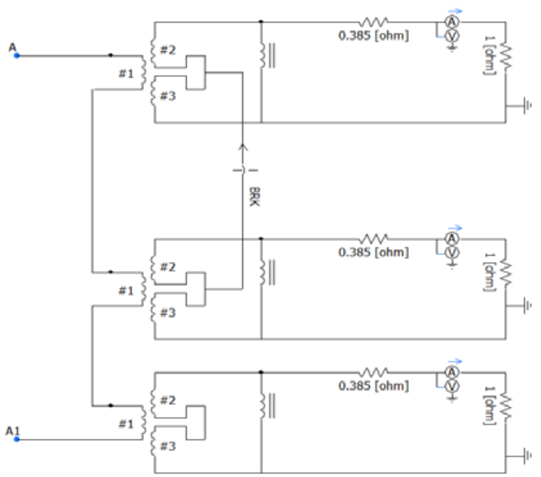
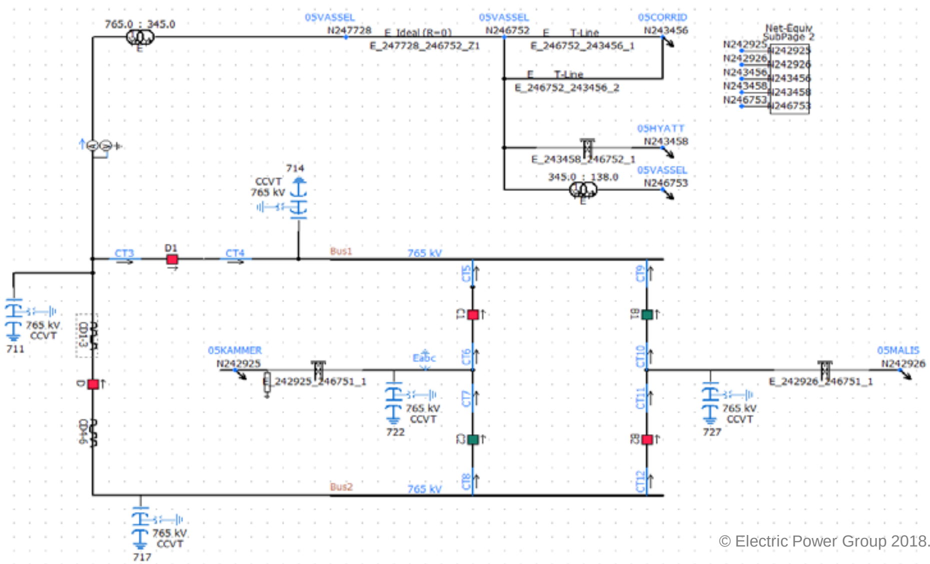
AEP PSCAD Simulation Cases–CT Scenarios





- Vassell Set 2: CT 20 Scenarios
- West Campus Set 2: CT 22 Scenarios

1. **Failure modes (First with all breaker closed)**
   - Short turns (turn to turn)
     - One CT turn-to-turn shortage occurs at 10sec in phase A, total simulation 40sec: please try different turns
     - Open breaker B1&C2, do the simulation again.
   - Short turns (turn to ground)
     - One CT turn-to-ground shortage occurs at 10sec in phase A, total simulation 40sec: please try different turns
   - Short turns (turn to turn between different coils)
     - turn-to-turn shortage between two CTs occurs at 10sec in phase A, total simulation 40sec: please try different turns
   - Ratio Error
     - The one you have now is good
   - Large burden (Loose Connections or Corroded Connections)
     - One CT, case occurs at 10sec, total 40sec
   - Open CT secondary in phase A at 10sec, total 40sec
   - CT polarity error: (Static). Is it possible to simulate this kind?
   - External events:
     - A bus fault at 10sec
     - A line fault at 10 sec

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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

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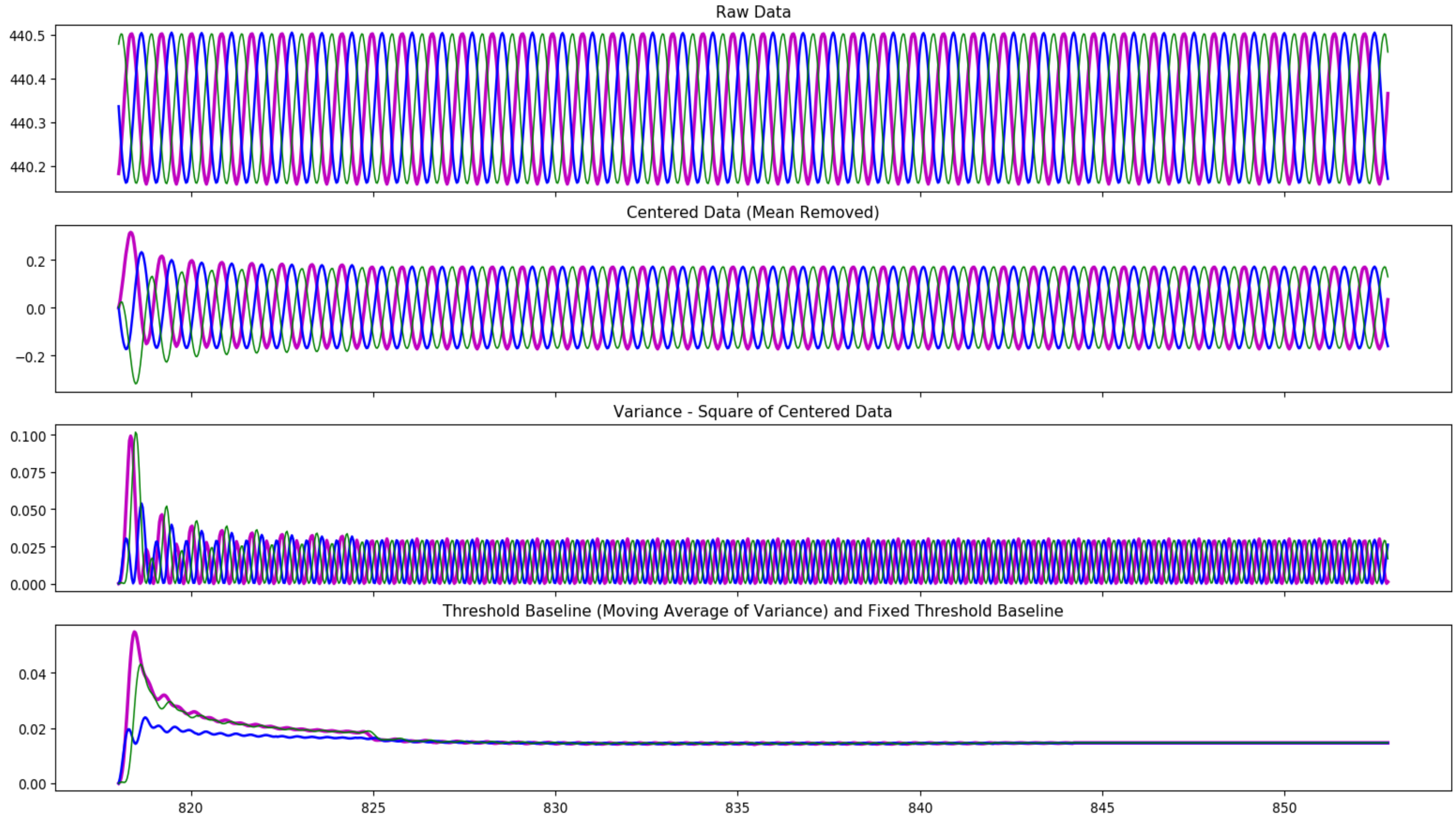
Preliminary Test Results – No Anomaly



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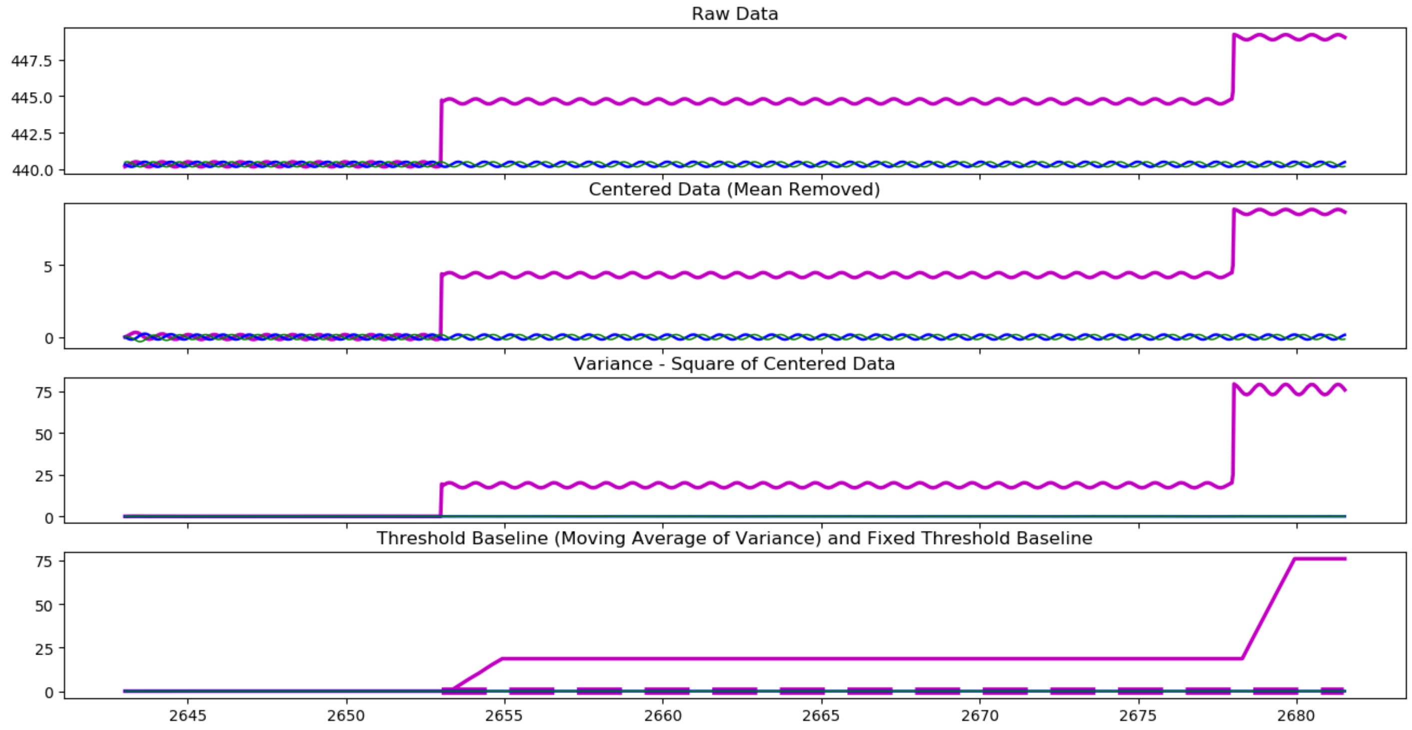
CCVT - Case 1C Results



1C - CCVT 711 - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

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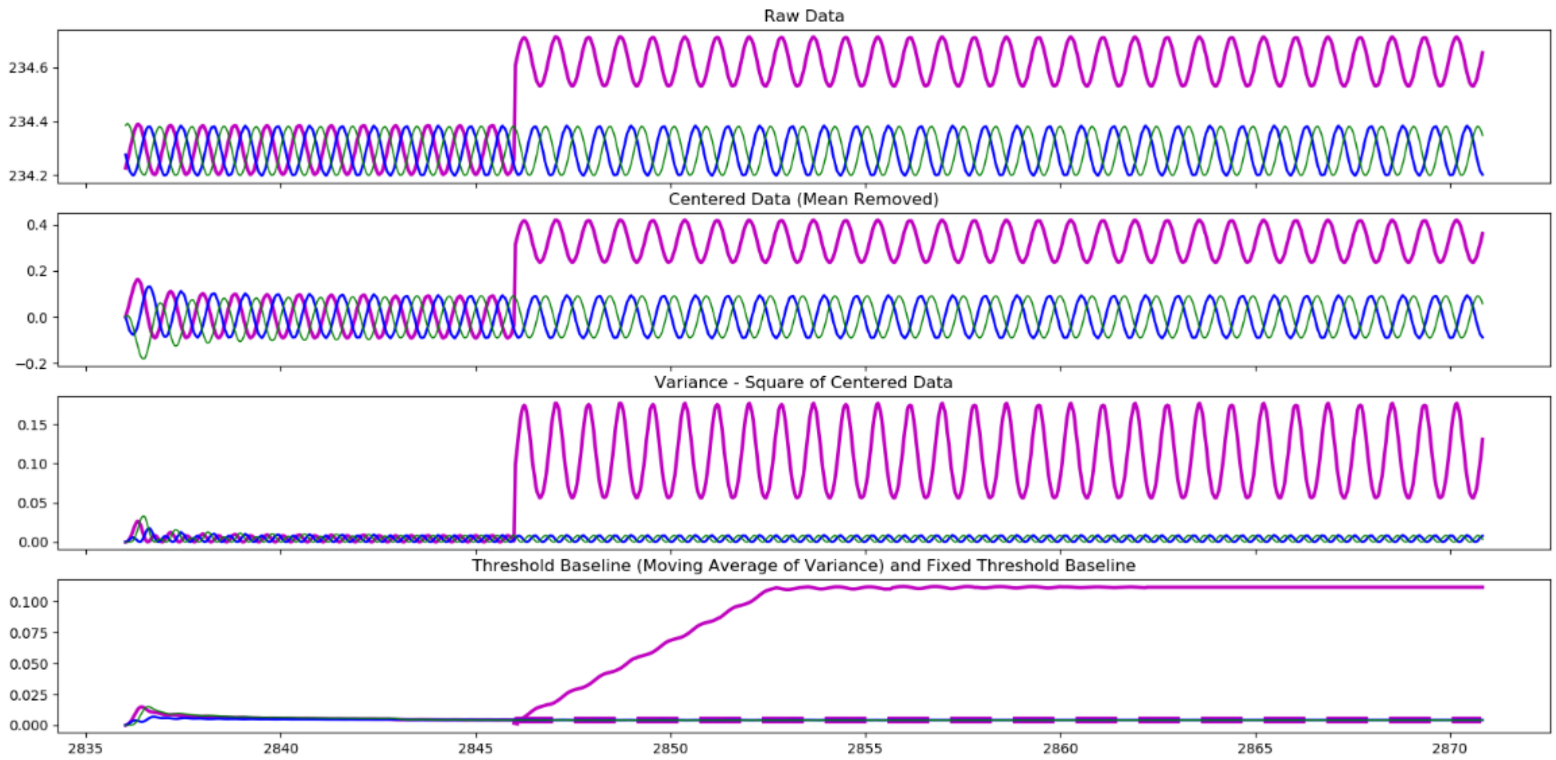
CT - Case 4A Results



4A - Normal Operation, one CT turn-to-turn shortage occurs at 10sec in phase A

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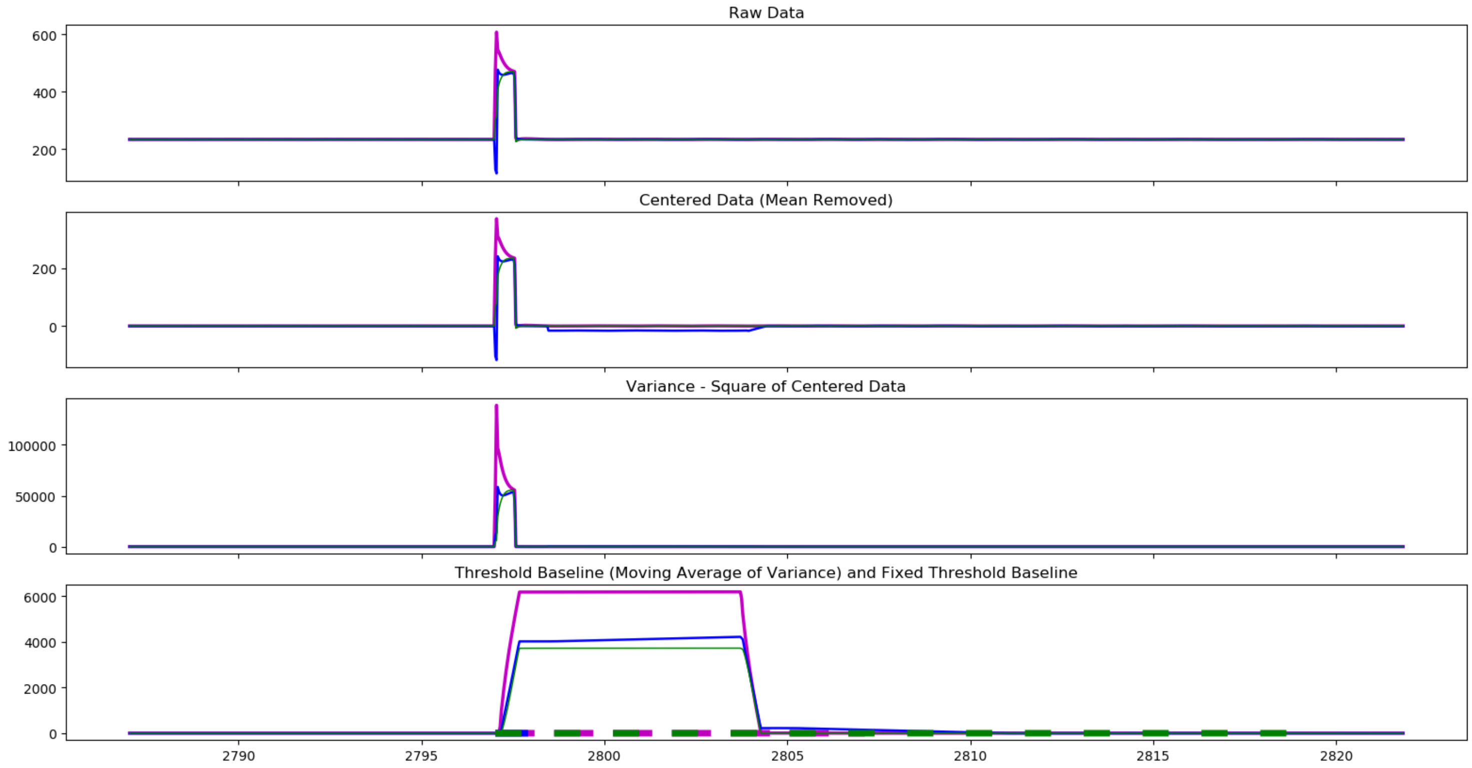
CT - Case 11B Results



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.

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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).

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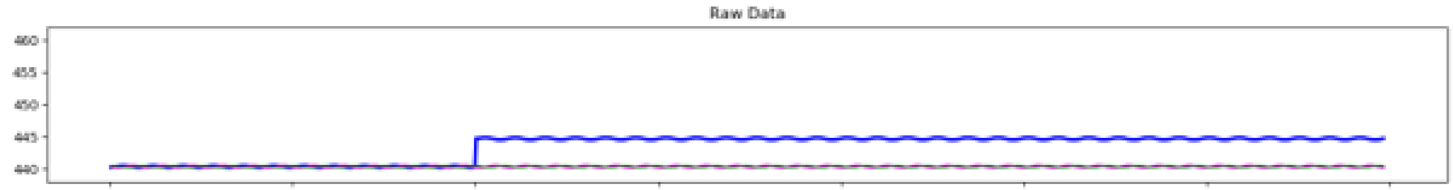
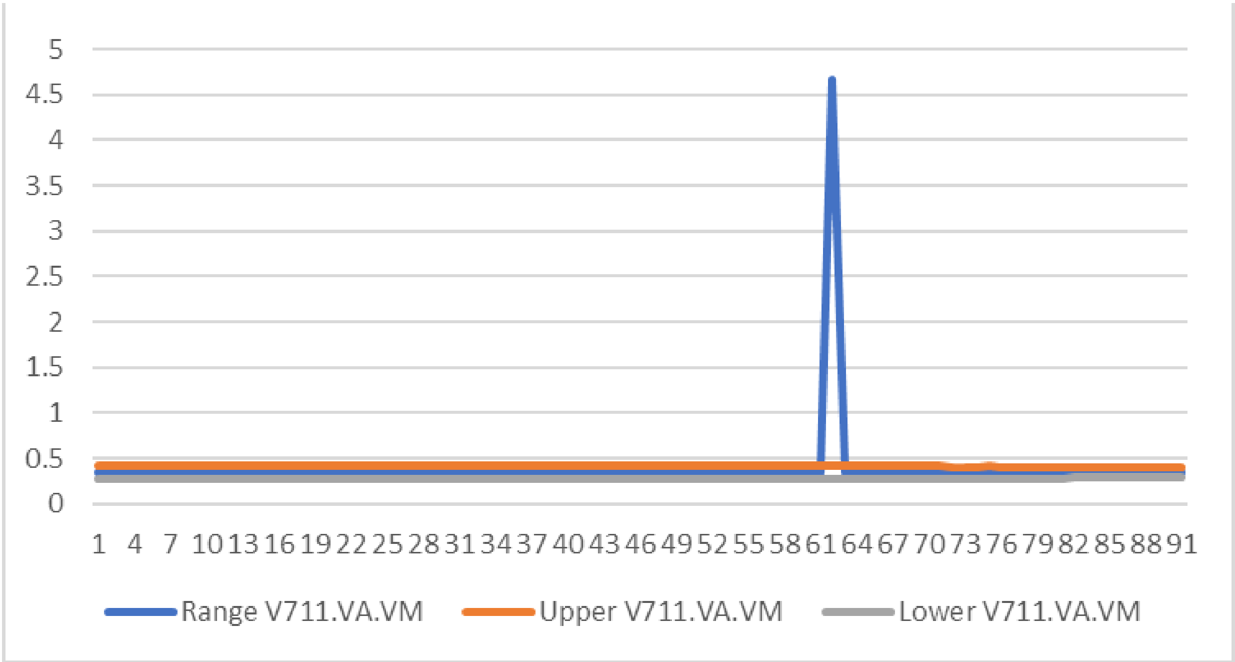
Control Chart Test - Case 1A Results





1A, graph of voltage data CCVT 711 - 1 capacitor fails (short circuit) in phase A at 10 s

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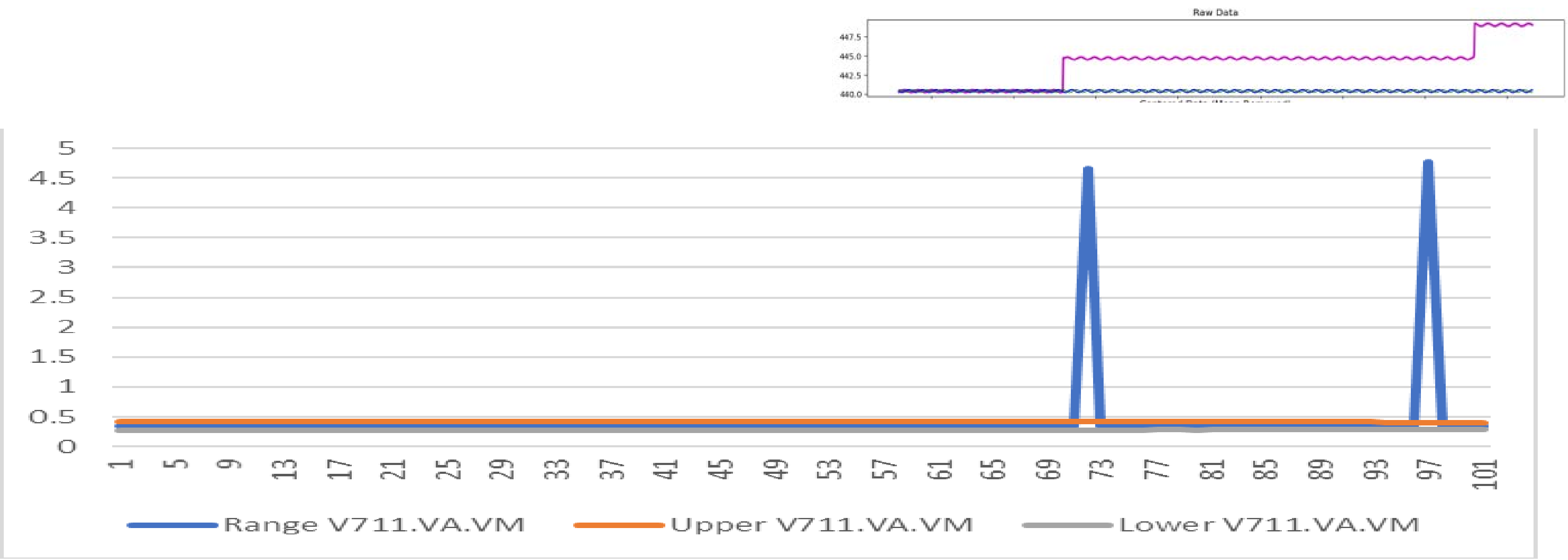
Control Chart Test - Case 1C Results



1C - CCVT 711 - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

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SLSE Method

- Current State Estimator: Estimate the breaker current. In this model, all the nodes and breakers at the same voltage level inside the substation construct a zero-impedance power system, and the measurement function can be established by applying KCL. For each branch current, it is a function with respect to two breaker currents if it is a breaker-and-a-half schema. For each breaker current, it is a function with respect to itself.

- Voltage State Estimator: Estimate the bus voltage from the voltage measurements at all the nodes comprising this bus. This is essentially a weighted average and is formulated here as a zero-impedance voltage state estimator. The states are the voltage of each bus, and the measurements are the voltage phasor measurements at the nodes belonging to the bus.

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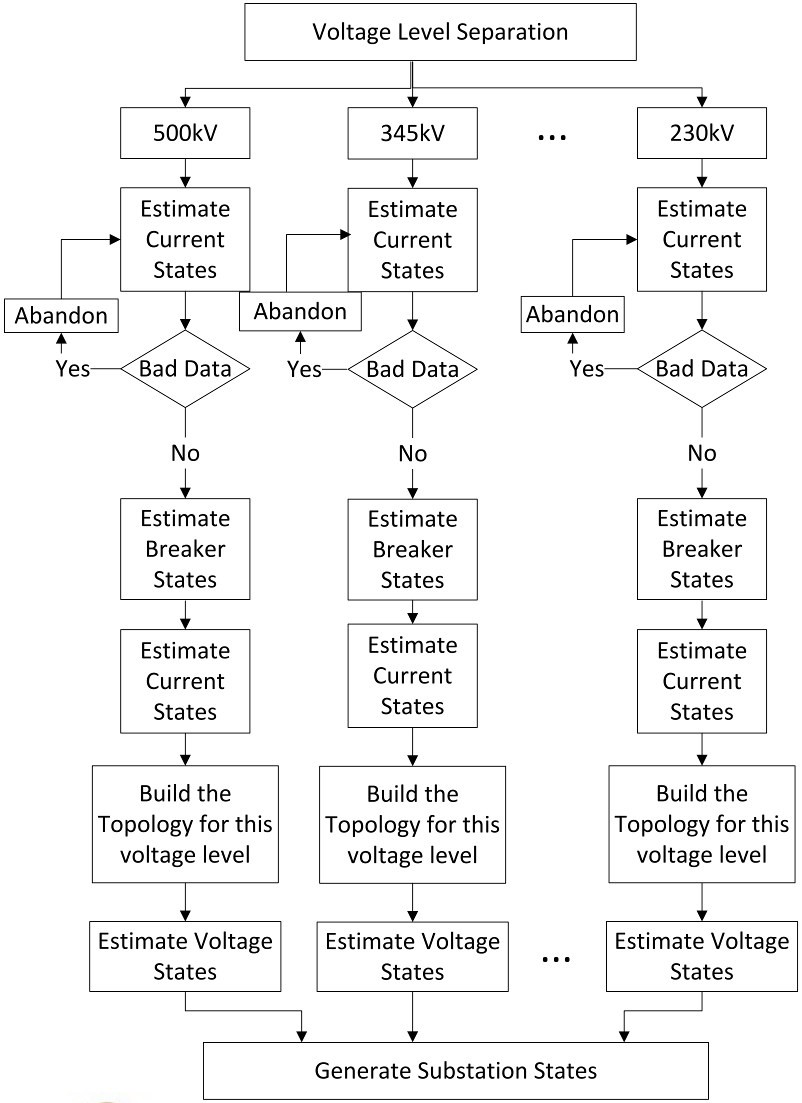
Flow Chart of SLSE



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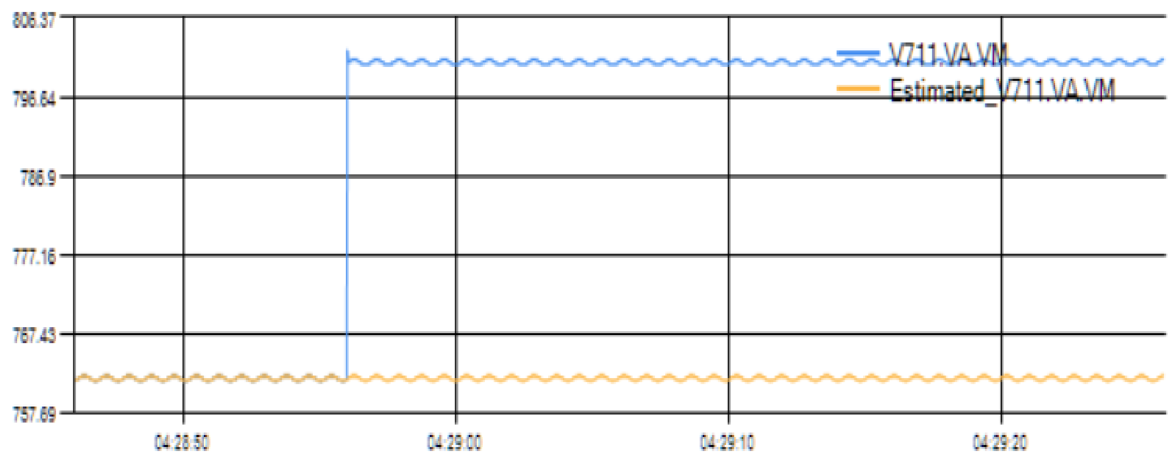
SLSE Test - Case 1B Results

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	☐



1B, graph of voltage data CCVT 711 - 5 capacitor fails (short circuit) in phase A at 10 s

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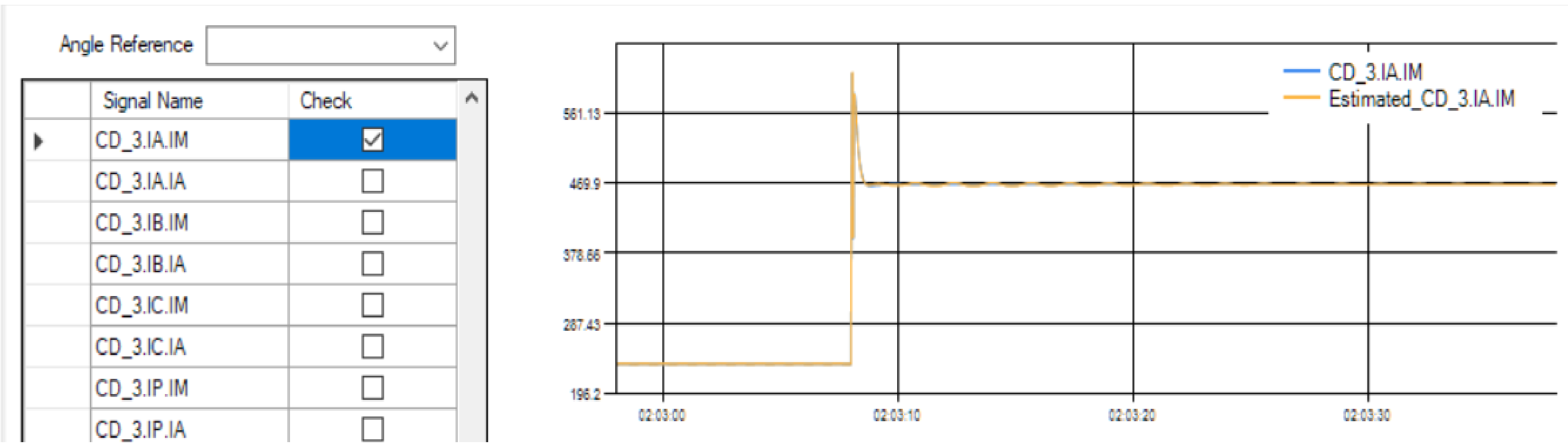
SLSE Test –System Fault

SLSE successfully bypassed the anomaly caused by the system fault and did not false alarm



11A - A single phase-to-ground bus fault on bus 1 phase A at 10sec , fault duration is 0.1 s, open D1, C1, B1 at t = 10.075s, no reclose.

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1 Hour Field PMU Data Testing

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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

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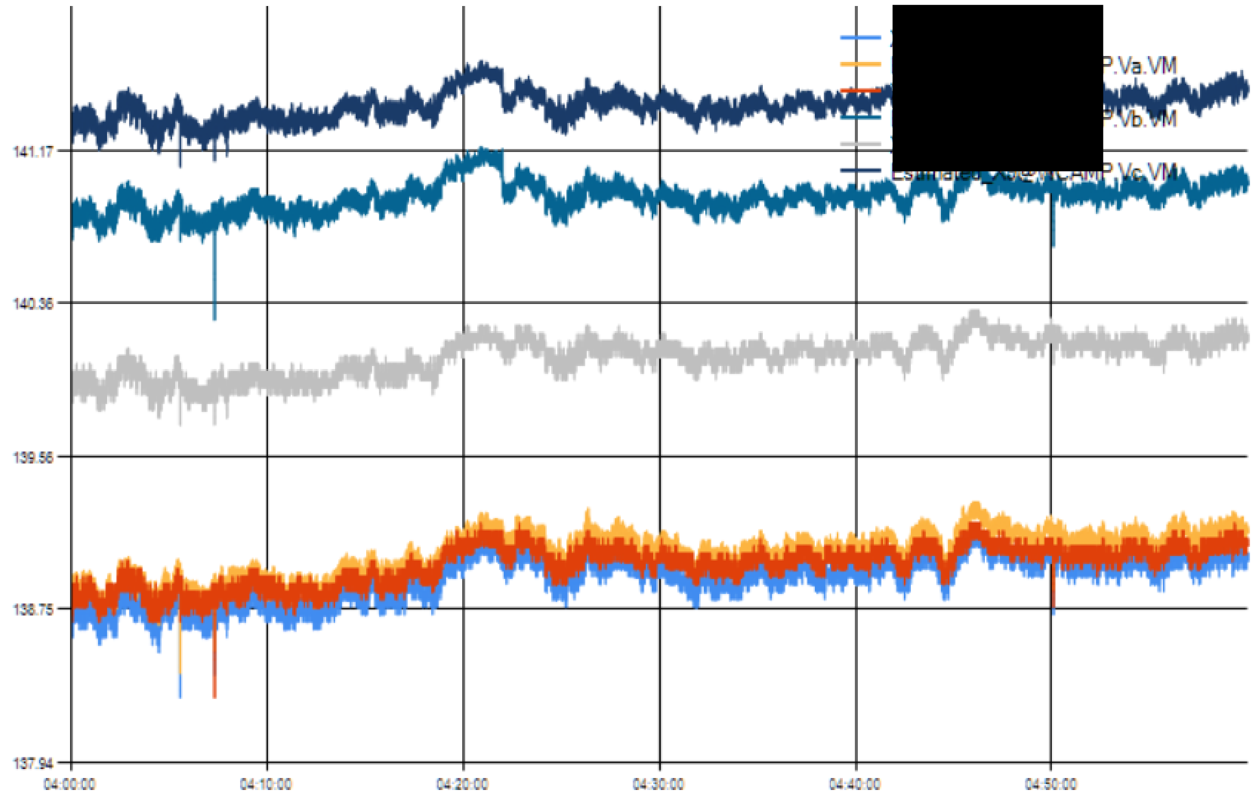
1 Hour Field PMU Data Test – SLSE

Validated the accuracy of the SLSE algorithms:

- 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	☑
[redacted].VA	☐
[redacted].VM	☑
[redacted].VA	☐
[redacted].VM	☑
[redacted].VA	☐
[redacted]quency.FR	☐
[redacted]b.IM	☐
[redacted]b.IA	☐
[redacted]c.IM	☐
[redacted]c.IA	☐
[redacted]/a.VM	☐
[redacted]/a.VA	☐
[redacted]/b.VM	☐
[redacted]/b.VA	☐
[redacted]/c.VM	☐
[redacted]/c.VA	☐
[redacted]Frequency.FR	☐



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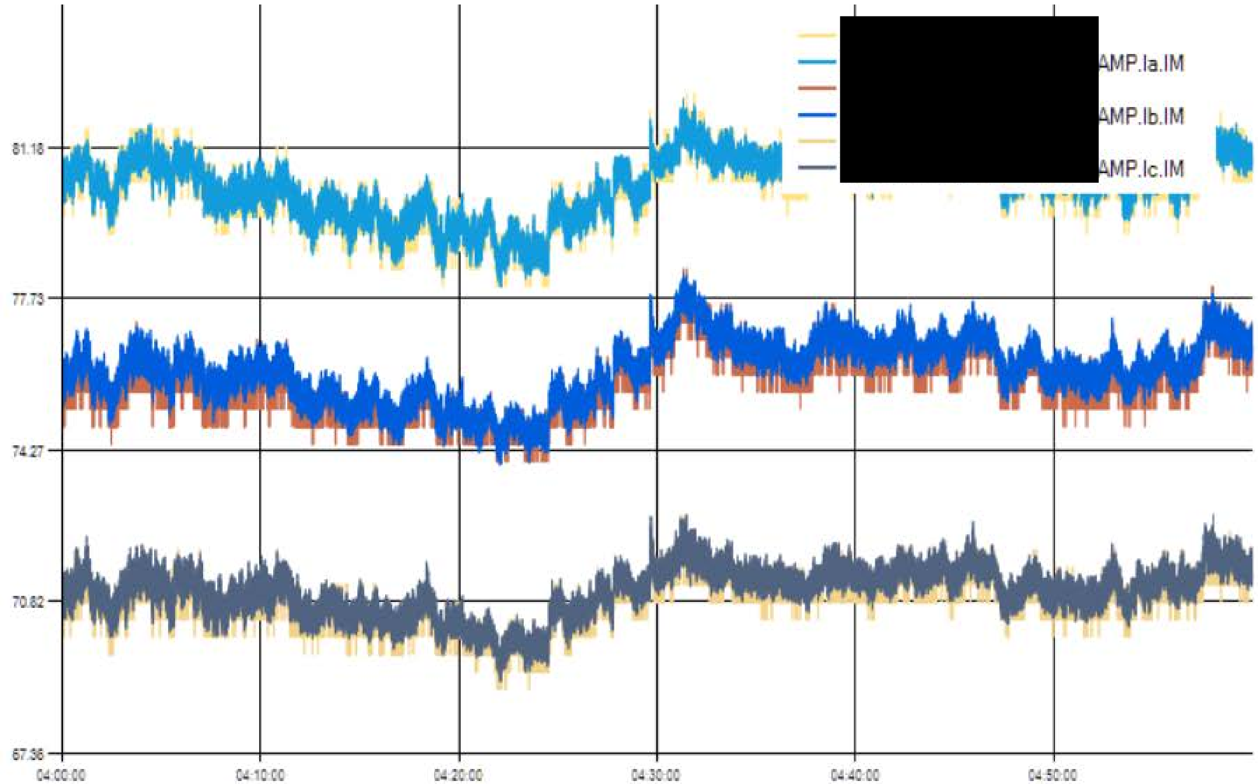
1 Hour Field PMU Data Test – SLSE

3 Phase breaker current signals:

Signal Name	Check
[redacted].Ia.IM	☑
[redacted].Ia.IA	☐
[redacted].Ib.IM	☑
[redacted].Ib.IA	☐
[redacted].Ic.IM	☑
[redacted].Ic.IA	☐
[redacted].Frequen...	☐
[redacted]P.Ia.IM	☐
[redacted]P.Ia.IA	☐
[redacted]P.Ib.IM	☐
[redacted]P.Ib.IA	☐
[redacted]P.Ic.IM	☐
[redacted]P.Ic.IA	☐
[redacted]P.Frequ...	☐
[redacted].Ia.IM	☐
[redacted].Ia.IA	☐
[redacted].Ib.IM	☐
[redacted].Ib.IA	☐



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Current Status & Next Steps

#	SOPO Tasks and Subtasks	Planned Timeline
3.0	**Development, Testing, and Demonstration**	**July 2017 – August 2018**
3.1	Pseudo-Synchrophasor Data	July – December 2017
3.2	Field Synchrophasor Data	December 2017 – March 2018
3.3	Sampled Data from Instrument Transformers	April – August 2018

- Working with AEP to establish synchrophasor connection to EPG
- System integration testing with SLSE and data-driven algorithms

- **Appreciate if any other utilities can contribute to an equipment failure "data library"**
- **Interested in this project for host demonstration? Still not too late to join!**

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Q & A

Thank You!

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