DOE/OE Transmission Reliability Program

Substation Secondary Asset Health Monitoring and Management System

DOE Grant Award #DE-OE0000850

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Outline

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- Background
- Objective
- Technical Merit
- Technical Approach
- Project Schedule
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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

Background

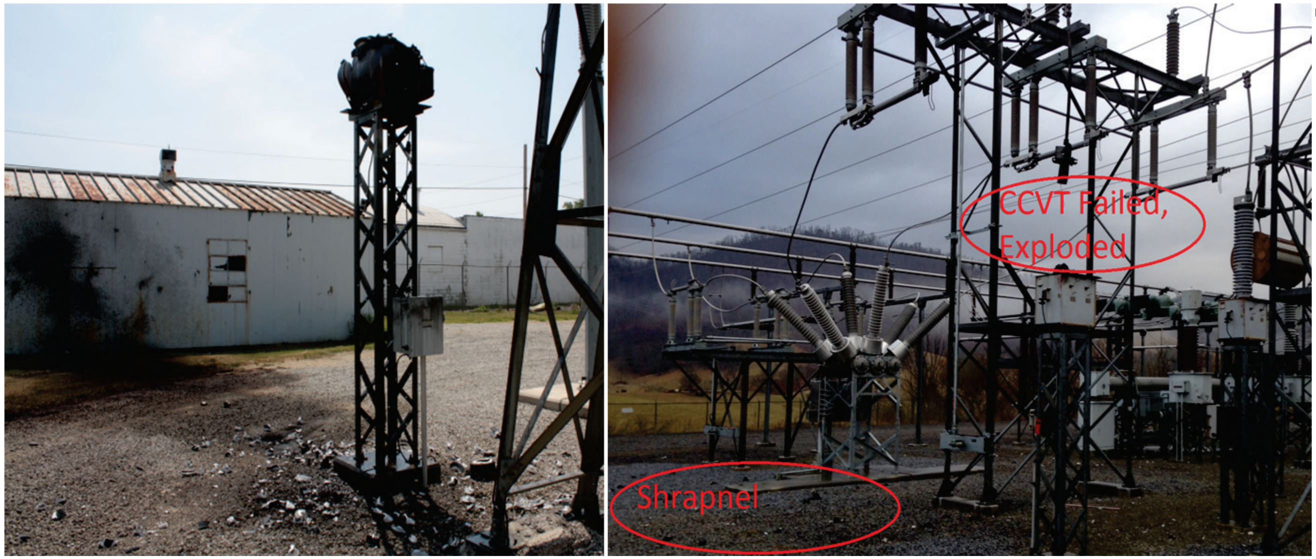
- Billions of dollars on transmission and distribution assets
- Key substation assets include transformers, circuit breakers, instrument transformers (CTs, PTs, CCVTs) and Intelligent Electronic Device (Relays, PMU, DFRs)
- Synchrophasor measurement systems have been widely installed in the North American 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

Objective

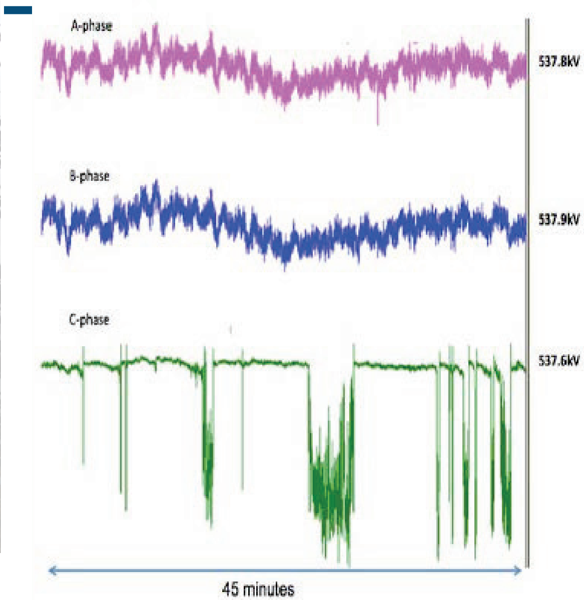
- Research, design, develop and demonstrate software application in substation(s) to:
  - Collect three phase measurements from substation equipment
  - Process data from PMUs, DFRs and Instrument Transformers to derive synchrophasor equivalents and run a three phase Substation Linear State Estimator (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

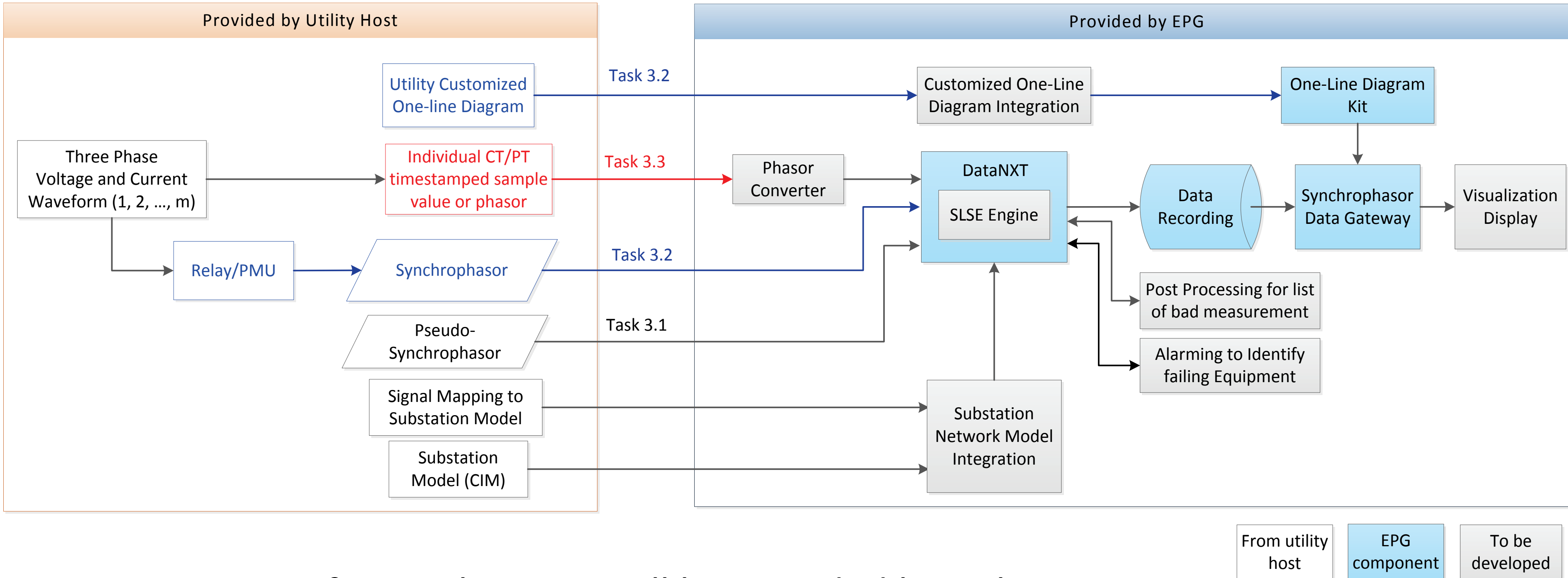


Example of CCVT voltage signals at Dominion

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

Technical Approach

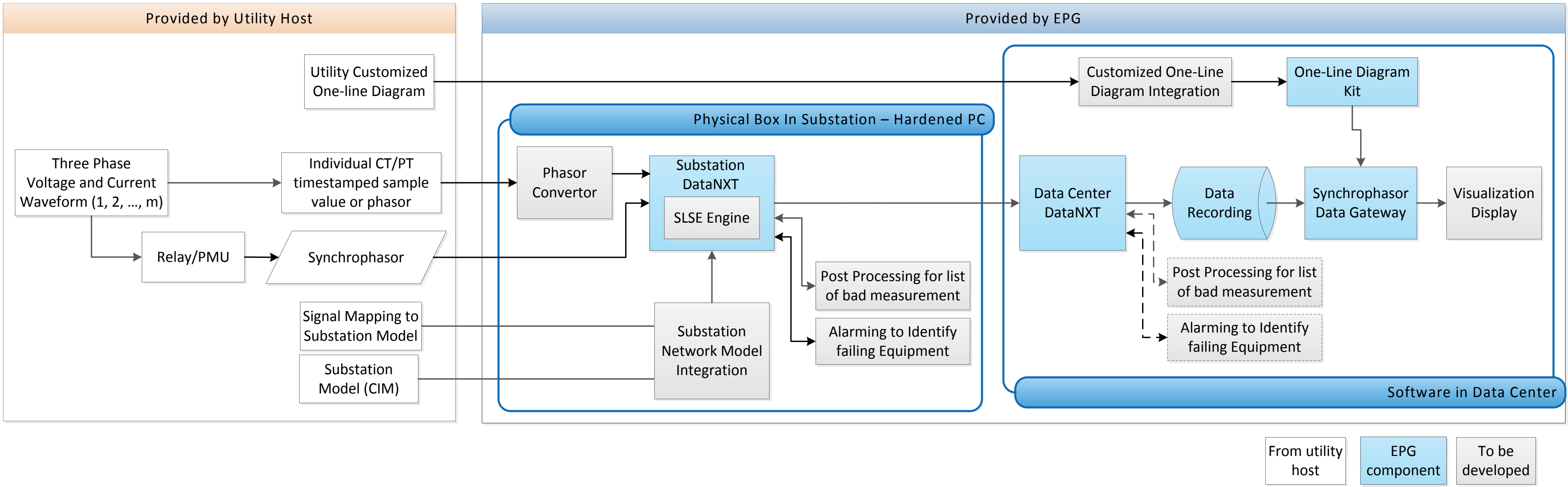
- Central Processing: Data sent from substations to central site



- 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

Technical Approach (Continued)

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



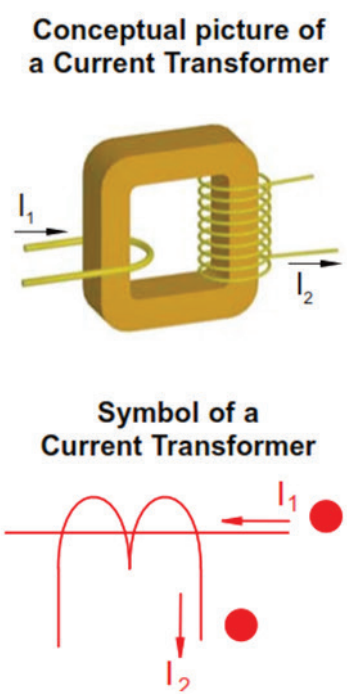
Project Schedule

#	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 – 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
4.0	**Deployment and Demonstration at Host Utility**	**September 2018 – March 2019**
4.1	Product Documentation	September – October 2018
4.2	Installation and Integration at Host Utility	October – November 2018
4.3	Site Acceptance Testing	November – December 2018
4.4	Demonstration at Host Utility	January – February 2019
4.5	Training	February – March 2019
5.0	**Marketing and Outreach**	**September 2018 – March 2019**
5.1	Market Research	September – December 2018
5.2	Commercialization Plan	January – March 2019
5.3	Outreach	September 2018 – March 2019

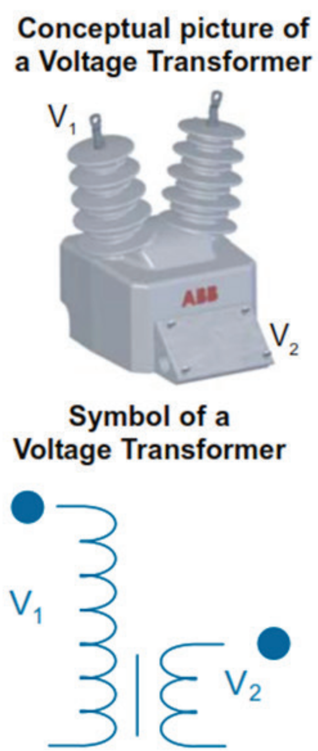
Task 2.2 Research and Scoping Study - Equipment

- 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

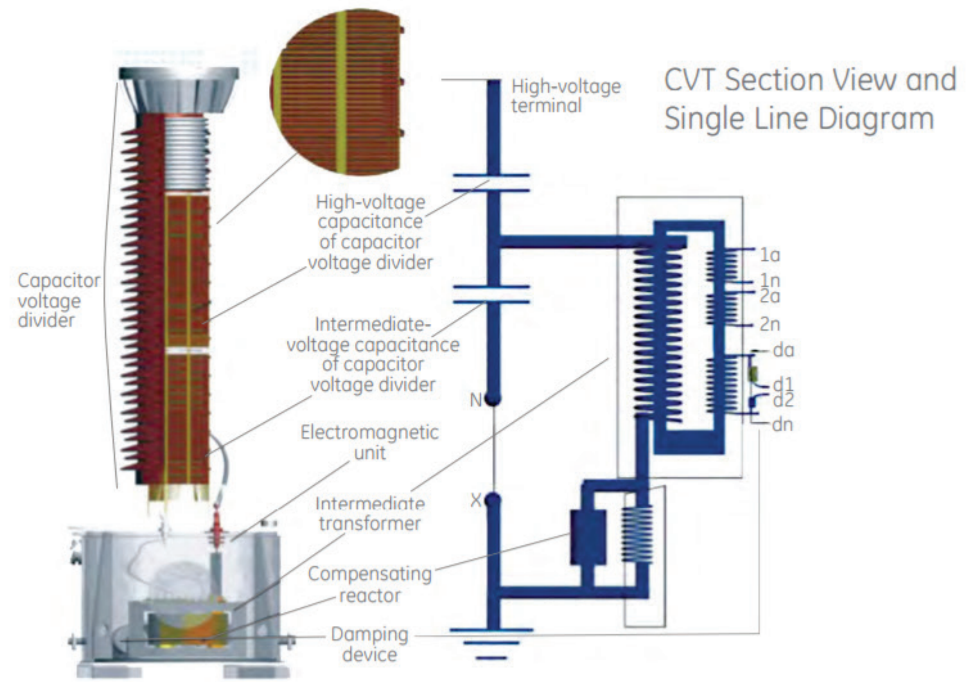
Current Transformer (CT)



Potential Transformer (PT)



Coupling Capacitor Voltage Transformer (CCVT)



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

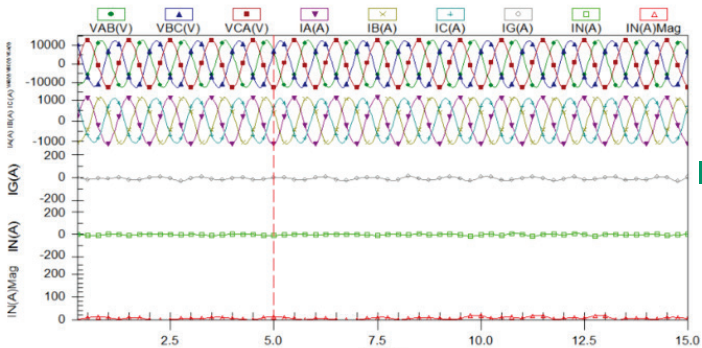
Source: IEC Capacitive & Coupling Capacitor Voltage Transformers (CVT & CCVT), http://www.gegridsolutions.com

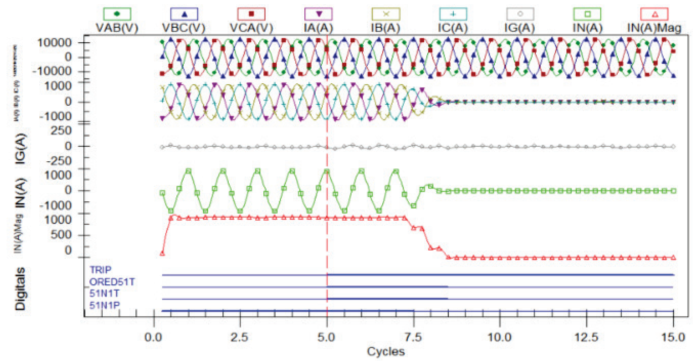
Research and Scoping Study – Equipment Failure Modes

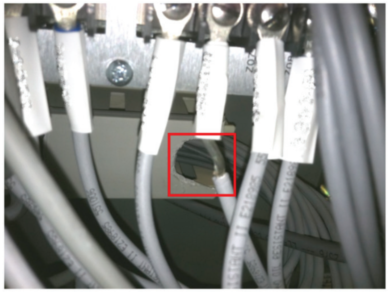
Cause of Failure / Failure Modes		
CT	PT	CVT/CCVT

•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



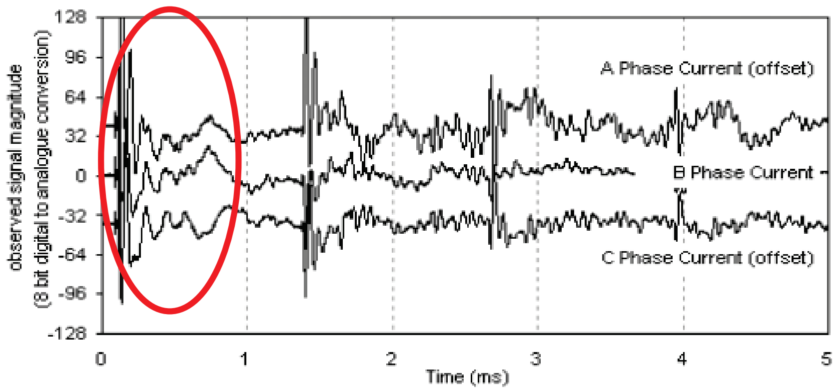


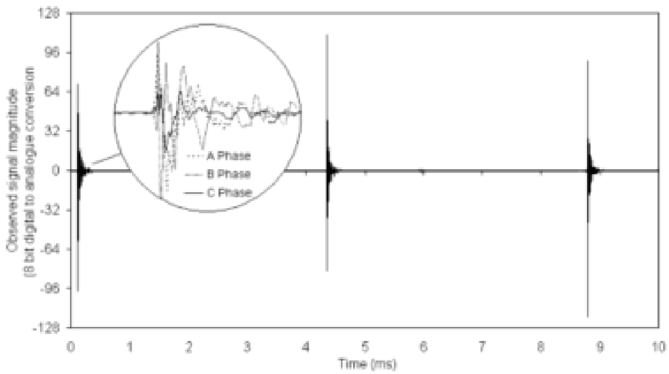


Normal Operation – No failure

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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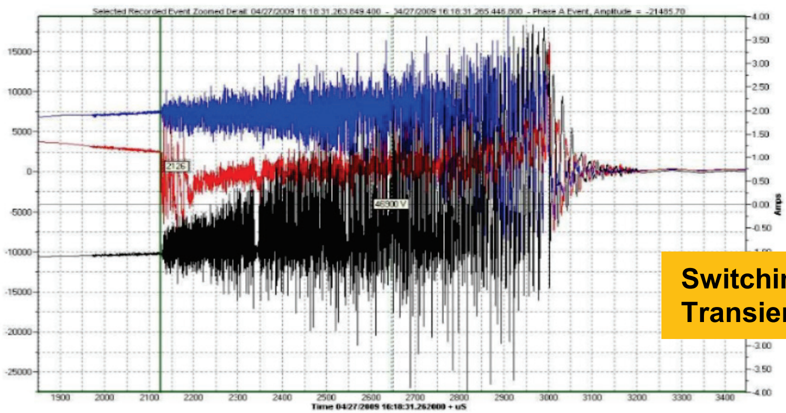
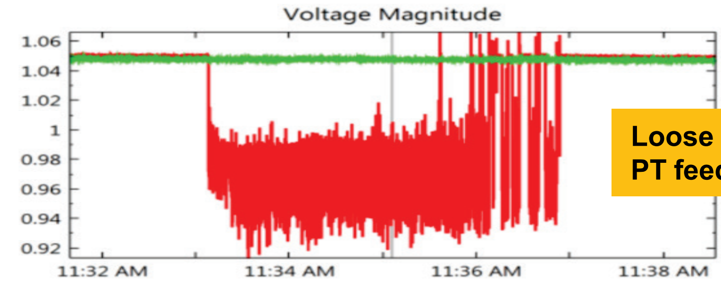
Signature Examples - PT

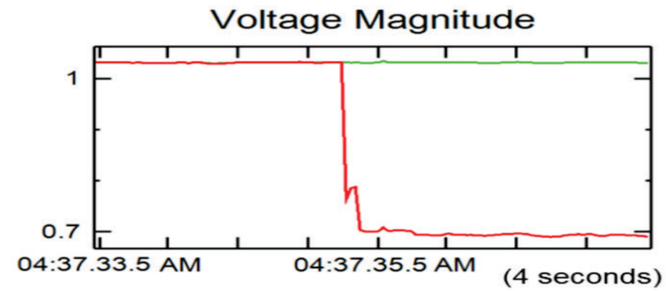


Switching Transients

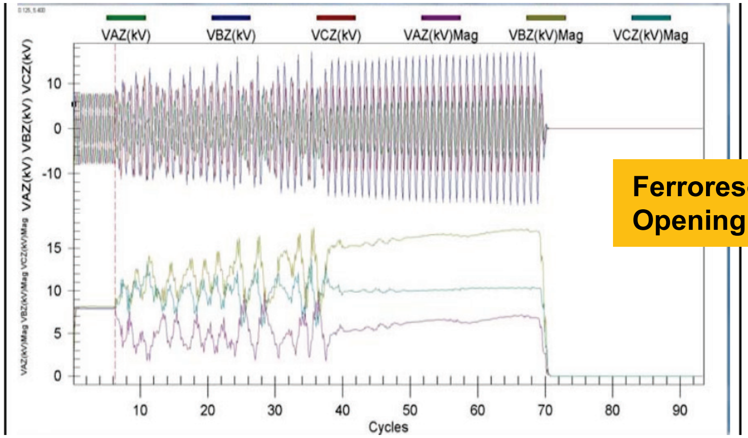
Reference: [A]



Loose Connection at PT feeding the PMU

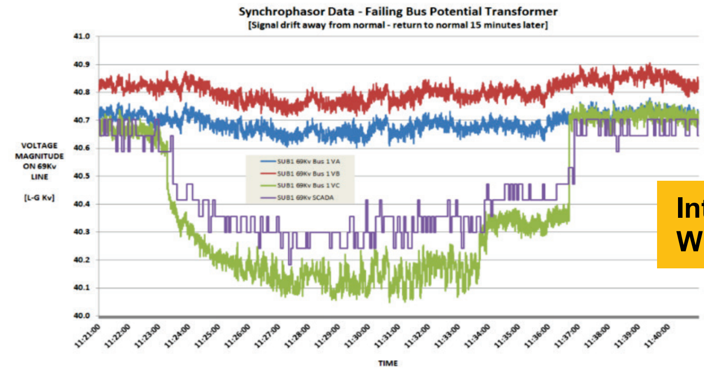


Blown fuse on One Phase of PT



Ferroresonance – Opening Breaker

Reference: [C]

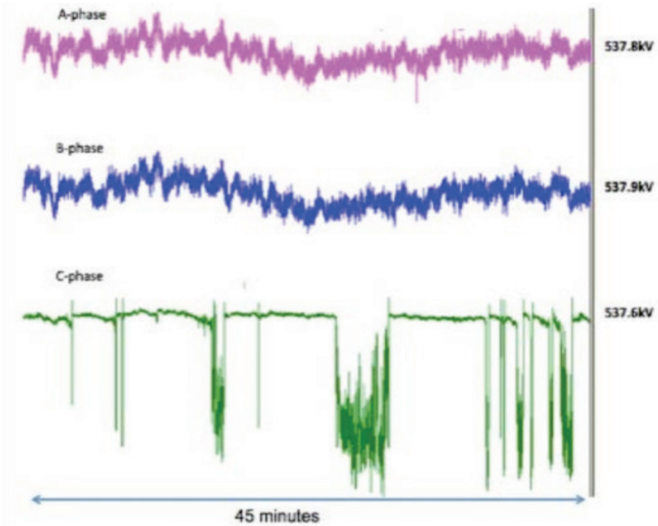


Internal Primary Winding Issue

Reference: [A]

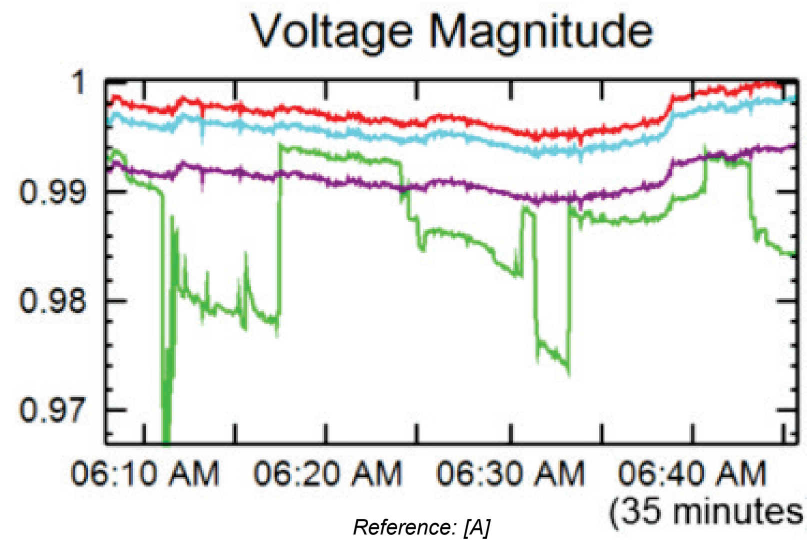
Signature Examples - CCVT

Capacitor Failure in C phase



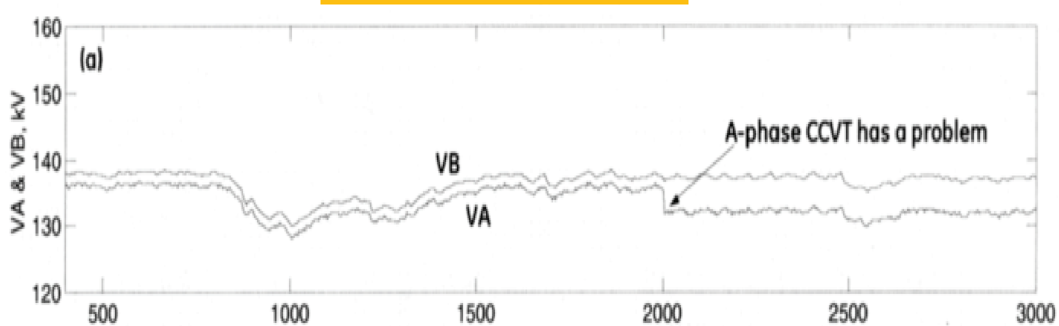
Reference: [A]

Loose Fuse Connections in CCVT Safety Switch



Reference: [A]

A - Phase CCVT Issue



Reference: [B]

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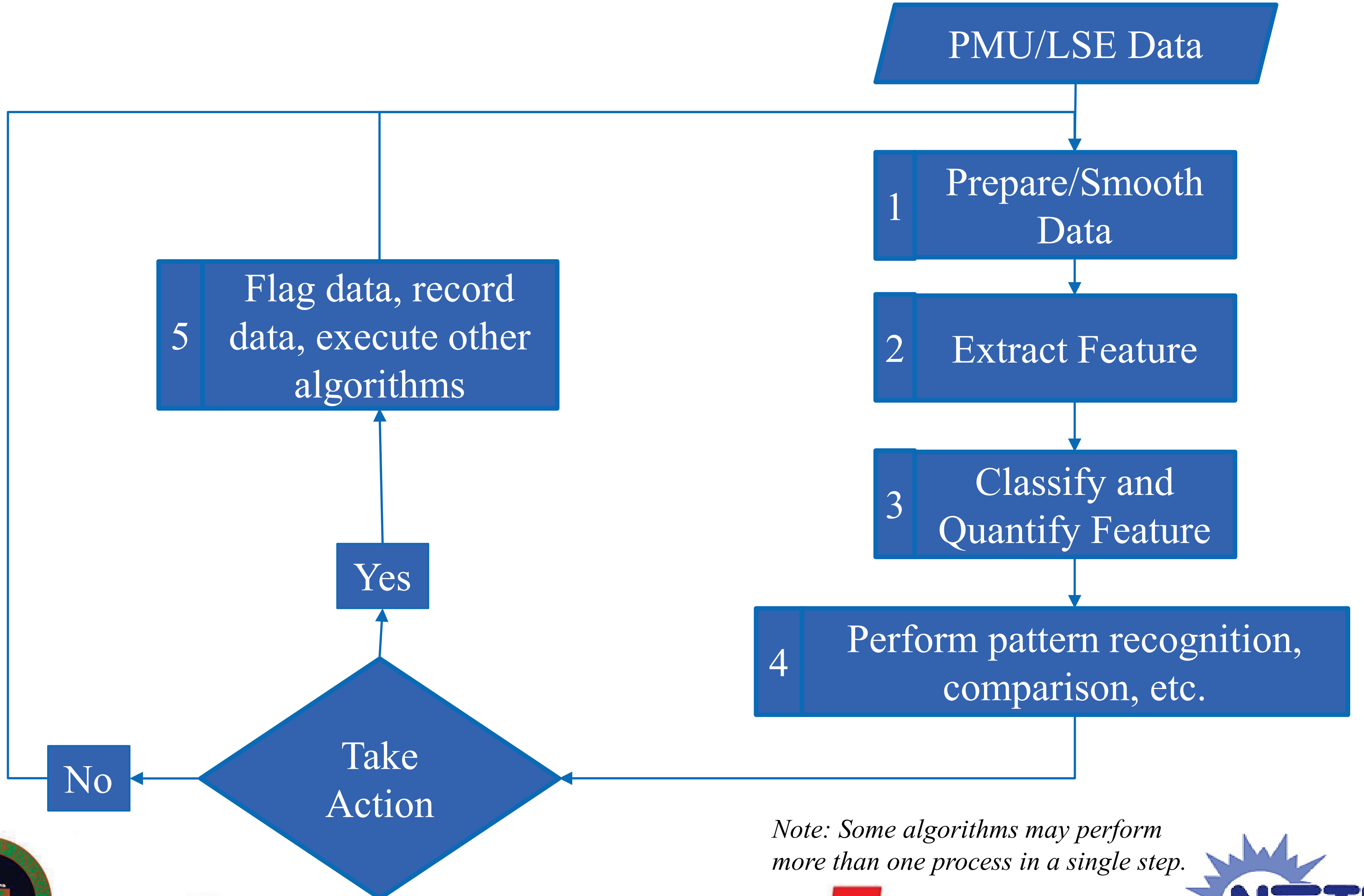
Available Inputs and Desired Output

Available Input - Data	Desired Output – Flag Asset Fail
• Raw PMU Data • LSE Data • Redundant PMUs • Other Phases • DFR Data*	• Minimal false positive • Minimal false negative • Maximize prediction time • Within Computing Constraints

5 Processes - Detect and React to Anomalies



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

Current Project Status

- Contract Awarded: March 15th, 2017
- Project Planning Meeting with AEP: March 29
- DOE Official Kickoff Meeting: April 10
- PMP Update Completion: April 14
- Project Update to Industry
  - NERC SMS: May 18
- Task 2.2 Research and Scoping Study completion: June 9
- Task 2.3 Functional Design and Design Specifications: Started

Q & A

Thank You!

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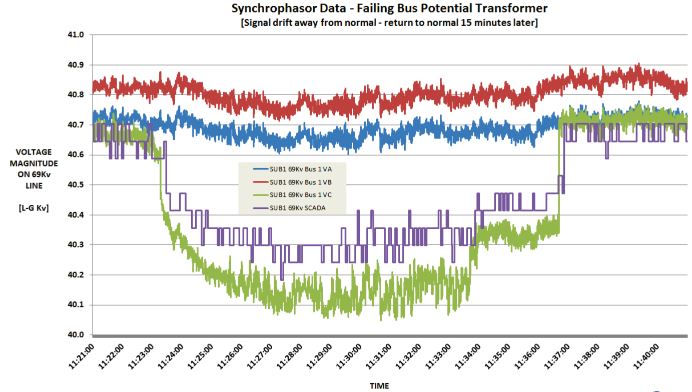
BACKUP SLIDES

Technical Approach

- Utilize Substation Linear State Estimator (SLSE) technology to solve the substation states and detects bad measurements from PMUs, DFR's and other measuring devices
- SLSE results will be saved in a local archiver for post processing
- Develop algorithms and logic to detect measurement anomalies and identify problem root causes
- Develop alarming module to trigger early warning and alarm information for failing equipment, to the responsible operators and engineers or transmission field service technician

5 Processes - Detect and React to Anomalies

1) Prepare/smooth and clearly delineated anomalous data
   - Critical - if anomalous data not clearly delineated
   - Unnecessary - if anomalous data clearly delineated
2) Extract the anomalous data from PMU data signal
   - Redundant PMU - difference in PMU signals
   - Single phase failures - difference in phase signals
   - Else - difference in prediction and actual signal
3) Classify and quantify the features/anomalies
   - Below min threshold –> ignore noise
   - Predetermined shape and magnitude –> threshold comparison
   - Indeterminate shapes, sizes, frequency, etc. –> wide net of complex algorithms such as pattern recognition
4) Perform threshold calculation dependent on:
   - Design parameters and constraints for project
   - Range of expected anomalous signals
   - False positive vs false negative balance
5) Take action
   - Flag
   - Record data
   - Further calculations



PMU data indicating failing potential transformer [7]

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Algorithm for Feature Extraction

- General approach to direct feature extraction without conditioning
  - Peak (max), derivative, difference, normalization, detrend, frequency filters, signal to noise ratio
- Simple processing/smoothing (moving window)
  - Averaging smoothing methods (moving average, moving RMSE, weighted moving average)
  - Exponential Smoothing Methods
- Dimension/Data reduction
  - Time or Frequency analysis
    - Singular value decomposition (SVD)/Principal component analysis (PCA) [5]
    - Discrete/Fast Fourier Transform (DFT)/(FFT)
      - Already performed on PMU data
  - Time-frequency analysis algorithm
    - Matching Pursuit Decomposition (MPD) [3][4]
    - Wavelet transform (WT) [11]
- Data conditioning and removing bad data
  - Quadratic prediction model and Kalman filter [9]

Note: Algorithms may be used in series, parallel or combination.

References

A. NASPI Technical Report, “Diagnosing Equipment Health and Mis-operations with PMU data”, May 2015

B. Bogdan Kasztenny and Ian Stevens, “Monitoring Ageing CCVTs – Practical Solutions with Modern Relays to Avoid Catastrophic Failures”, March 2007

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[8] Xiaodong Liang and S. A. Wallace, “Processing synchrophasor data using a feature selection procedure,” in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2016, pp. 273–277.

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[11] J. Ning and W. Gao, “Multi-feature extraction for power system disturbances by wavelet transform and fractal analysis,” *IEEE PES Gen. Meet. PES 2010*, pp. 1–7, 2010.

[12] J. Patel, “Real time big data mining,” The State University of New Jersey, 2016.

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