DOE/OE Transmission Reliability Program

Substation Secondary Asset Health Monitoring Using Synchrophasors

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Outline

- Industry Need
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- EPG's Substation Asset Health Monitoring Platform
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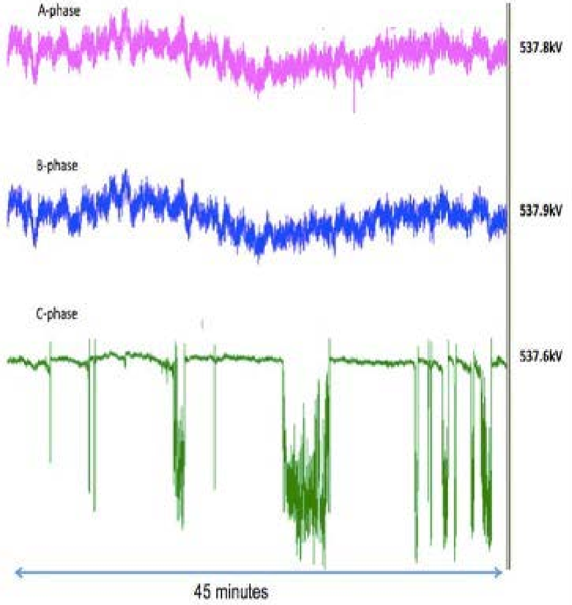
Industry Need

- 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)
- Proper functioning of substation assets is critical for power system operations, reliability and personnel safety
- Equipment Failure causes increases in operation and maintenance cost and poses a risk to personnel safety and system reliability
- Identifying precursors to equipment failure can help prevent failure and minimize the impact on the system

Equipment Failure – Increases Costs, Affects Personnel Safety

Example of failing CCVT in a substation



*Example of CCVT voltage signals at Dominion**

- Equipment Failure can cause significant damage/explosion to substation equipment
- Can jeopardize Personnel Safety
- Can cause Misoperations and impact reliability
- May even lead to system-wide events

*NASPI Technical Report, "Diagnosing Equipment Health and Mis-operations with PMU data", May 2015

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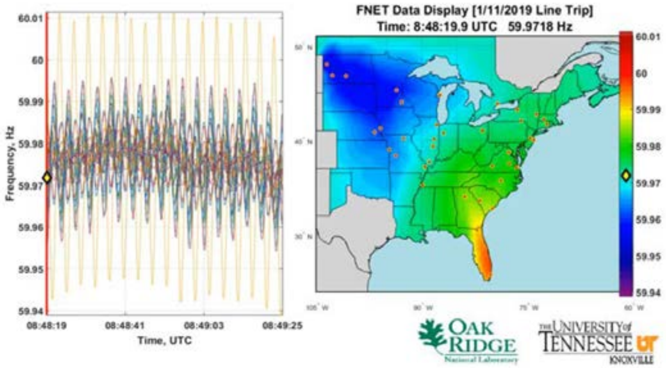
Jan 11 Eastern Interconnection Oscillations

- NERC findings point to wiring issue in PT that triggered Interconnection Wide Oscillations
- Important to identify oscillations and locate source
- Also important to identify and address root-cause to prevent system wide impact



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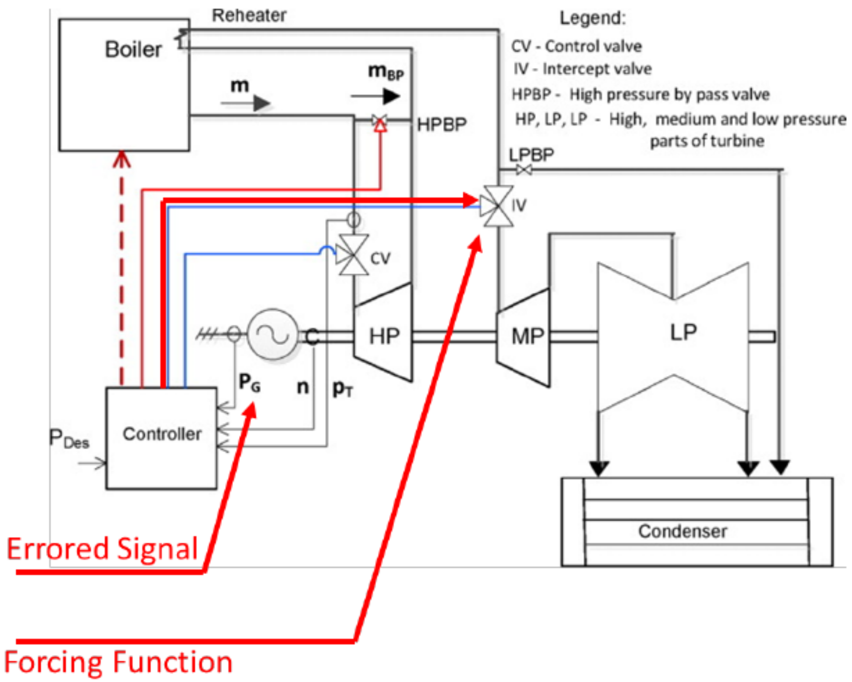
Forced Oscillation Source



- Steam turbine at combined cycle plant
- Power-load imbalance (PLI) controls
  - Failed voltage input to feedback
  - Measured P_{gen} reading 2/3 of actual
  - Perceived power-load imbalance
- PLI trigger shuts intercept valves
- 4 second timer to reopen valves
- Imbalance eliminated and valves reopen
- … and repeat …. and repeat
- Different voltage measurements for relaying and controls/metering
  - Hence no relay operation
- Plant manually tripped by operator
- Upon inspection, failed wiring in PT cabinet
- Damaged intercept valves
  - Replacement needed
  - Unit off-line for multiple weeks

Source: NERC, Oscillation Analysis Webinar, September 13, 2019

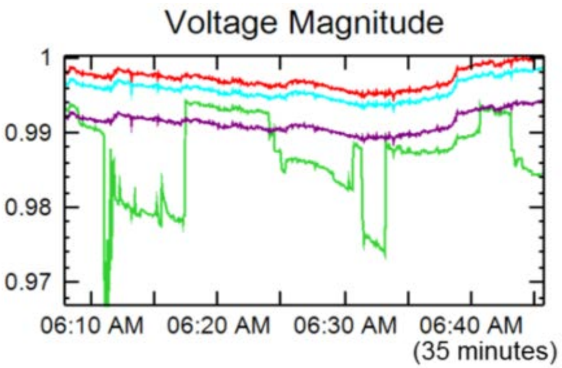
Synchrophasors for Asset Health Monitoring

- Synchrophasor measurement systems have been widely installed in the North American power grids over the last decade
- High-Resolution Data (30 frames/second and above) from such assets can be used for asset health monitoring and take proactive steps to prevent equipment failure
- Monitor the status and health of substation equipment and 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

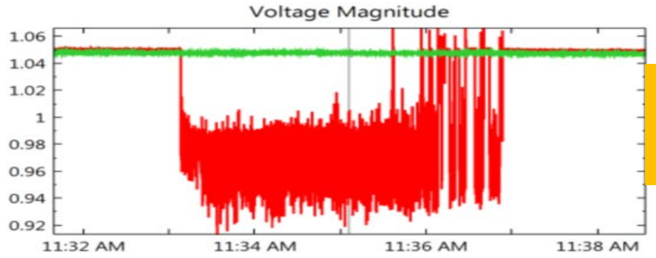
Signatures for Equipment Failure – Some Examples

Loose Connections, Winding Issues, Blown Fuse

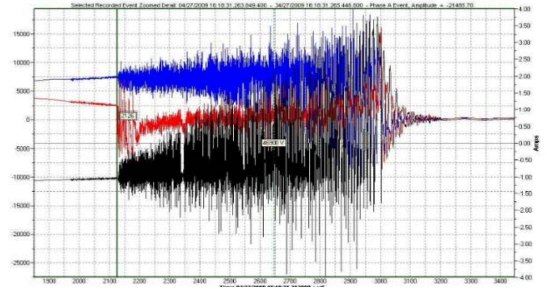
Loose Fuse Connections in CCVT Safety Switch



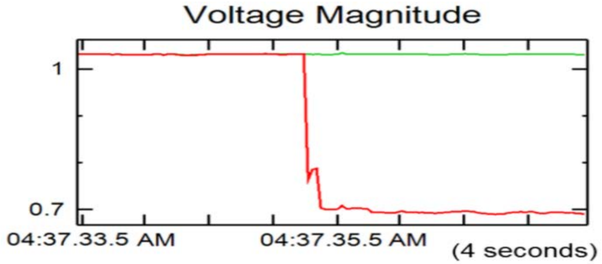
Loose Connection at PT feeding the PMU



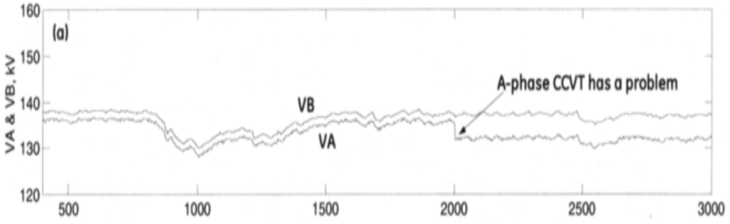
Switching Transients due to Ferroresonance



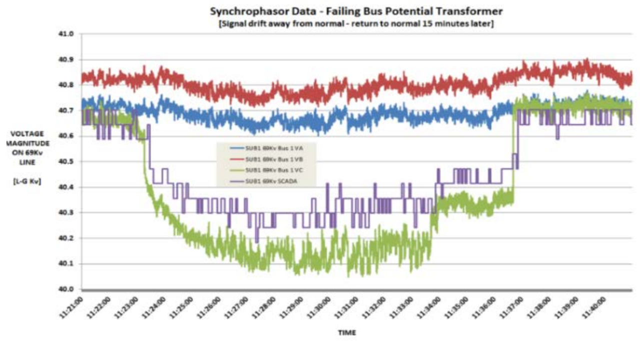
Blown fuse on One Phase of PT



A - Phase CCVT Issue



Internal Primary Winding Issue



References:

1) NASPI Technical Report, “Diagnosing Equipment Health and Mis-operations with PMU data”, May 2015
2) Bogdan Kasztenny and Ian Stevens, “Monitoring Ageing CCVTs – Practical Solutions with Modern Relays to Avoid Catastrophic Failures”, March 2007
3) David Shipp and Thomas Dionise, IEEE Tutorial, “ Switching Transients, Transformer Failures, Practical Solutions”, Feb 2016

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

EPG's Platform for Asset Health Monitoring

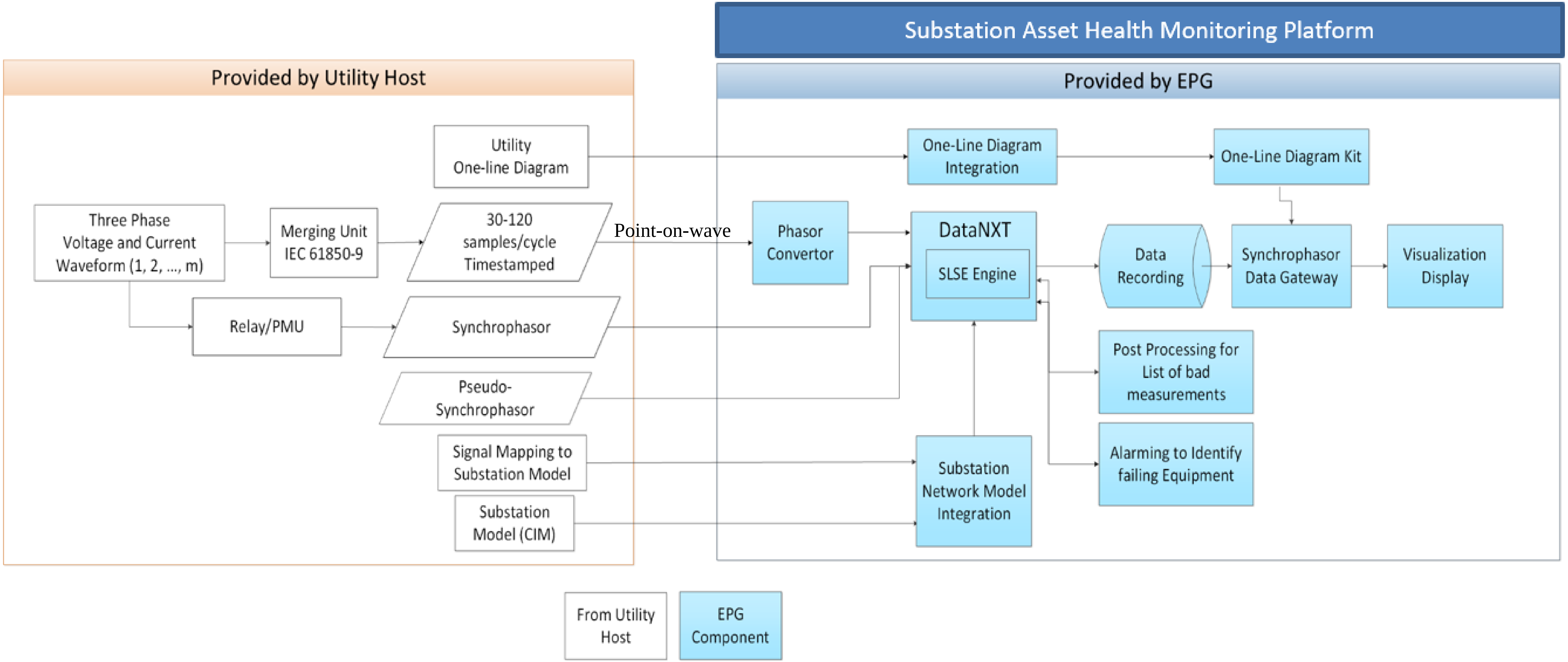
- Platform: EPG developed a Substation Secondary Health Monitoring Platform to detect precursors to Equipment Failure
- Data: PMU and point-on-wave DFR data
- Equipment: Instrument Transformers (CT, PT, CCVT)
- Deployment Flexibility: In control centers or in substations
- Testing and Validation: American Electric Power (AEP)
- Field Testing and Deployment: Planned for Deployment in two substations (138 kV & 765kV) by end of 2019

Methodology

- Data from substation collected by PMUs and DFRs
- Use two methods
  - Data-driven Methods
    - Moving Variance – Use Moving windows and moving threshold to identify anomalies
    - Control Chart - Use upper control limit to identify maximum change in a moving window
  - Substation Linear State Estimator (SLSE) Method
    - Model-based approach running linear state estimation at substation level for 3-phase voltages and currents

Architecture

- Can be deployed in Substations or in Control Centers



Validation & Testing– Over 60 Cases

Simulation Scenarios

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

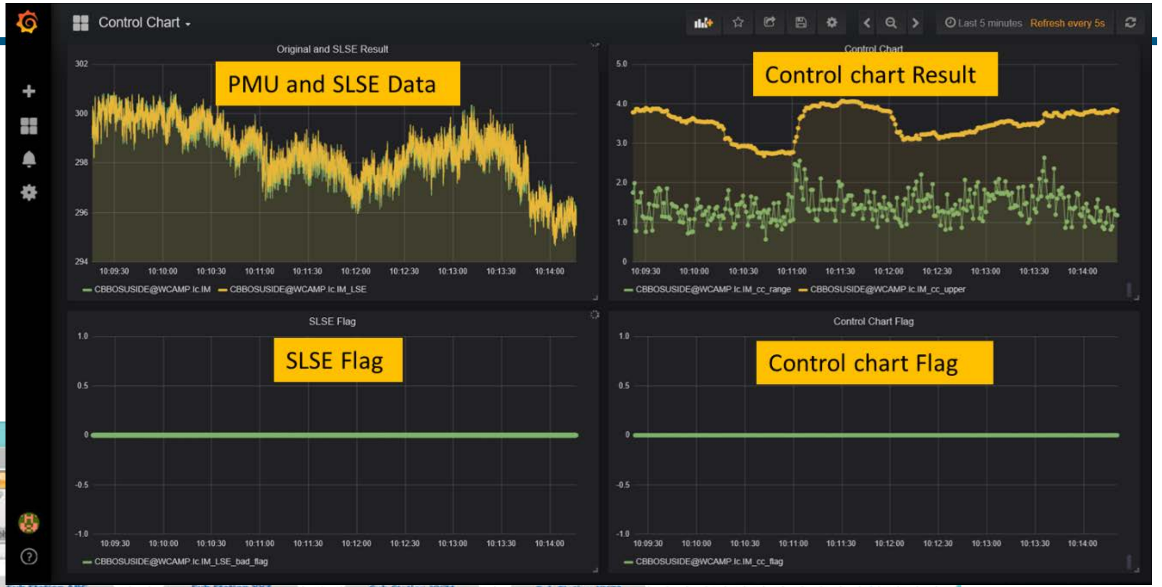
Tested with
- Simulated Data
- Live data from PMUs
- Point-on-wave Data from DFRs
- Equipment Failure Data

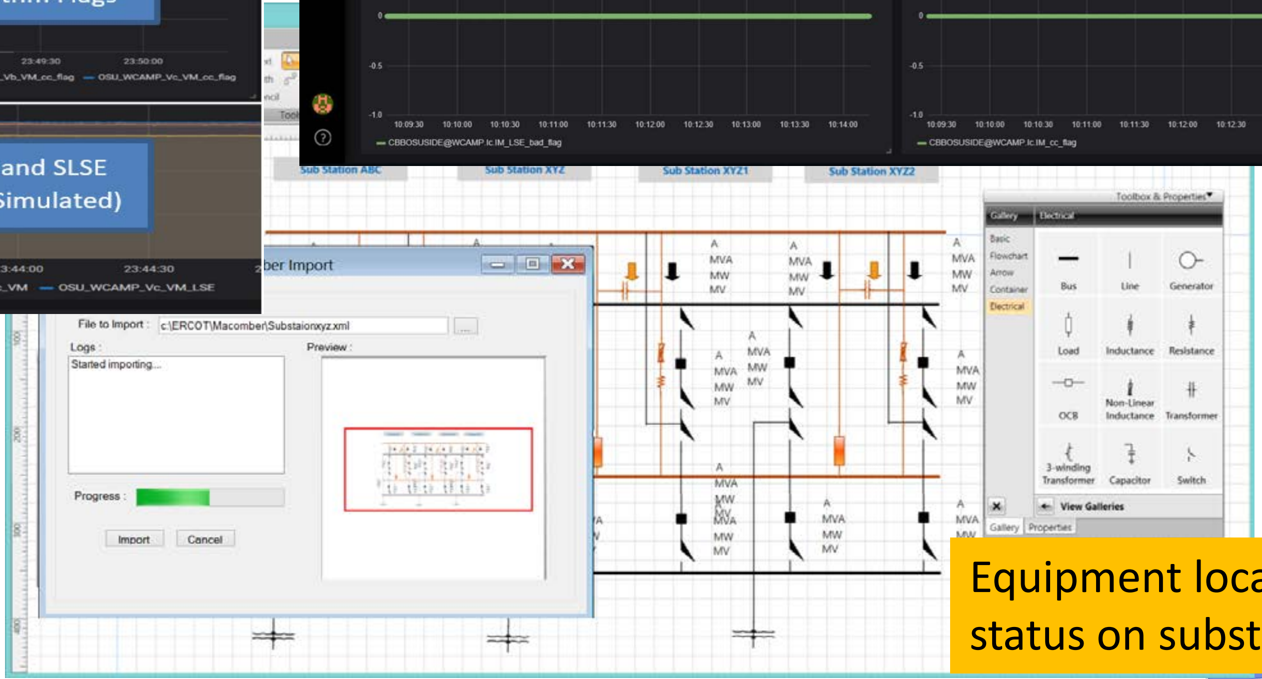
Overview of Test Findings

Assessment

- **Data-Driven Methods:**
  - Statistical Approach
  - Looks for patterns that may be indicative of equipment failure
  - Fast and powerful but requires events and datasets that can be used for tuning
  - Uses Multiple windows
  - Biased by bad data if not validated
- **SLSE Method:**
  - Based on power system models and focuses on physical phenomenon
  - Looks at Measured vs Estimated to identify anomalies
  - Robust to bad data
  - Requires model integration
  - Requires redundant PMU measurements

Visualization Example– Web-Based, One-line Diagrams





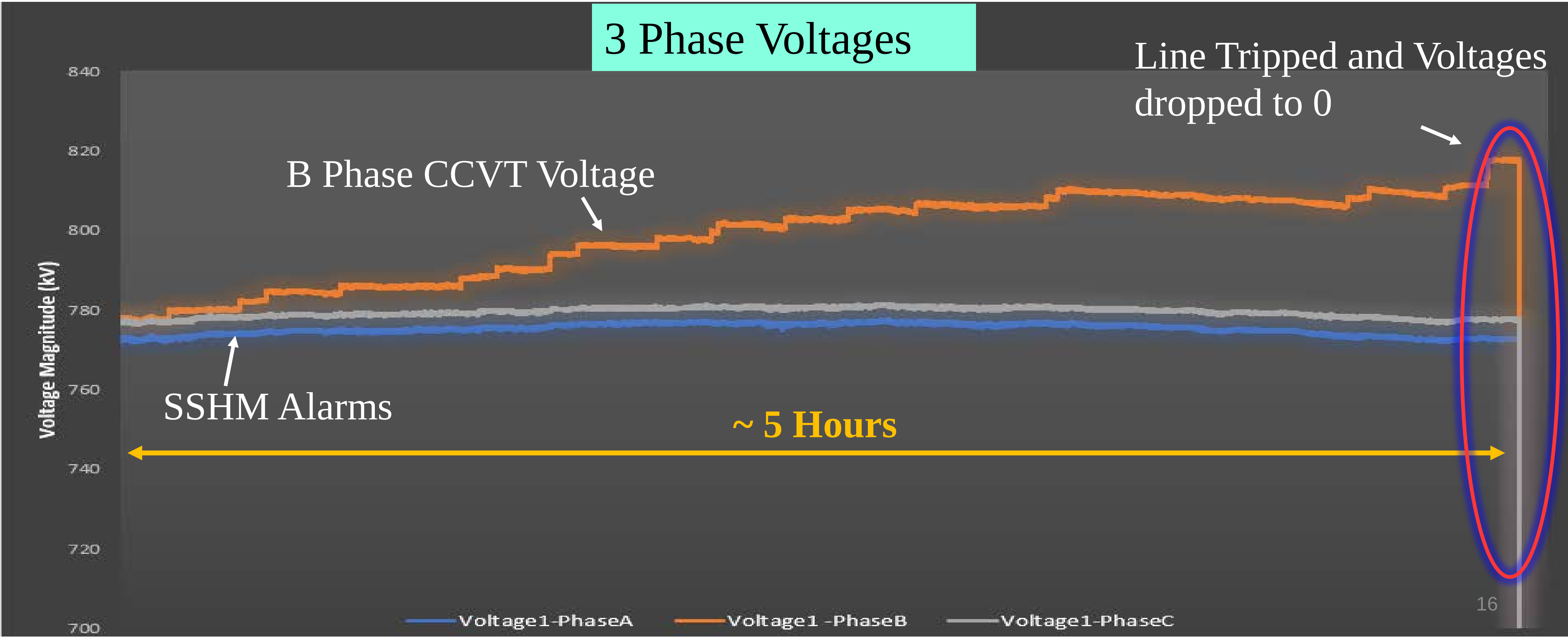
Monitor multiple equipment

- Independent alarming
- measurement signal & status trending

Equipment location and status on substation one-line

Real Event Replay – CCVT Failure

- CCVT Failure Event - B Phase Voltage has anomalies/precursors before equipment failed
- Event Replay after system tuning indicates that such failures can be detected 5 hours prior to failure



Alarm Panel

Time Increment

LSE Alarms for 3 Phases

Control Chart Alarms for 3 Phases

Moving Variance Alarms for 3 Phases

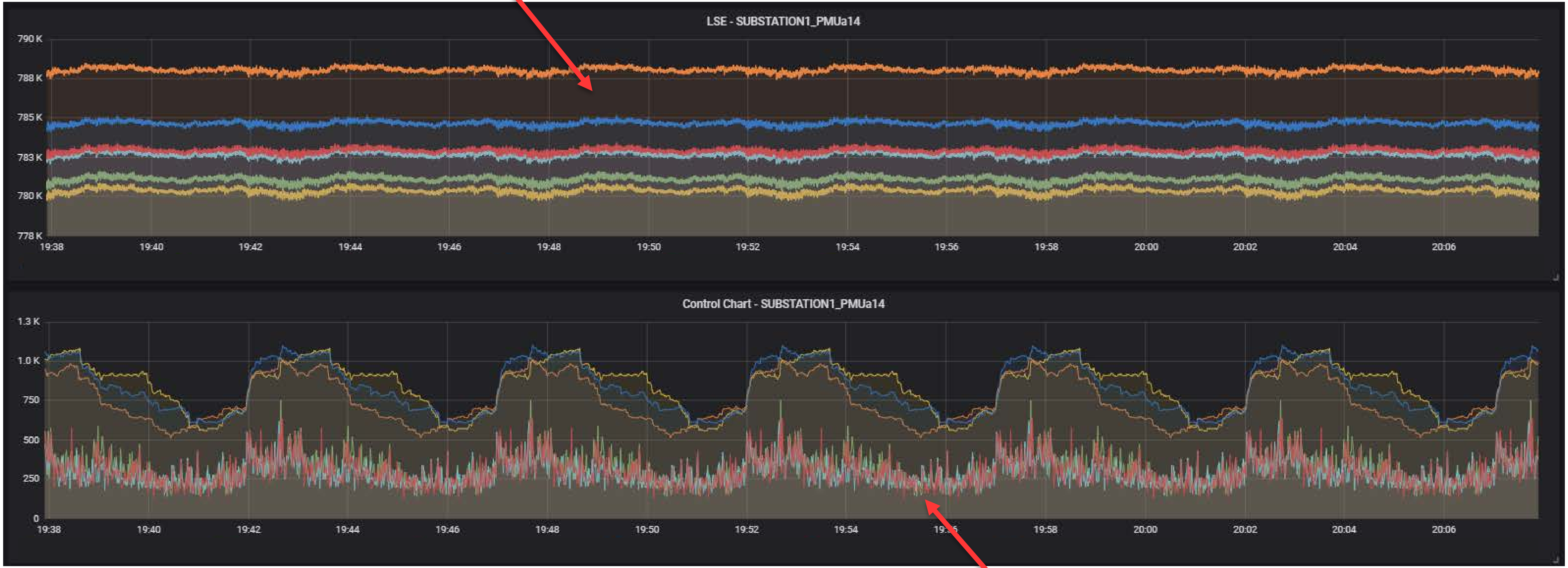
Alarm Panel_SUBSTATION1_PMUs14

Time	Va_LSE	Vb_LSE	Vc_LSE	Va_cc	Vb_cc	Vc_cc	Va_mv	Vb_mv	Vc_mv
2019-10-22 20:04:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 20:03:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 20:02:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 20:01:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 20:00:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:59:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:58:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:57:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:56:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:55:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:54:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:53:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:52:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:51:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:50:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:49:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:48:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:47:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:46:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:45:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:44:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 19:43:00	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear

Multi-device Alarm Panel

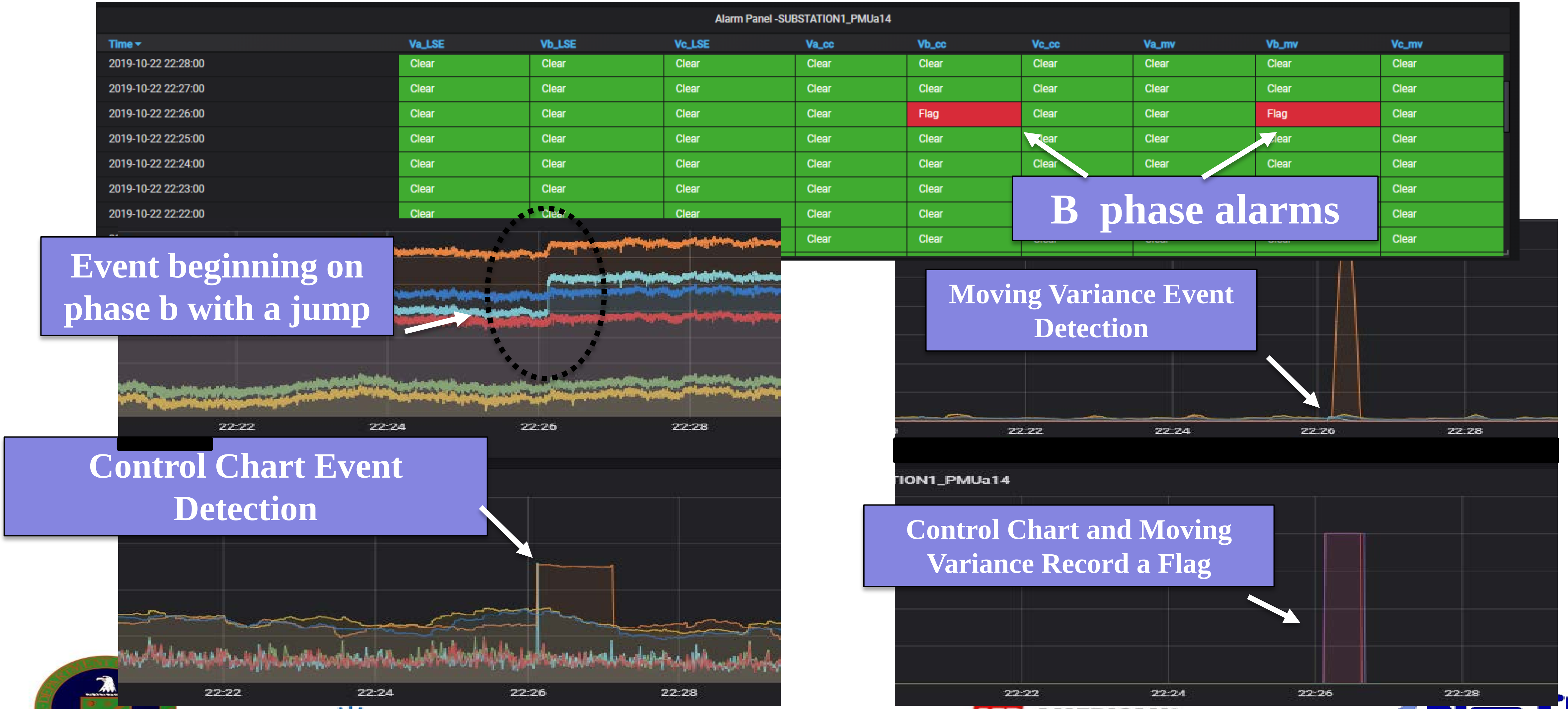
Line Charts – Raw and LSE, Control Chart

LSE and raw data, 3 phase each



Control Chart criteria and threshold, for 3 phases

Event Beginning – 5 hours before Line Trip



Event End – 5 hours after first signal jump

Alarm Panel -SUBSTATION1_PMUa14

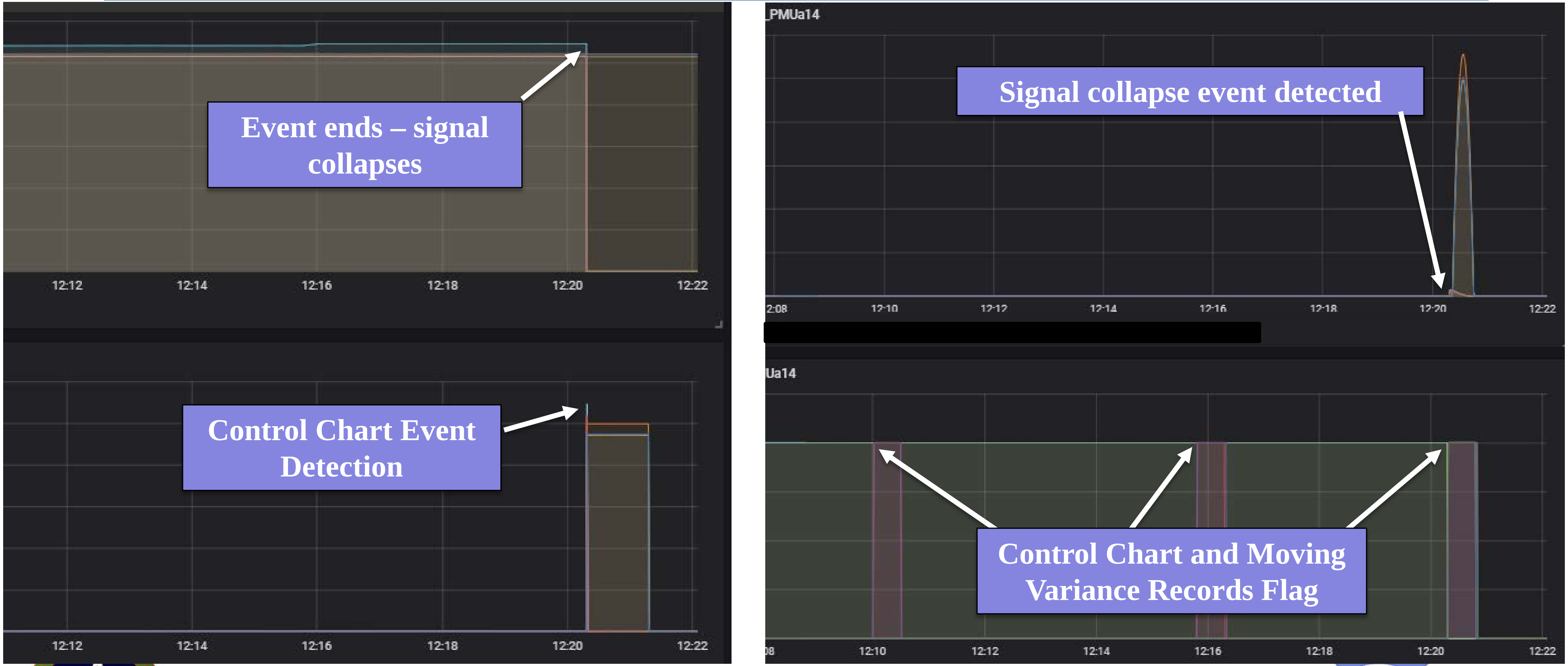
Time	Va LSE	Vb LSE	Vc LSE	Va cc	Vb cc	Vc cc	Va mv	Vb mv	Vc mv
2019-10-22 12:20:00	Flag	Flag	Flag	Flag	Flag	Flag	Flag	Flag	Flag
2019-10-22 12:19:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:18:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:17:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:16:0	[illegible]	Flag	Flag	Clear	Flag	Clear	Clear	Flag	Clear
2019-10-22 12:15:00	Clear	Flag	Flag	Clear	Flag	Clear	Clear	Flag	Clear
2019-10-22 12:14:00	Clear	Flag	Flag	Clear	Clear	[illegible]	[illegible]	[illegible]	Clear
2019-10-22 12:13:00	Clear	Flag	Flag	Clear	Clear	[illegible]	[illegible]	[illegible]	Clear
2019-10-22 12:12:00	Clear	Flag	Flag	Clear	Clear	[illegible]	[illegible]	[illegible]	Clear
2019-10-22 12:11:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:10:00	Clear	Flag	Flag	Clear	Flag	Clear	Clear	Flag	Clear
2019-10-22 12:09:00	[illegible]	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:08:00	[illegible]	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:07:00	[illegible]	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:06:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:05:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:04:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:03:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:02:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:01:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 12:00:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear
2019-10-22 11:59:00	Clear	Flag	Flag	Clear	Clear	Clear	Clear	Clear	Clear

Line Trip

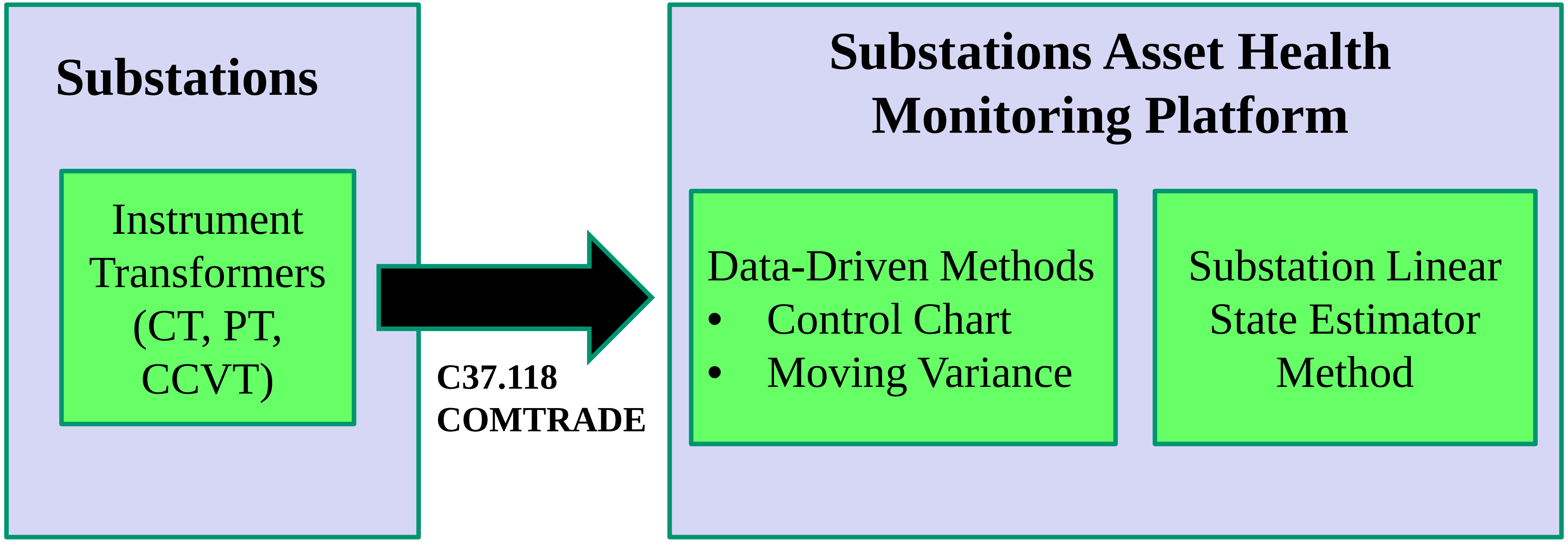
LSE Alarms constantly

Each jump is flagged by data driven methods

Event End – 5 hours after first signal jump



Substation Asset Health Monitoring Platform



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Summary

- Platform for Substation Asset Health Monitoring Using Synchrophasors
- Deployed in AEP test environment and planned for deployment in two substations by end of 2019
- Provides ability to detect precursors to equipment failure
- Avoid equipment failure and misoperations
- Alarms can be integrated with other monitoring systems using DNP3
- Plan to extend to generators and power transformers

Thank You!

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