Substation Secondary Asset Health Monitoring and Management System

Heng (Kevin) Chen and Lin Zhang
Electric Power Group
chen@electricpowergroup.com;
zhang@electricpowergroup.com
Oct. 23, 2018
Philadelphia, PA

Acknowledgement and Disclaimer

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

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Outline

- **Project Introduction & Objective**
- **Technical Merit & Approach**
  - Data-driven Method: Moving variance, control chart
  - Substation Liner State Estimator (SLSE) Method
- **Testing & Results**
  - Simulation Data
  - Field PMU Data
- **Major Accomplishments till Now**
- **Planned Activities and Schedule**
- **Q&A**

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 Investigators – Kevin Chen, Lin Zhang
  - Key Project Personnel – Ken Martin, Simon Mo, Tianyu Hu, Neeraj Nayak, Joshua Chynoweth

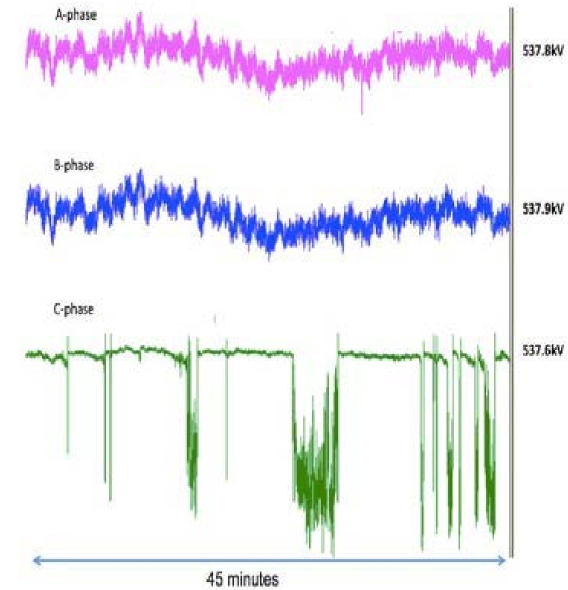
Project Objective

- 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

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Technical Approach

- Data from substation will be provided by utility partners
- Leverage existing synchrophasor technology
- Research new algorithms in this project
  - Data-driven Method
  - Substation Linear State Estimator (SLSE) Method
- Validate at cost share partner substation locations
- 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).

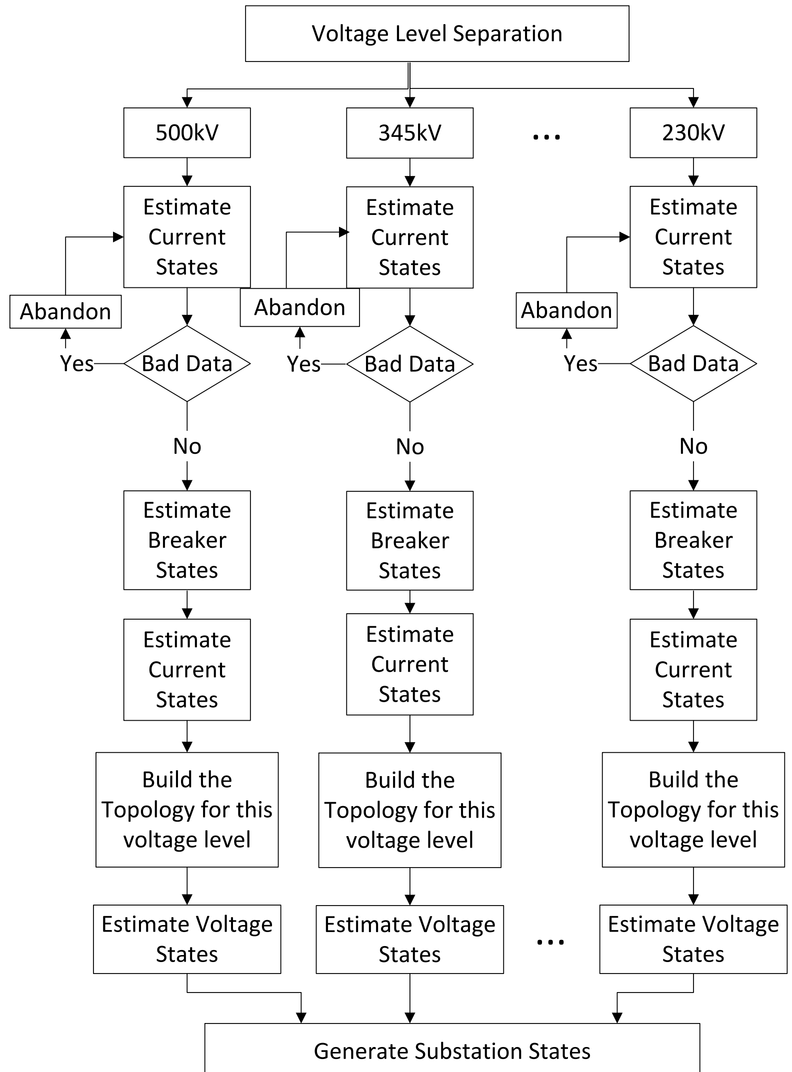
The UCL and LCL are calculated based on a 20σ

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).

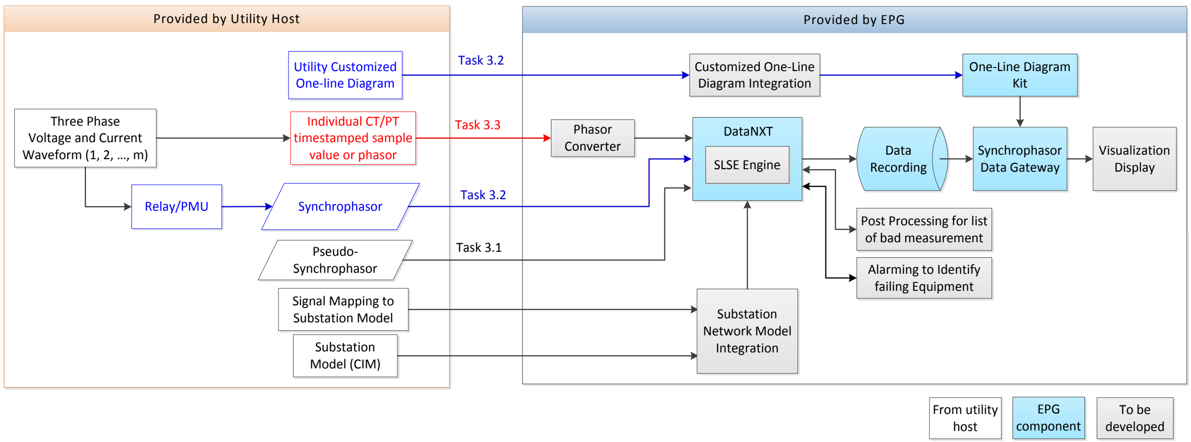
SLSE Method

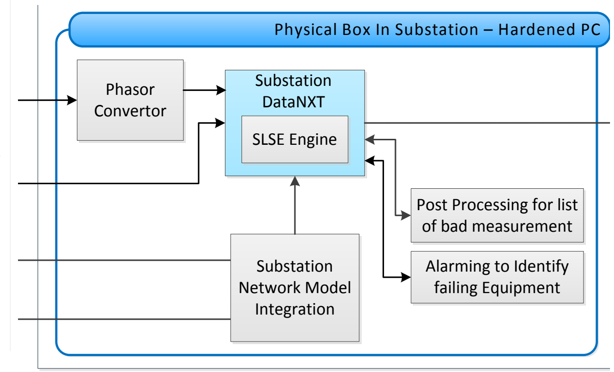
3 phase current state estimator

3 phase voltage state estimator



Deployment Options



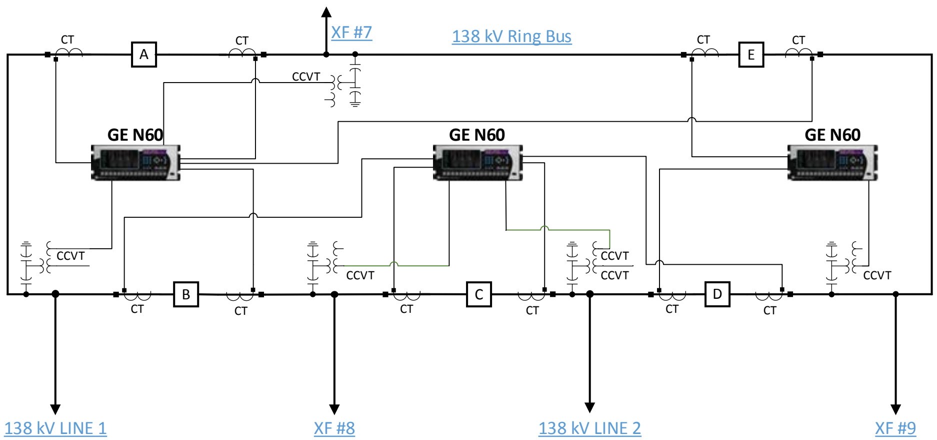


- **Central Processing**
- **Data sent from substations to central site**
- Pro:
  - Monitoring multiple substations
  - Simple deployment
- Con:
  - Need large bandwidth
  - Deployment

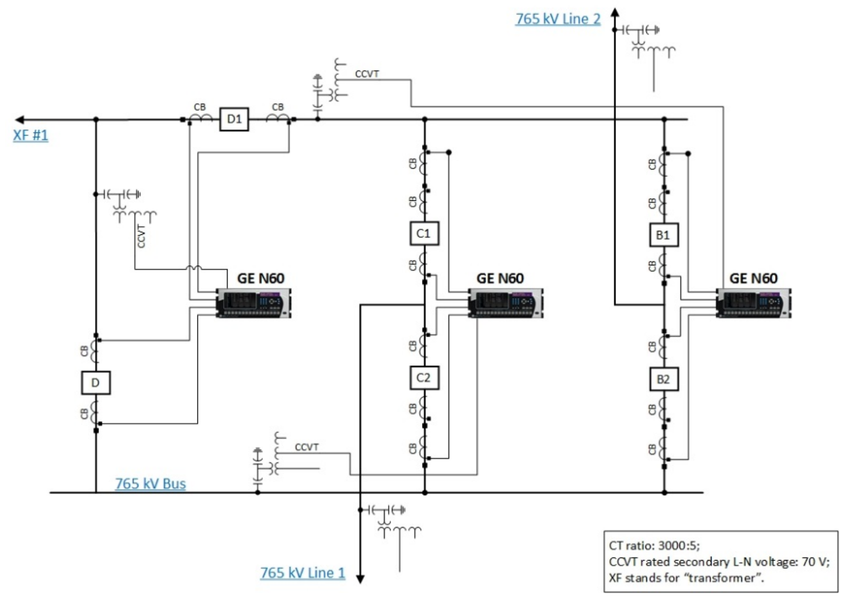
- **Local Processing at substations**
- **Results sent to asset monitoring center**
- Pro:
  - Less latency
  - Less bandwidth
- Con:
  - Deployment not as easy

PMU Deployment at AEP

138 kV STATION PMU Connection



765 kV STATION PMU Connection



3 PMUs deployed at a 138 kV station by March 2018

3 PMUs planned at a 765 kV station by Dec. 2018

- Mainly to get breaker current signals

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Simulation Data

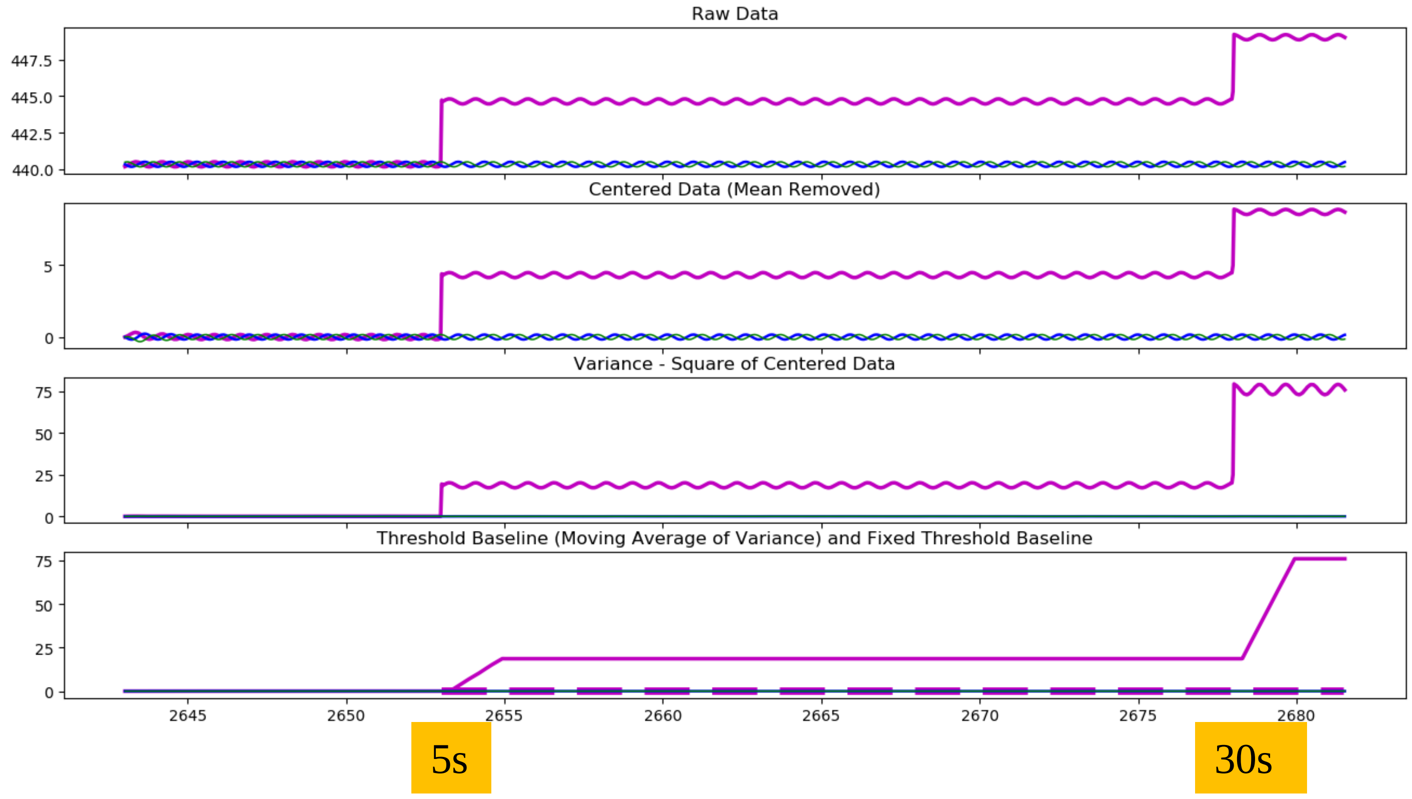
Field PMU Data

TESTING & RESULTS

AEP PSCAD Simulation Cases

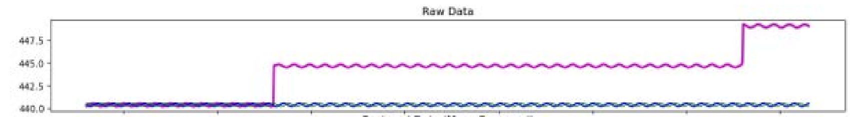
Faulted Instrument Transformer	Fault Type	No. of Scenarios
CCVT	High voltage capacitor stack failure	3
	Low voltage capacitor stack failure	3
	Ferroresonance suppression circuit (FSC) failure	2
CT	Turn-to-turn shortage within the same coil	2
	Turn-to-ground shortage	4
	Turn-to-turn shortage between different 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

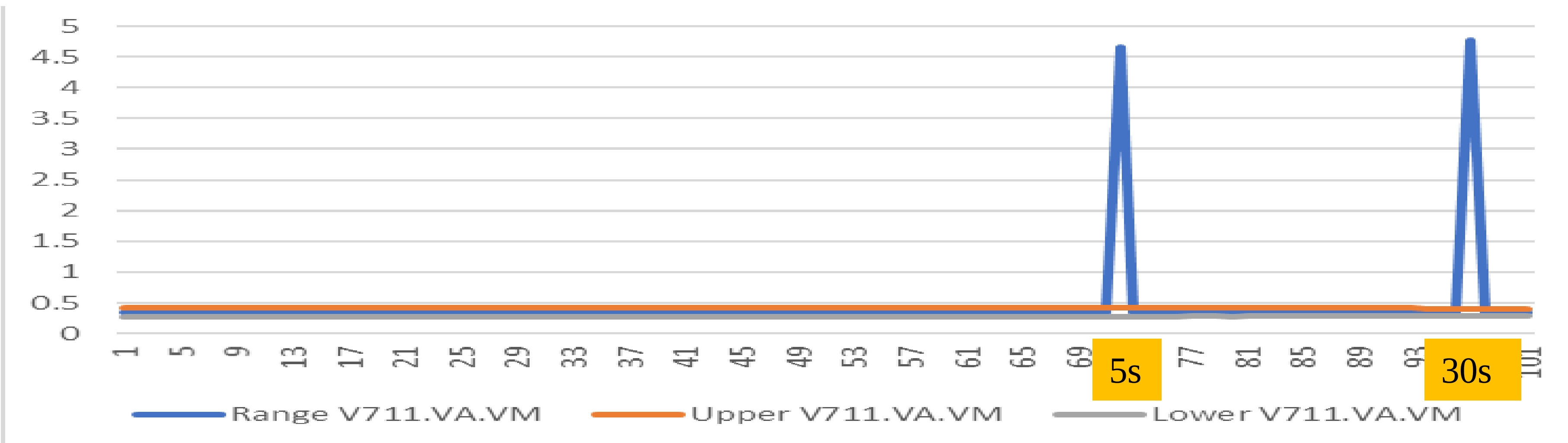
Moving Variance Test - CCVT - Case 1C



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

Control Chart Test - Case 1C Results





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

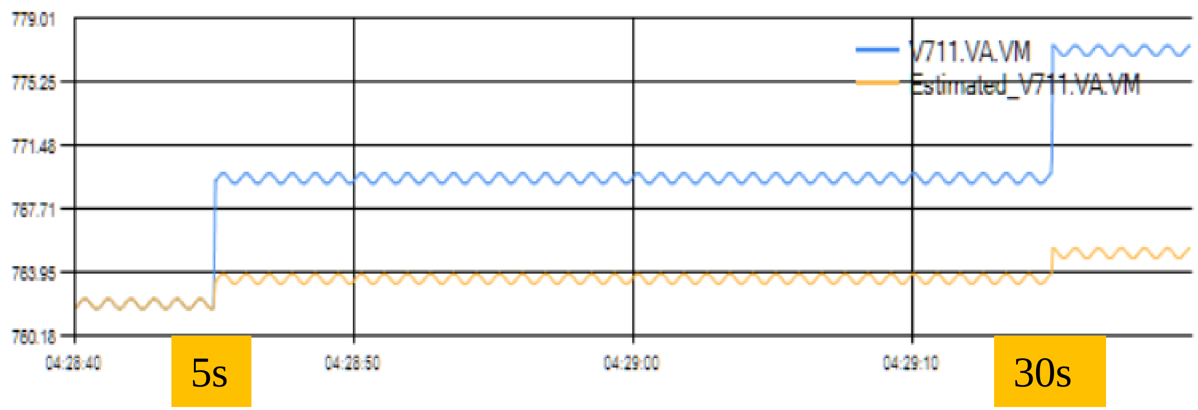
SLSE Test - Case 1C Results

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	☐



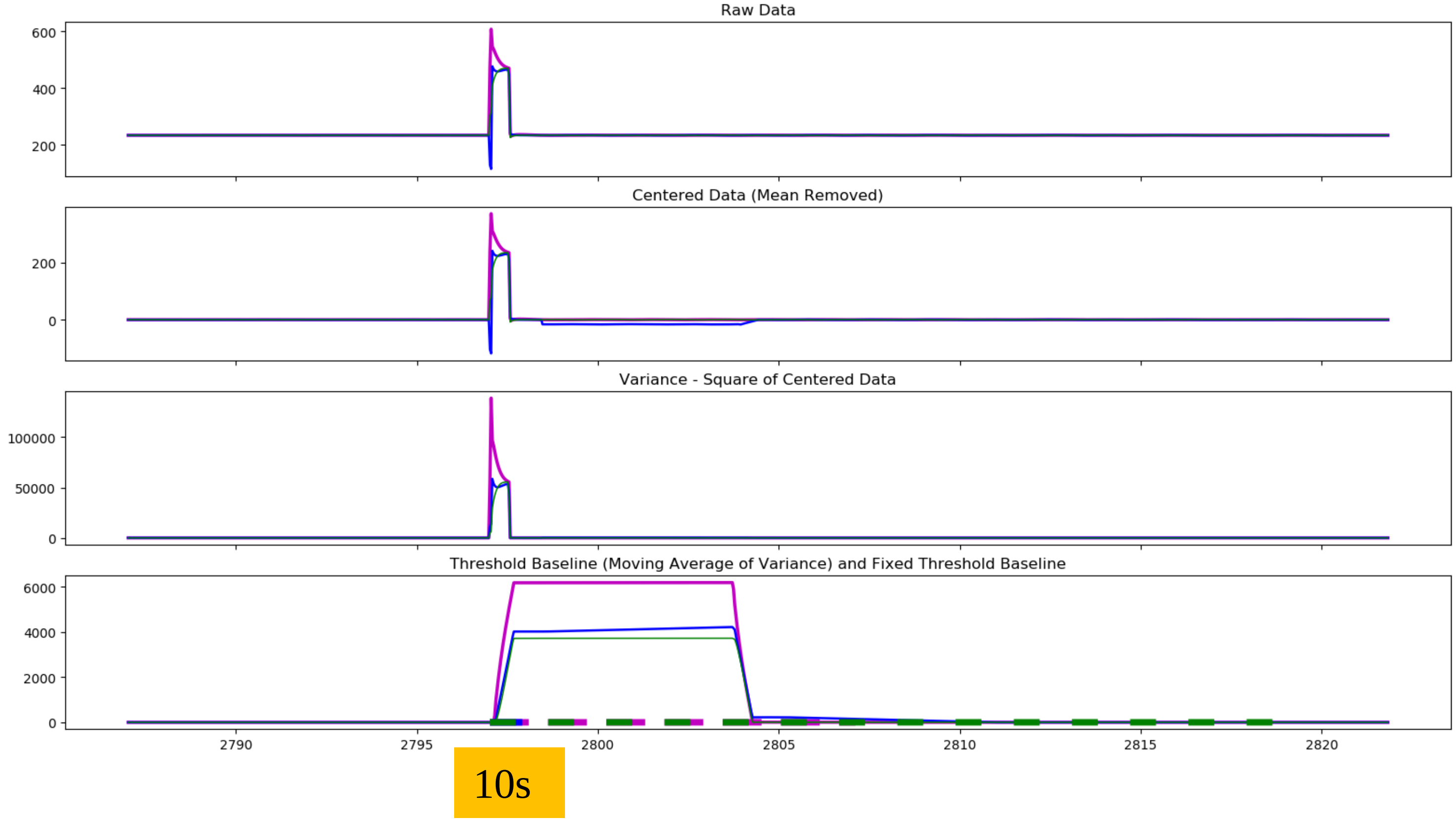
1C - 1 capacitor fails first at 5 s, 2nd capacitor fails after 30sec, in phase A

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Moving Variance Test – System Fault



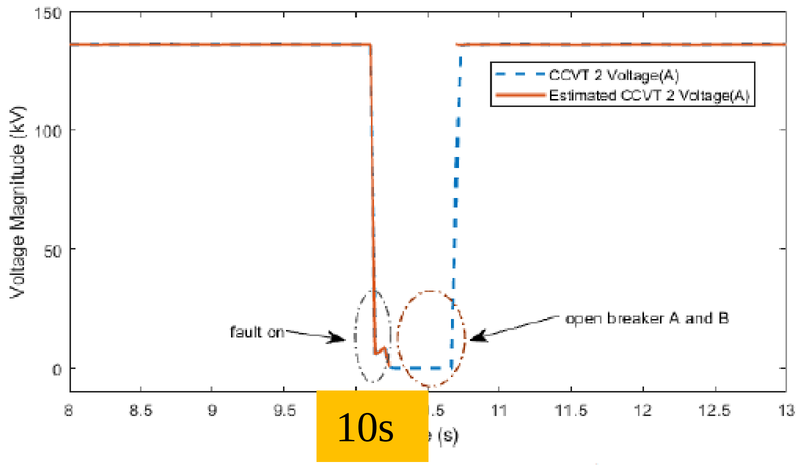
11B - A single phase-to-ground bus fault on bus 1 phase A at 10sec, fault duration is 0.06 s, open D1, C1, B1 at t = 10.05s, reclose at t=10.55s.

Electric Power Group

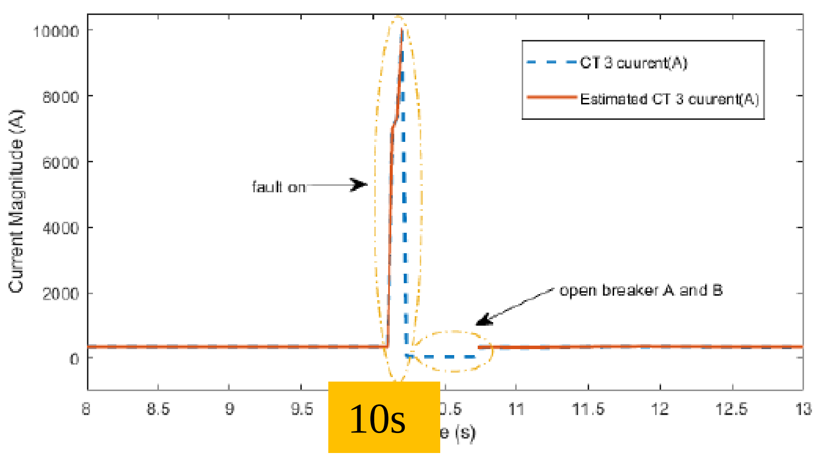
AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

SLSE Test – System Fault



(a) CCVT 2 Voltage Magnitude



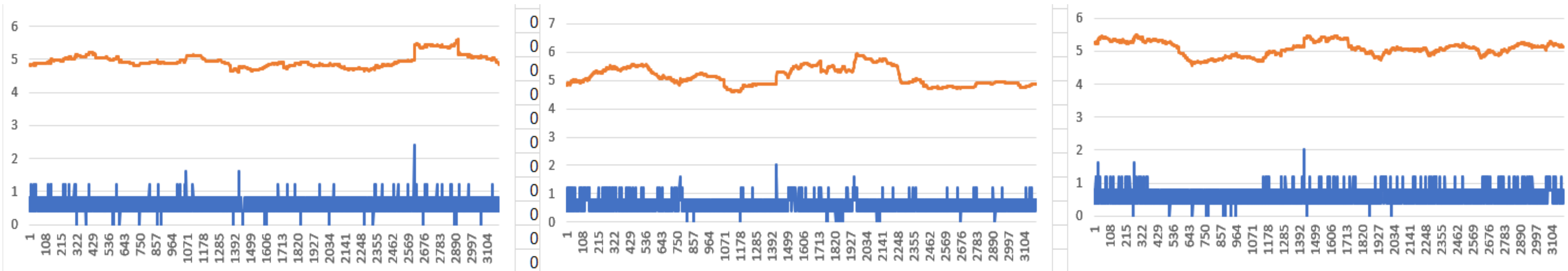
(b) CT 3 Current Magnitude

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

1 Hour Field PMU Data Test – Control Chart

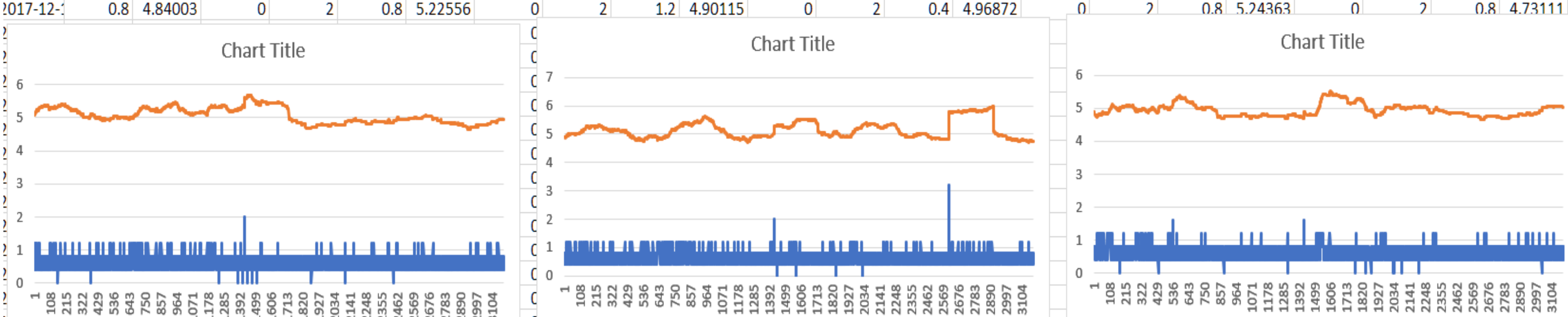
Normal operation data without equipment failure nor system event

- 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	



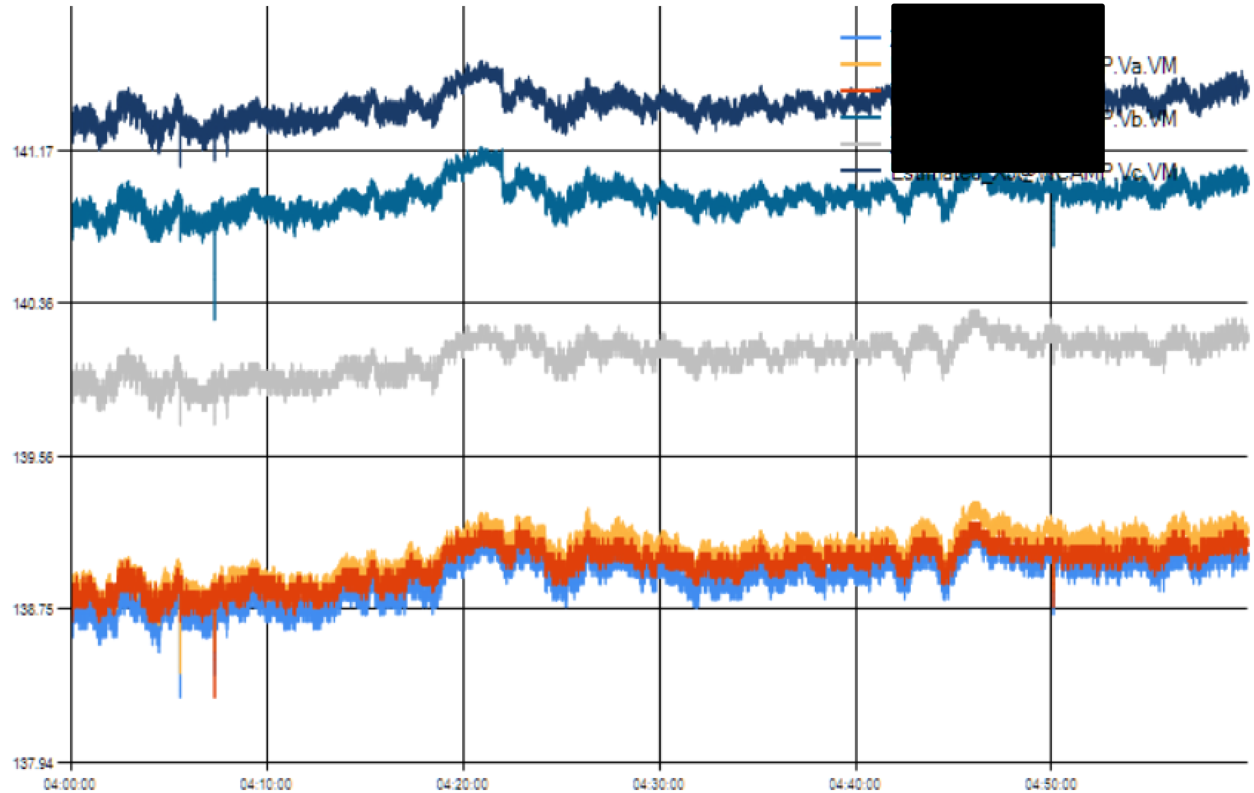
[redacted]

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:

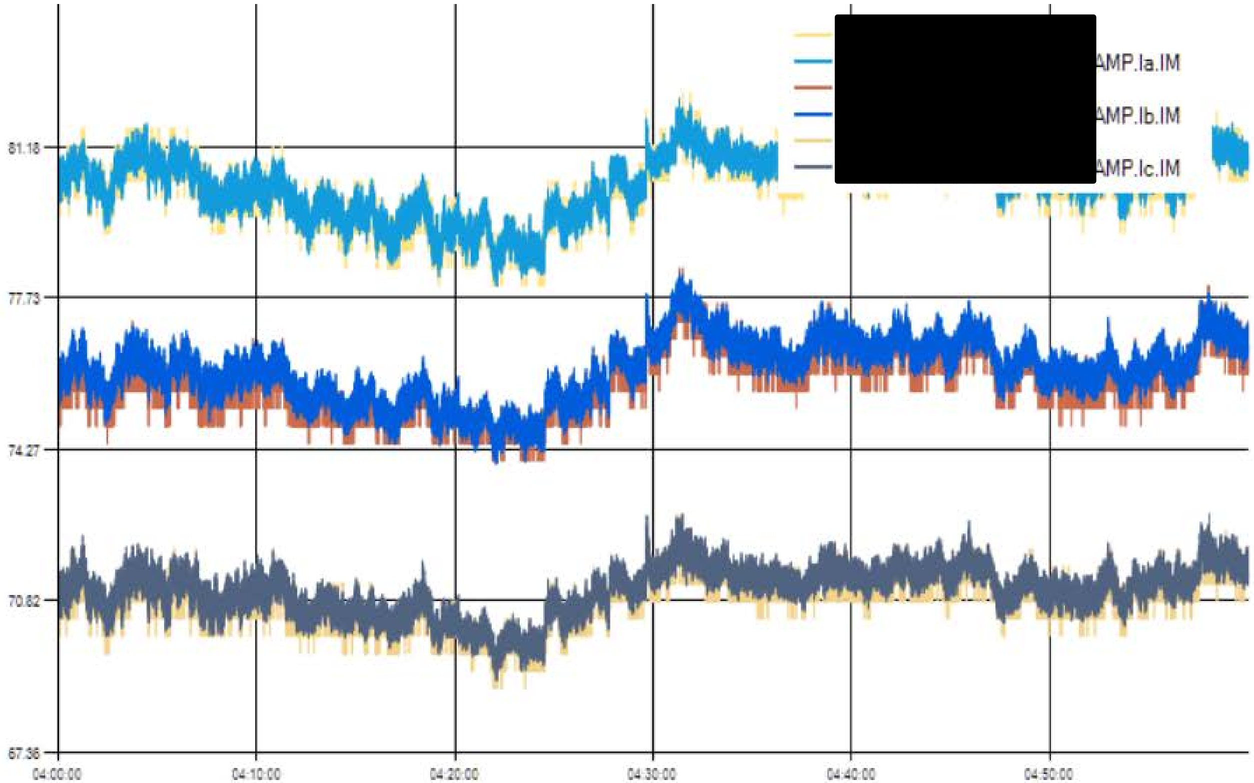
Signal Name	Check
[redacted].VM	☑
[redacted].VA	☐
[redacted].VM	☑
[redacted].VA	☐
[redacted].VM	☑
[redacted].VA	☐
[redacted]quency.FR	☐
[redacted]b.IM	☐
[redacted]b.IA	☐
[redacted]c.IM	☐
[redacted]c.IA	☐
[redacted]/a.VM	☐
[redacted]/a.VA	☐
[redacted]/b.VM	☐
[redacted]/b.VA	☐
[redacted]/c.VM	☐
[redacted]/c.VA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



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	☐

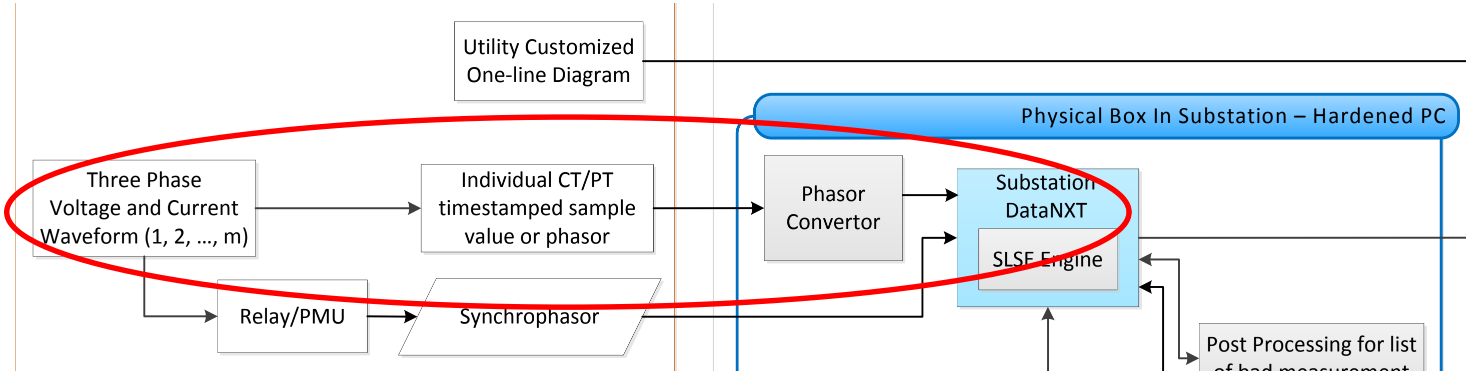


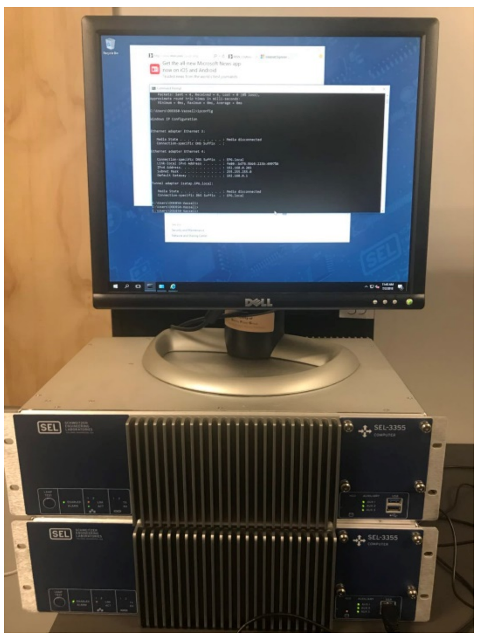
Key Testing Findings

- Validated 3 methods

▪ **Data-driven Method** **(moving variance & control chart)**	▪ **SLSE Method**
▪ Pro: › Fast › Configure Multiple windows ▪ Con: › Biased by bad data › Can not distinguish system fault	▪ Pro: › Robust with system fault and bad data ▪ Con: › Dependent on model

Testing of Local Processing Deployment





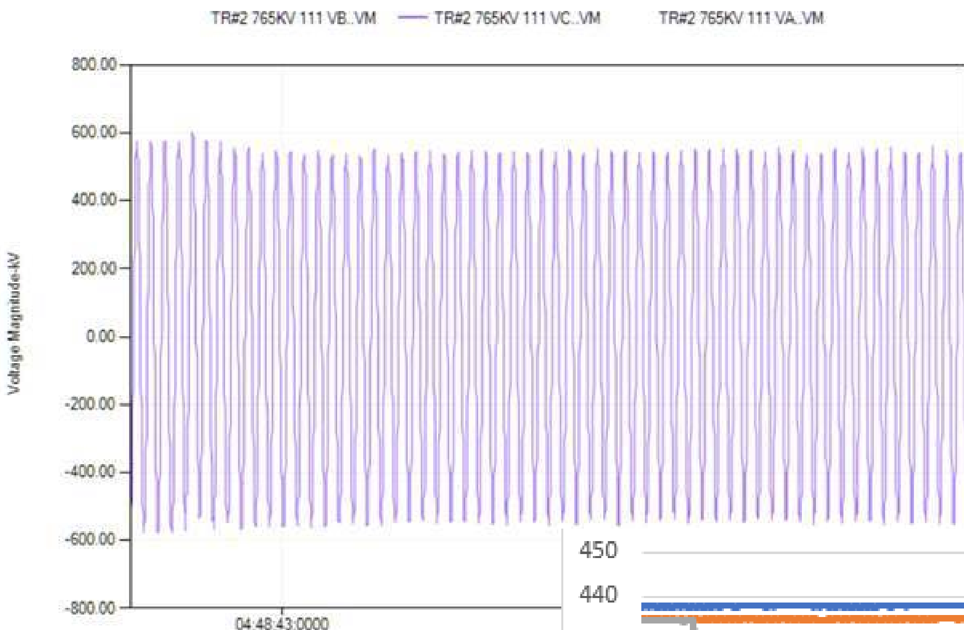
- Sampled CT, CCVT waveform data in COMTRADE format
- Trigger 1 time/hour
- 48 cycles of data, 64 samples/cycle
- Multiple COMTRADE files from multiple PMUs in one station
- Timestamp using same GPS clock as PMU

Electric Power Group

AEP AMERICAN ELECTRIC POWER

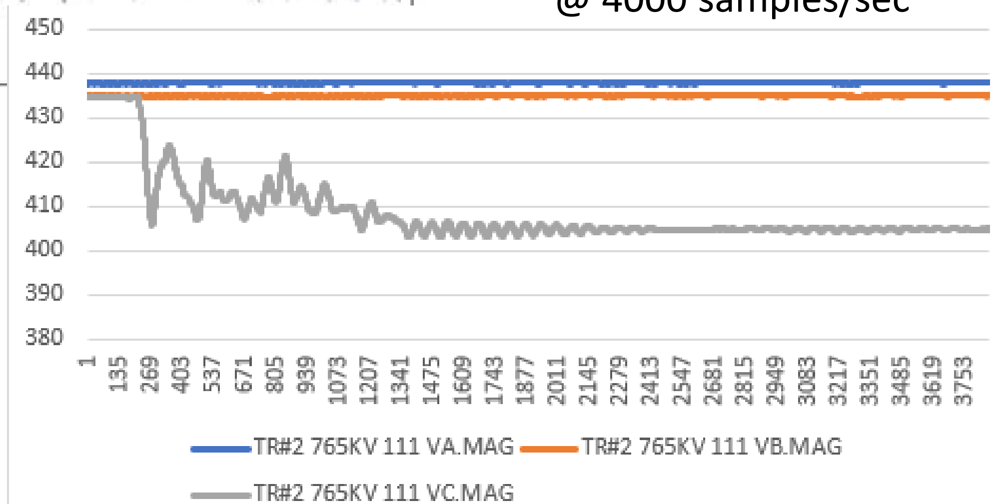
NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Phasor Converter

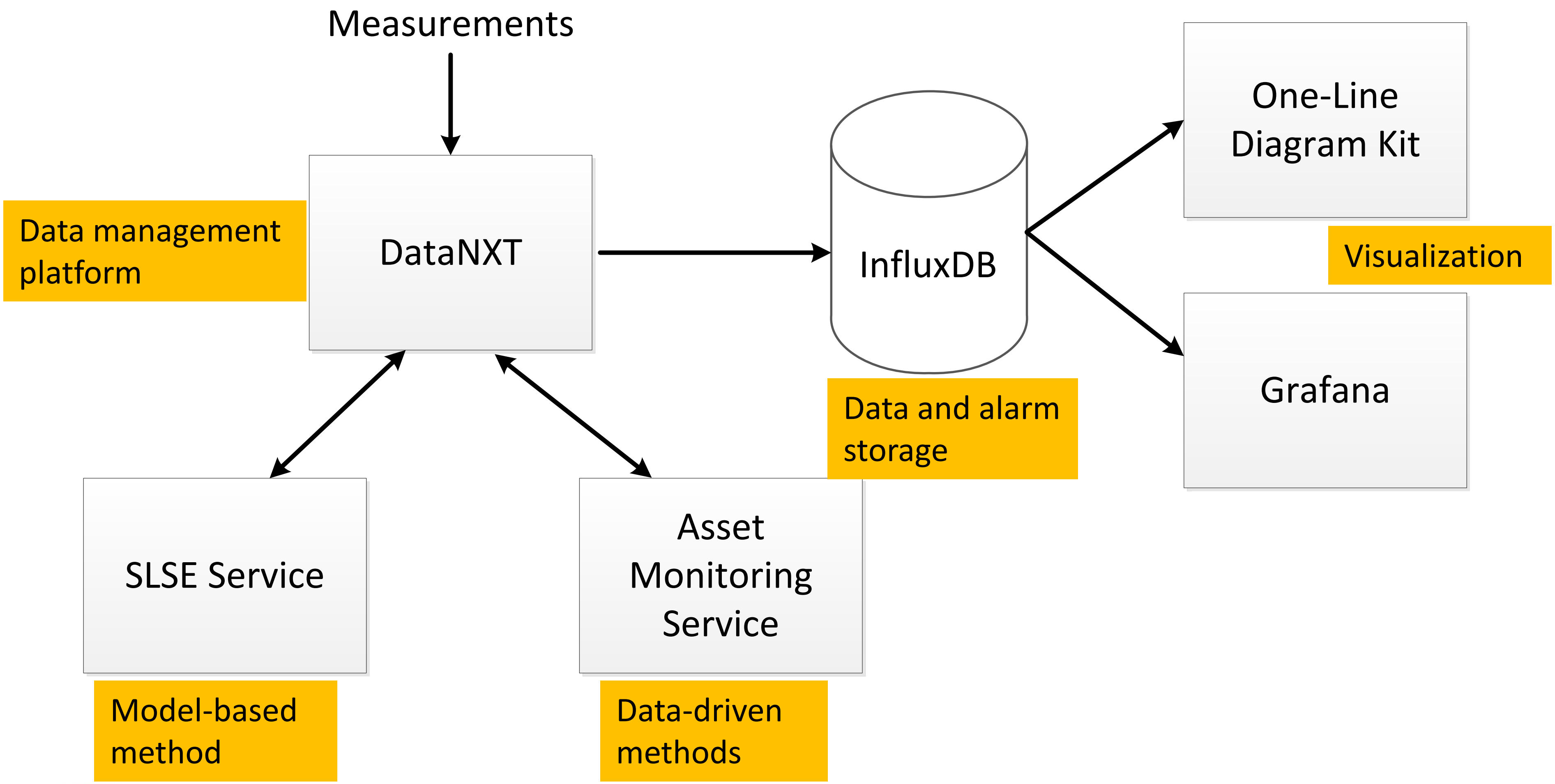


Original Sampled waveform voltage data @ 4000 samples/sec

Converted to phasor, original sample @ 4000 samples/sec



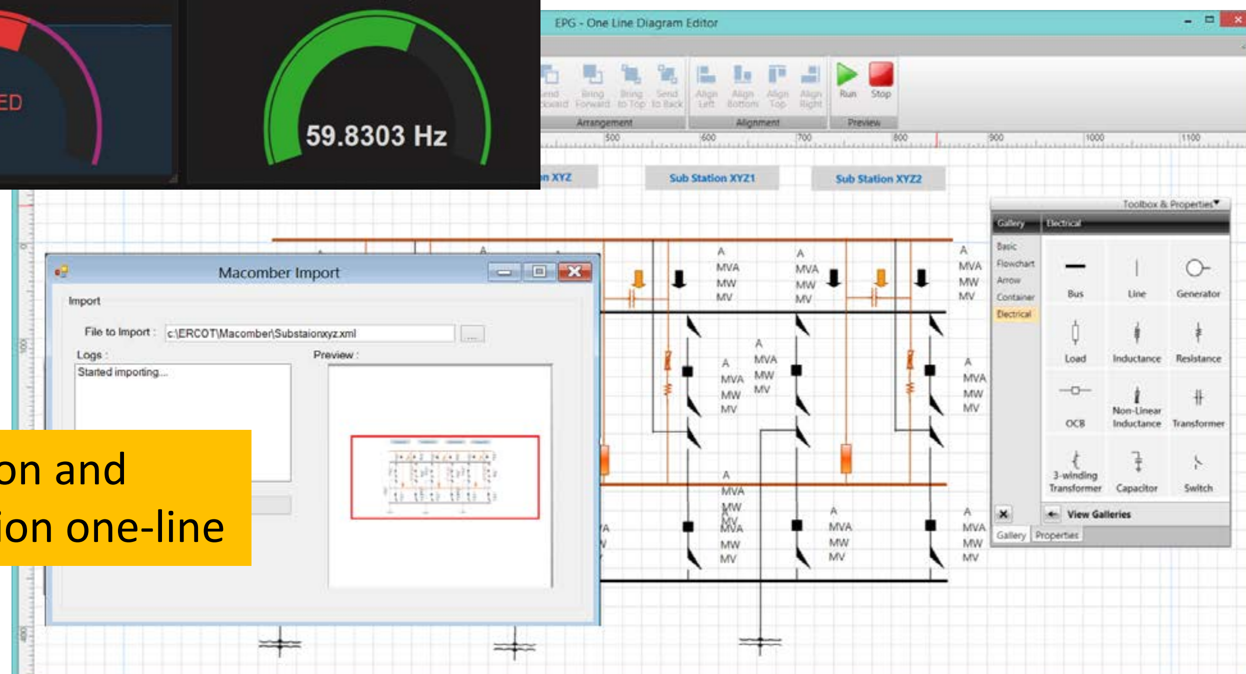
Software Package Testing at EPG & AEP



Grafana & One-line Diagram Visualization

Monitor 5 equipment

- Independent alarming
- measurement signal & status trending



Equipment location and status on substation one-line

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Major Accomplishments till Now

- Completed research & scoping study, and system functional design milestone on time
- Developed two data-driven methods and the model-based SLSE method for anomaly detection
- Simulated 60 cases of equipment failure and system event
- Tested methods using simulated data and historical field PMU data
- Deployed 3 new PMUs at one demonstration substation
- Completed software prototype
- Integration testing under way at EPG & AEP
- Presented project work/paper at multiple conferences

Planned Activities and Schedule

#	SOPO Tasks and Subtasks	Planned Timeline
1.0	**Project Management and Planning**	**March – April 2017**
2.0	**Planning, Research, Design, and Specification**	**April 2017 – March 2019**
2.1	Overall Project Management	April 2017 – March 2019
2.2	Research and Scoping Study	March – June 2017
2.3	Functional Design and Design Specifications	March – July 2017
3.0	**Development, Testing, and Demonstration**	**July 2017 – June 2019**
3.1	Pseudo-Synchrophasor Data	July – December 2017
3.2	Field Synchrophasor Data	December 2017 – March 2019
3.3	Sampled Data from Instrument Transformers	April 2018 – June 2019
4.0	**Deployment and Demonstration at Host Utility**	**July 2019 – December 2019**
4.1	Product Documentation	July 2019
4.2	Installation and Integration at Host Utility	August 2019
4.3	Site Acceptance Testing	August – September 2019
4.4	Demonstration at Host Utility	October – November 2019
4.5	Training	November – December 2019
5.0	**Marketing and Outreach**	**September 2018 – March 2020**
5.1	Market Research	September – December 2019
5.2	Commercialization Plan	January – March 2020
5.3	Outreach	September 2018 – March 2020

Thank You!

Heng (Kevin) Chen and Lin Zhang
Electric Power Group
chen@electricpowergroup.com;
zhang@electricpowergroup.com

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

Backup Slides

Background

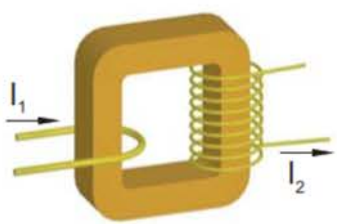
- Utilities have invested billions of dollars in transmission and distribution equipment and substations
- Key substation assets include transformers, circuit breakers, instrument transformers (CTs, PTs, CCVTs) and Intelligent Electronic Device (Relays, PMU, DFRs)
- Synchrophasor measurement systems 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

Task 2.2 Research and Scoping Study - Equipment

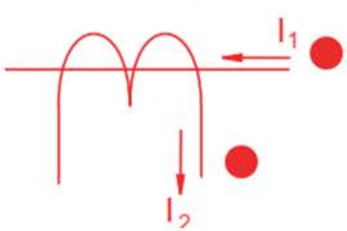
- Conducting a research and scoping study of bad data pattern and relationship to types of equipment failure, as well as alarming criterial for failure detection

Current Transformer (CT)

Conceptual picture of a Current Transformer



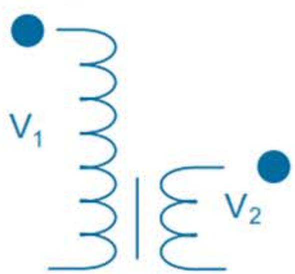
Symbol of a Current Transformer



Potential Transformer (PT)

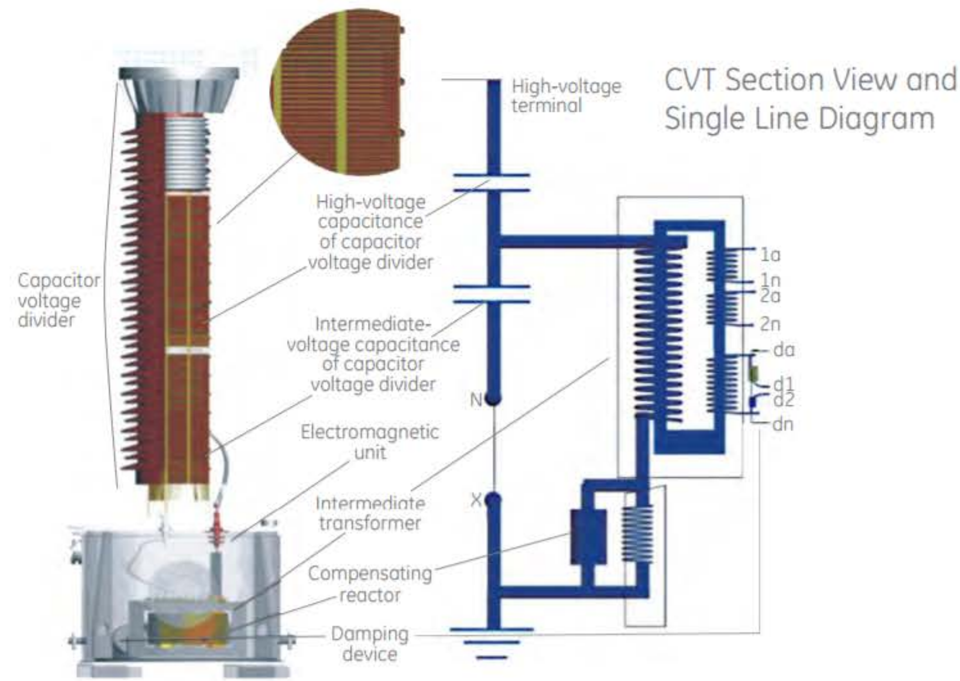
Conceptual picture of a Voltage Transformer

Symbol of a Voltage Transformer



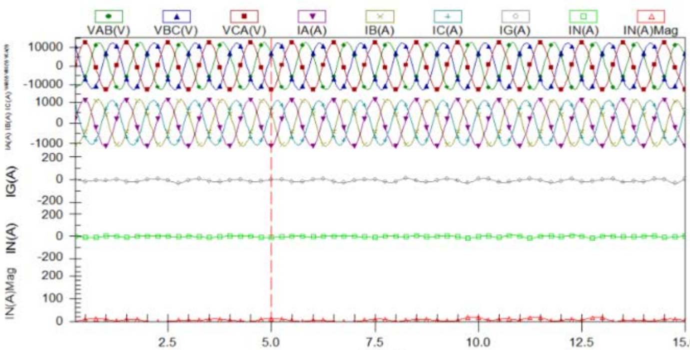
Source: Instrument Transformers – Technical Information & Application Guide, http://www.abb.com

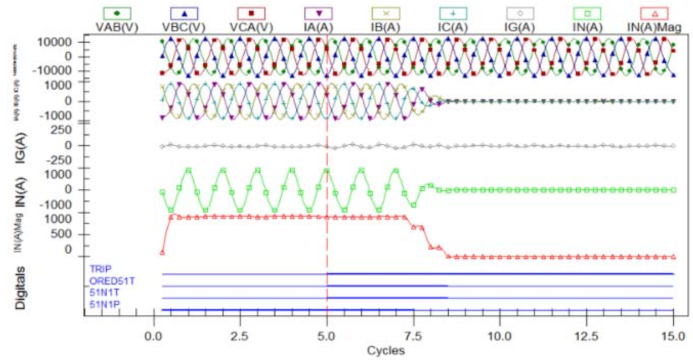
Coupling Capacitor Voltage Transformer (CCVT)

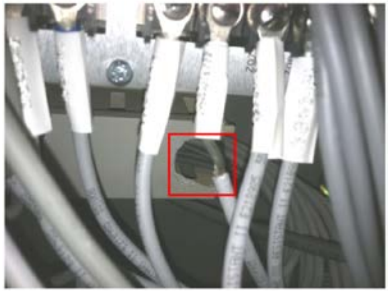


Source: IEC Capacitive & Coupling Capacitor Voltage Transformers (CVT & CCVT), http://www.gegridsolutions.com

Signature Examples – CT



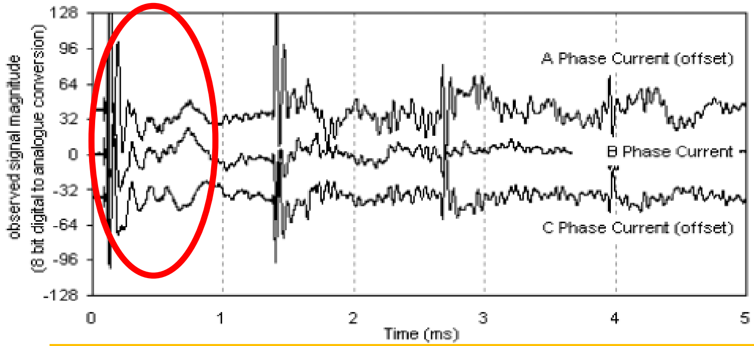


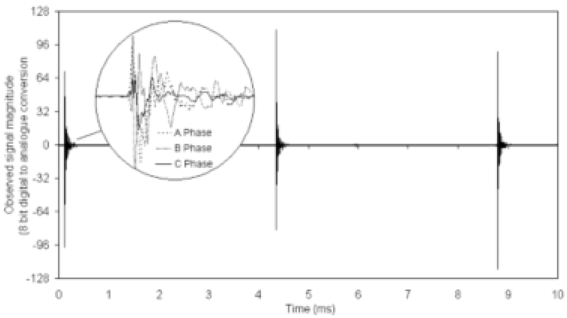


Normal Operation – No failure

Reference: [G]

Open Circuit in CT secondary due to Wiring damage

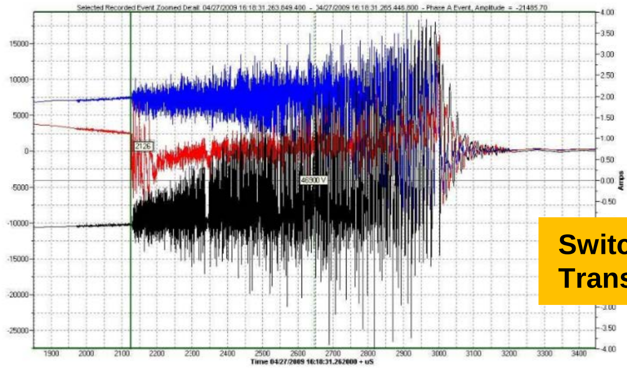




High frequency transients observed 8 minutes before CT failure (partial discharge in insulation)

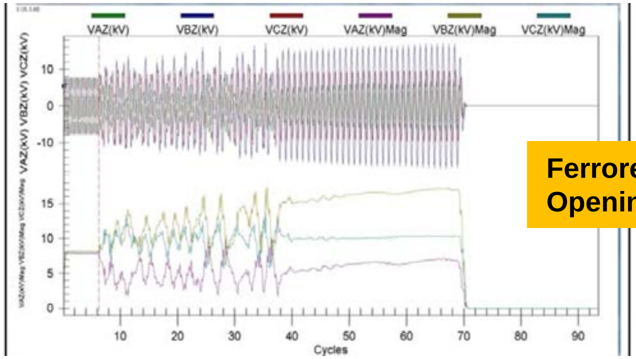
Reference: [F]

Signature Examples - PT



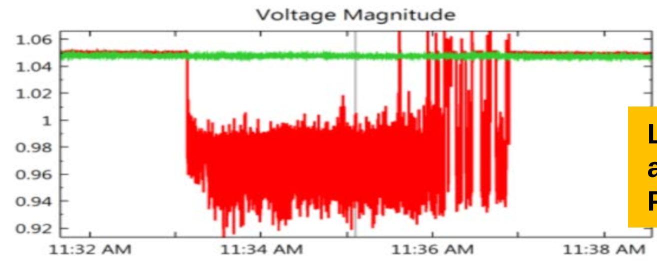
Switching Transients

Reference: [A]

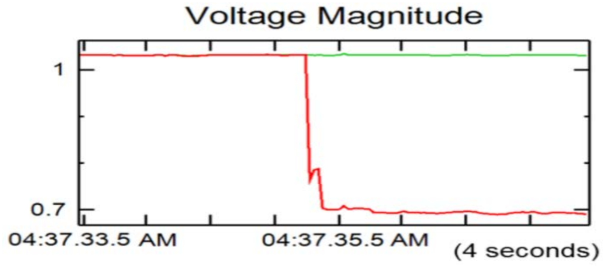


Ferroresonance – Opening Breaker

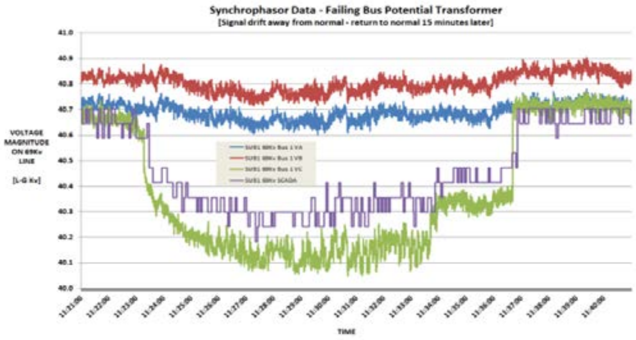
Reference: [C]



Loose Connection at PT feeding the PMU



Blown fuse on One Phase of PT



Internal Primary Winding Issue

Reference: [A]

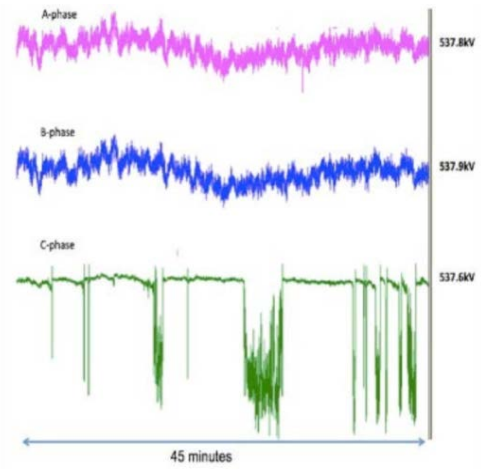
Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

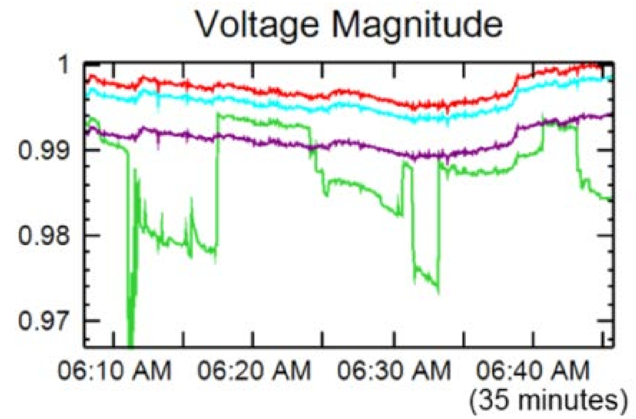
Signature Examples - CCVT

Capacitor Failure in C phase



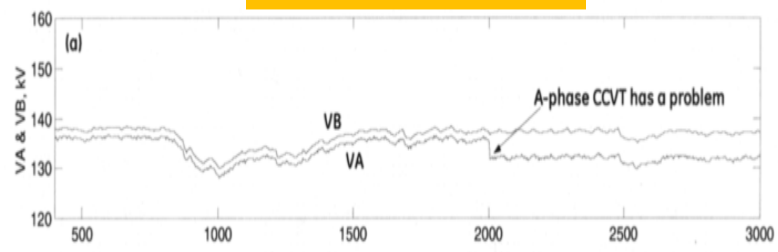
Reference: [A]

Loose Fuse Connections in CCVT Safety Switch



Reference: [A]

A - Phase CCVT Issue



Reference: [B]

Electric Power Group

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

SLSE Method

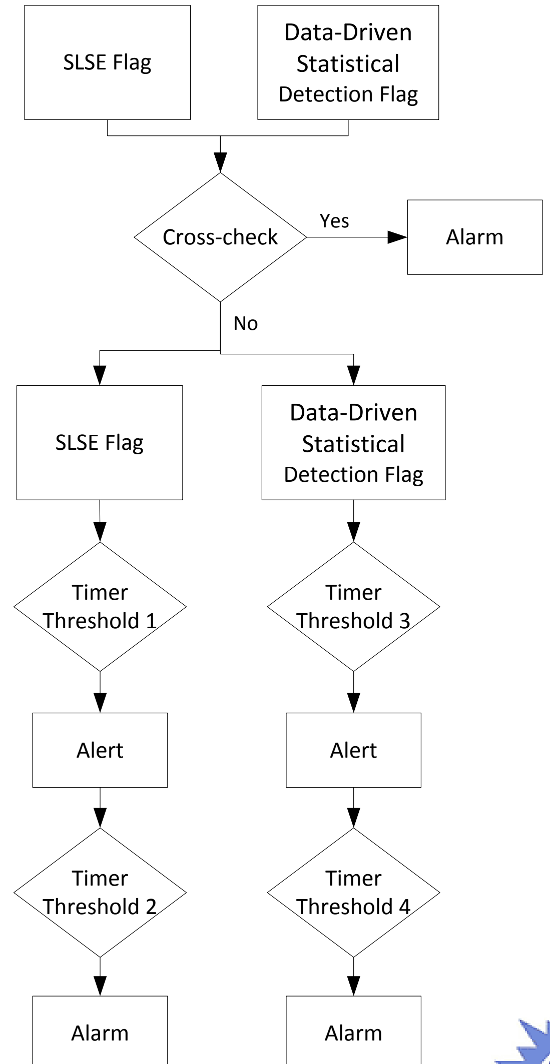
- Current State Estimator: Estimate the breaker current. In this model, all the nodes and breakers at the same voltage level inside the substation construct a zero-impedance power system, and the measurement function can be established by applying KCL. For each branch current, it is a function with respect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

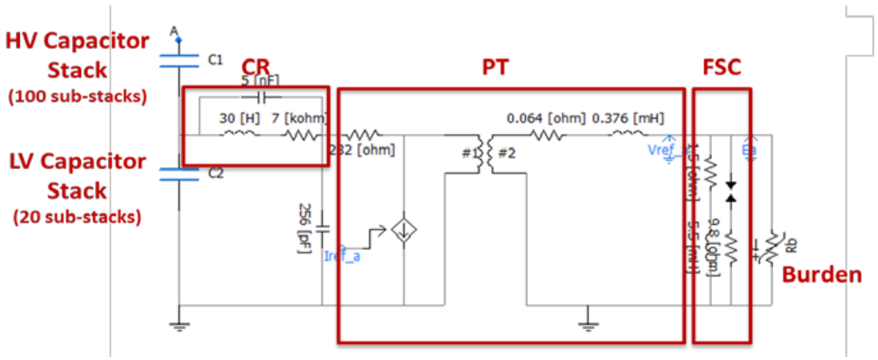
Anomaly Alarming

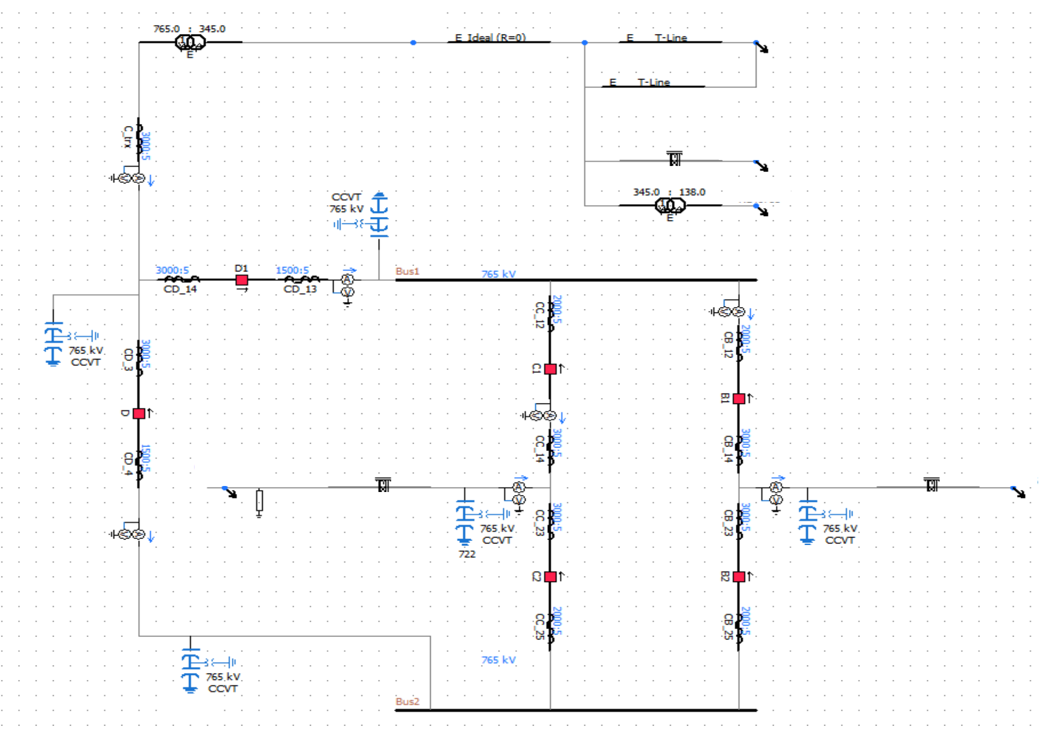
- SLSE and data-driven statistical detection flags are cross checked for consistence

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



AEP PSCAD Simulation Cases – CCVT Scenarios





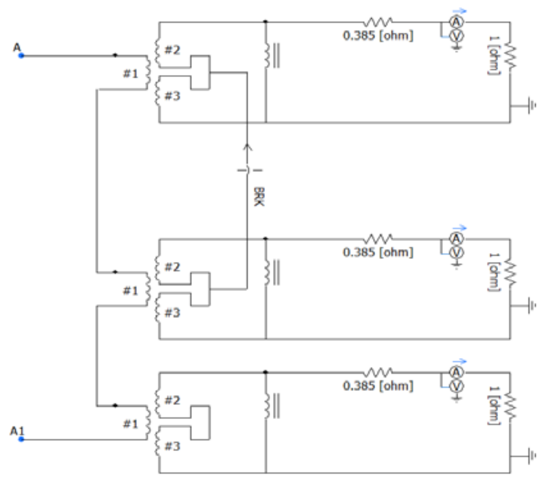
- 765kV Set 1: CCVT 8 Scenarios
- 138kV Set 1: CCVT 10 Scenarios

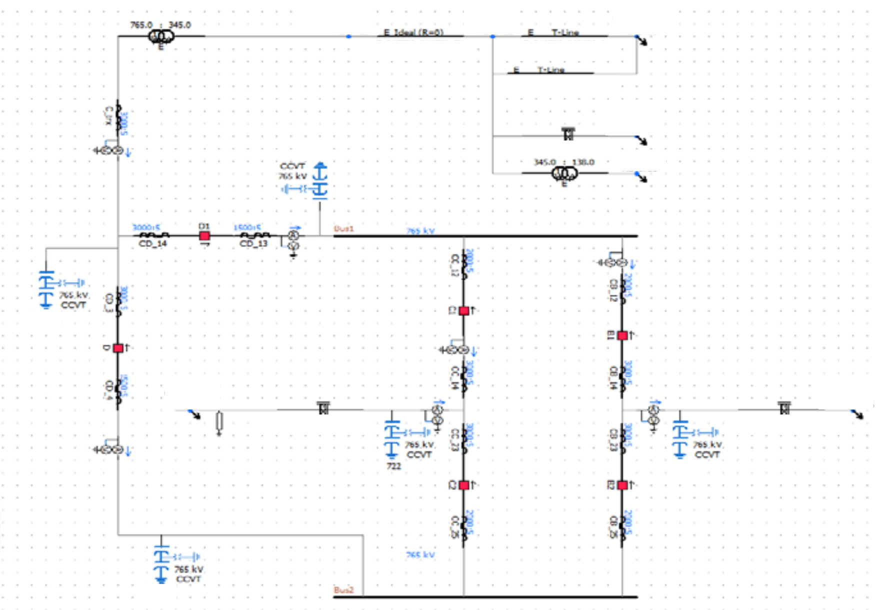
1. **Failure modes**
   - Failure of one or more capacitor elements in HV stack (capacitor stack shortage)
     - One capacitor fails (short circuit) in phase A
     - Five capacitors fail in phase B
     - One capacitor fails first, 2nd capacitor fails after 30sec, in phase C
   - Failure of one or 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

AEP AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

AEP PSCAD Simulation Cases – CT Scenarios





- 765kV Set 2: CT 20 Scenarios
- 138kV 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

AMERICAN ELECTRIC POWER

NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

List of Accepted Publications/Presentations

1. Heng Chen, Lin Zhang, et al, “Substation Secondary Asset Health Monitoring and Management System: Task 2.2 Update to AEP,” May 15, 2017.
2. Heng Chen and Lin Zhang, “Substation Secondary Asset Health Monitoring and Management System Project Overview,” NERC Synchronized Measurement Subcommittee (SMS) meeting, May 18, 2017.
3. Heng Chen and Lin Zhang, “Substation Secondary Asset Health Monitoring and Management System DOE Grant Award #DE-OE0000850,” DOE Peer Review Meeting, June 13, 2017.
4. Heng Chen, Lin Zhang, et al, “Substation Secondary Asset Health Monitoring Based on Synchrophasor Technology,” Poster, NASPI General Meeting, September 26-27, 2017.
5. Heng Chen and Lin Zhang, “Substation Secondary Asset Health Monitoring and Management System Project Overview,” WECC JSIS Meeting, October 11-13, 2017.
6. Heng Chen, Lin Zhang, et al, “Substation Secondary Asset Health Monitoring Based on Synchrophasor Technology,” IEEE PES Transmission & Distribution Conference & Exposition, April 16-19, 2018.
7. Neeraj Nayak, Heng Chen and Lin Zhang, “Substation Secondary Asset Health Monitoring and Management System Project Update,” NASPI General Meeting, April 25, 2018.
8. Heng Chen and Lin Zhang, “Substation Secondary Asset Health Monitoring and Management System Project Update,” WECC JSIS Meeting, May 17, 2018.