DOE/OE Transmission Reliability Program

Substation Asset Health Monitoring Using Synchrophasors

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NASPI

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Acknowledgement & Disclaimer

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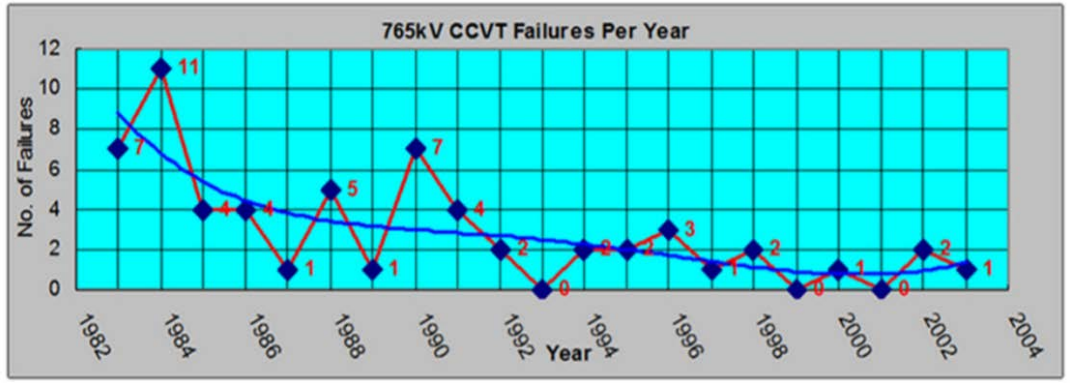
Introduction

- EPG was awarded a Contract by DOE for Substation Asset Health Monitoring with AEP as a demonstration host and cost share partner (Award Number DE-OE0000850)
- DOE Project was completed in 1Q 2020
- The proof-of-concept demonstration identified gaps
- EPG leveraged the DOE funded cost share project work to develop *i*TAM
- *i*TAM is a commercial, scalable, production grade application for Transmission Asset Health Monitoring using Substation Linear State Estimation (SLSE) Technology and Data Driven Methods

Need for Asset Health Monitoring

Using Synchrophasor Data to Prevent Equipment Failure

Example of failing CCVT in a substation



AEP 765kV CCVT Failure Rate

~ 60 Reported Failures between 1982-2004

*T. Yang, Applying Substation Linear State Estimator to Instrument Transformer Health Monitoring and Management: Roadmap, CIGRE 2016.

- 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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*i*TAM - EPG's Platform for Substation Asset Health Monitoring

- Platform: EPG developed *i*TAM (*intelligent* Transmission Asset Monitor) to detect precursors to Equipment Failure
- Data: PMU and point-on-wave DFR data
- Equipment: Instrument Transformers (CT, PT, CCVT)
- Deployment Flexibility: Central Location or in substations
- Testing and Validation: American Electric Power (AEP)
- Field Testing and Deployment: Deployed and validated at two substations (138 kV & 765kV). Planning on central monitoring center with *i*TAM

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Technical Approach – Model Based and Advanced Data Analytics

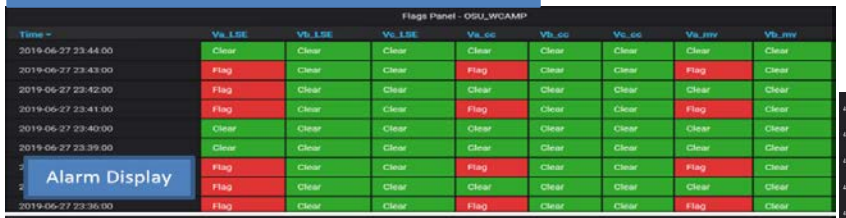
- Data from substation collected by PMUs
- Uses three methods for detecting measurement anomalies that are precursors to equipment failure
  - **Method 1 – Model based - Substation Linear State Estimator (SLSE)**
    - Model-based approach running linear state estimation at substation level for 3-phase voltages and currents
    - Compares linear sate estimation to measured data – discrepancy implies measurement anomaly
  - **Method 2 – Advanced Data Analytics - Control Chart (CC)**
    - Uses the average range of a moving window
    - Compares average range to each new data point
  - **Method 3 – Advanced Data Analytics - Moving Variance (MV)**
    - Compares moving variance to each new data point

*i*TAM – Robust Design and Filters out False Positives

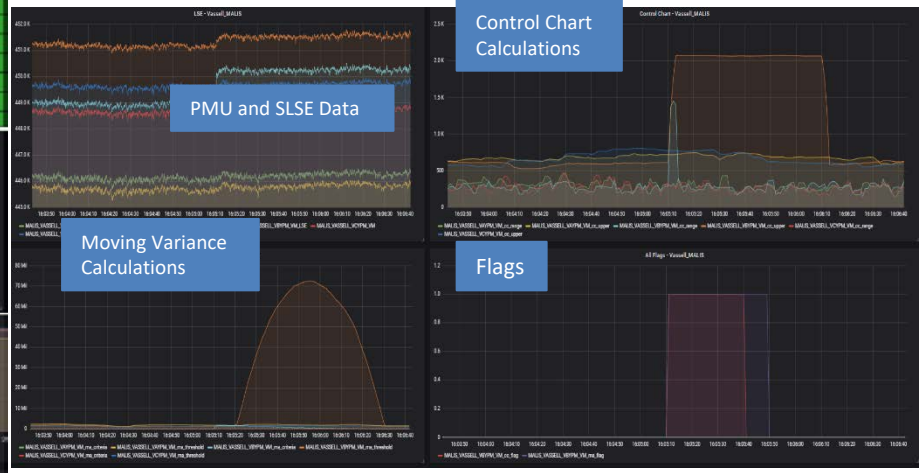
- False Positives can be caused by System Events and Bad Data
- System events – anomalies in the data caused by real events in the electrical system
  - Line trip
  - Generation trip
  - Grounding event, lighting strike
  - Transients caused by switching, breaker open/close
- Bad Data – issues in the measurement system causing data quality problems
  - Dropouts
  - Erroneous Values
  - Stale Data
  - Time Errors
  - Communication Errors
  - Noisy Data

Visualization Example– Web-Based, One-line Diagrams, Email Notifications

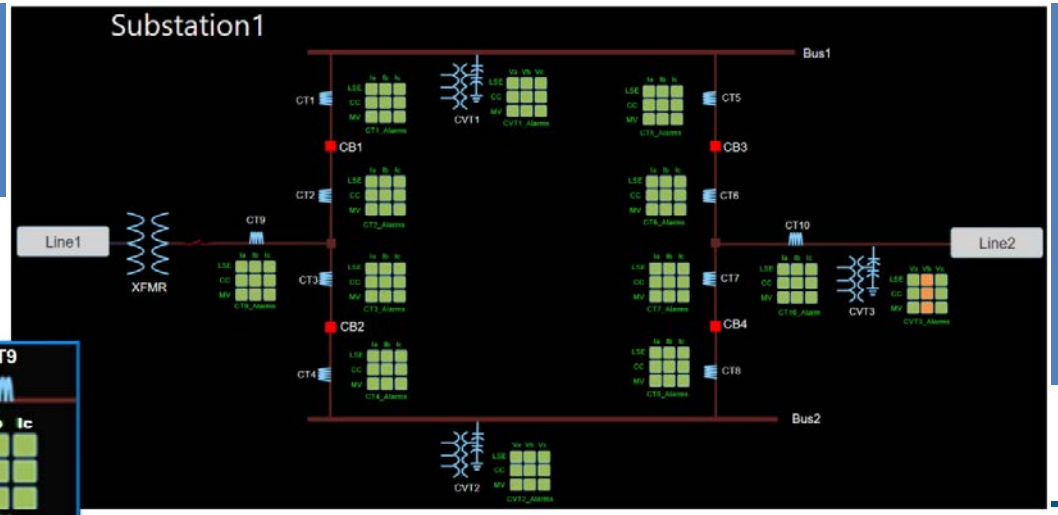
Alarm Dashboard

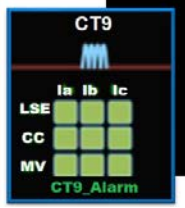


Trend Charts



One-Line Diagram – alarm mapping to equipment - 3 phases



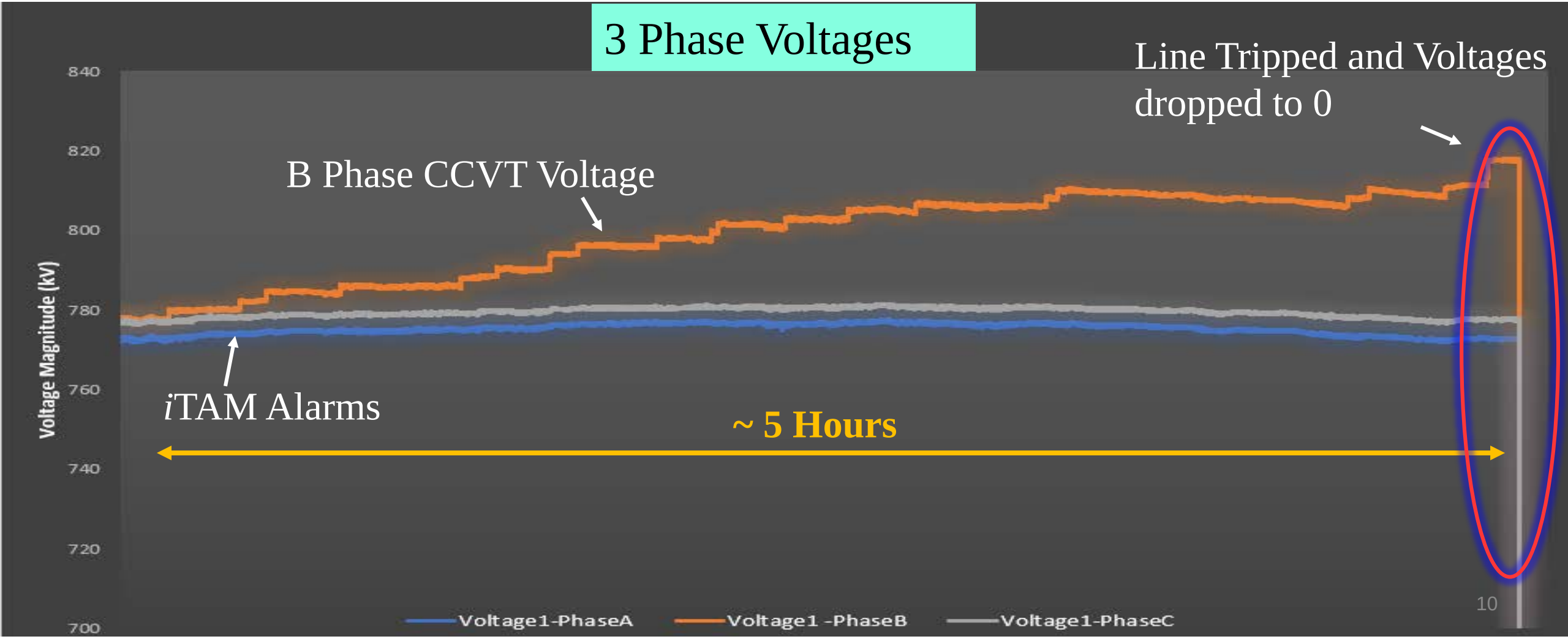


*i*TAM

- Monitor equipment – 3 phases
- 3 methods
- Visualization
  - Alarm dashboard
  - Trend charts
  - One-line

*i*TAM Real Event – CCVT Failure

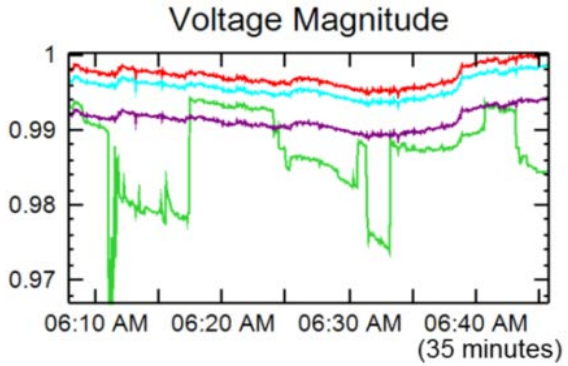
- CCVT Failure Event - B Phase Voltage has anomalies/precursors before equipment failed
- Can be detected 5 hours prior to failure, System is tuned to capture these failures and provide early warning



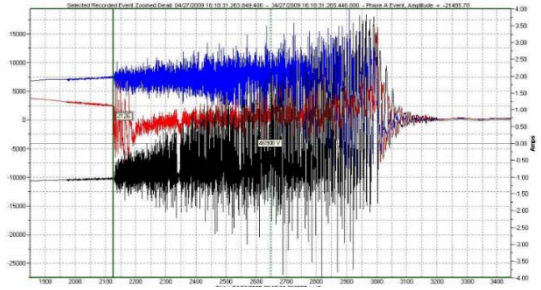
Examples of *i*TAM Detection Capabilities

Loose Connections, Winding Issues, Blown Fuses, etc.

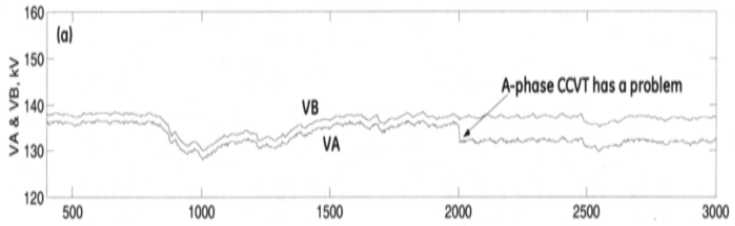
Loose Fuse Connections in CCVT Safety Switch – OG&E

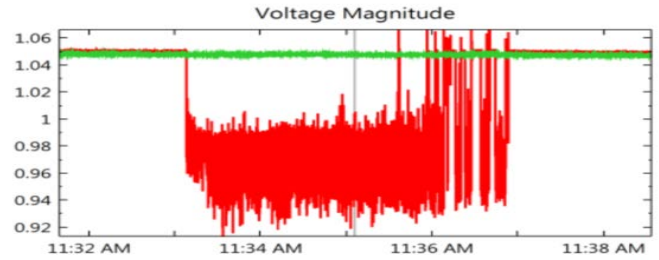


Switching Transients due to Ferroresonance

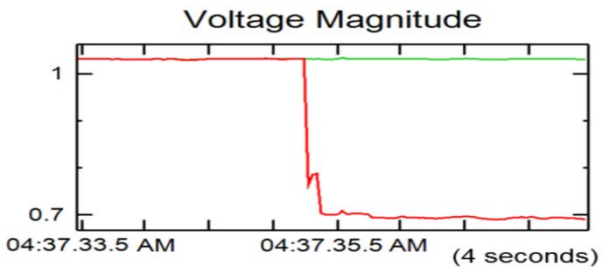


A - Phase CCVT Issue

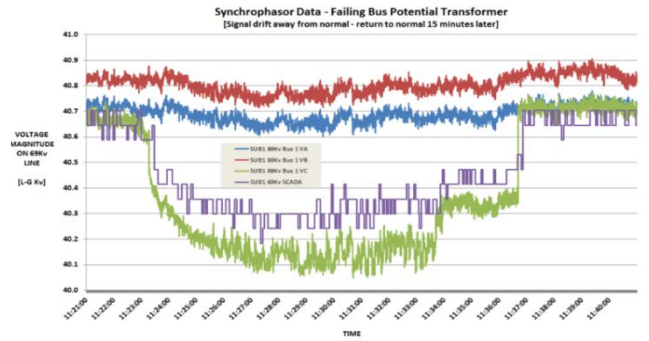




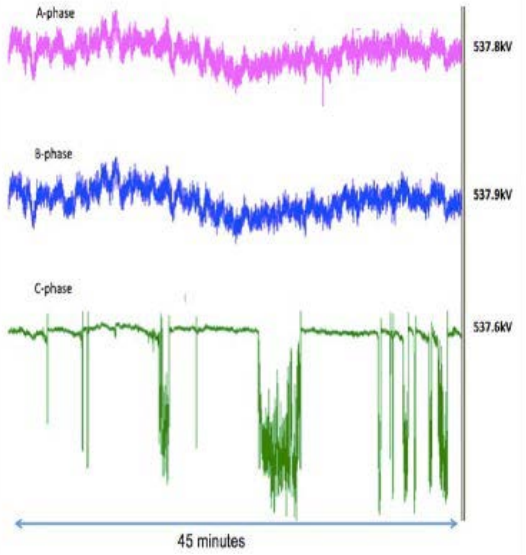
Loose Connection at PT feeding the PMU – OG&E



Blown fuse on One Phase of PT – OG&E



Internal Primary Winding Issue - ATC



CCVT Failure example from Dominion – PMU Data showed precursors 4 days before alarms from SCADA system

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

Use-case Example

From NERC Lesson Learned Report

- NERC & NPCC Event Analysis Team Published a Report on April 14, 2020
- CCVT Failure Event caused a single-phase-to-ground fault
- CCVT had exhibited low, out-of-tolerance output prior to the event.
- Event caused communication equipment failure due to transient
- Primary and Back-up relay protection failed
- Fault continued for over 4 minutes causing significant damage

"Monitoring the output for "stair steps" can warn of developing failure"

https://www.nerc.com/pa/rrm/ea/Pages/Lessons-Learned.aspx

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Lesson Learned

Protracted Fault in a Transmission Substation

Primary Interest Groups
Transmission Operators (TOPs)
Transmission Owners (TOs)

Problem Statement
Electronic communications equipment utilized to transmit and receive information from the remote terminals of a transmission line automatically shut down within milliseconds when a bus fault occurred at one terminal of the line. Neither the primary nor the back-up relay protection cleared the fault. The fault continued for over four minutes.

Details
A single-phase-to-ground fault occurred on an instrument voltage transformer connected to the bus section that serves as the transmission line's terminal at Substation 1. The instrument voltage transformer was a capacitive coupling voltage transformer (CCVT)[1], comprised of a stack of coupling capacitors that form a voltage divider that supplies approximately 5 kV to a small potential device that in turn steps down the voltage to 120 volts for utilization by metering and back-up protective relaying. (See Figure 1). This instrument voltage transformer had exhibited low, out-of-tolerance output prior to the event. Low output voltage is often thought to be a benign condition for coupling capacitor devices.[2] The output to metering and back-up relaying had been temporarily isolated prior to the event to preclude false readings and avoid the risk of relay misoperation, but the coupling capacitors remained connected[3] to the transmission bus.

Communications equipment shut down at the substation where the fault occurred because of an electrical transient associated with the fault. The communication channels carried information utilized by the line differential relaying essential to the protection of the line

Expansion / Rupture Diaphragm
High Voltage Section Capacitor String
Nominal 5kV Tap for Step-down Transformer
Low Voltage Section Capacitor String
Ground
High Voltage Terminal
Top Cap
Spring
Porcelain or Polymer Housing with Sheds
Step-down Transformer is inside
Cables for Voltage Indication, Carrier, 120 / 240V power
To Cable Trench

Figure 1: Typical CCVT

common substation equipment types listed in the NERC Event Analysis' "Addendum for Events with Failed Station
failure modes and mechanisms in reported events.
to fail in a CCVT, it is usually by shorting out of individual capacitor packs in the string. If packs short out above the
" the output voltage rises. If packs below the 'low voltage tap' short out, the output voltage would lower. In either
reased voltage stress across all the remaining capacitors in the string, accelerating their failure. As long as the string
ads to a continuous sequence of shorting packs out and eventual catastrophic failure. Monitoring the output for "stair
loping failure.

Failed C Phase of CCVT

Remnants of Bus Insulators

Jan 11, 2019 - 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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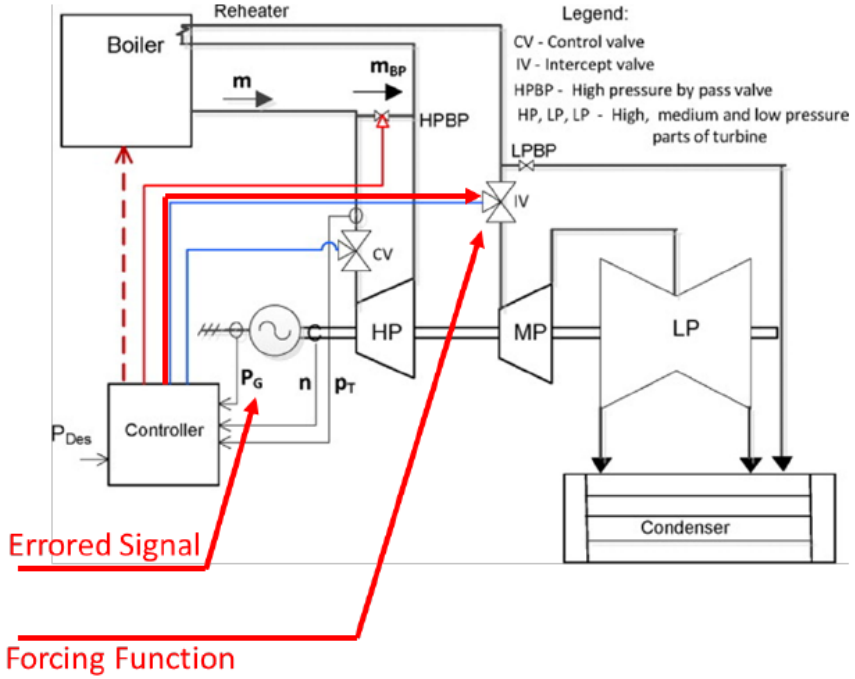
Forced Oscillation Source



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

- 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

Instrument Transformer Failure Events in Australia

- **March 3, 2017 – CCVT Failure** *Source: AEMO Incident report, 10 March 2017*
  - Explosive Failure of a CCVT in 275 kV Switchyard
  - Caused series of faults and tripping of Busbar and generator
  - Damage to generator disconnector
  - Loss of 610 MW generation across 5 units
  - CCVT was tested and physically/visually inspected 38 days before failure
- **February 13, 2017 – CCVT Failure** *Source: AEMO Incident report, 26 July 2017*
  - Explosive Failure of a CCVT associated with 275kV line
  - Caused single phase fault that developed into multiphase fault and tripping line
  - Loss of 475 MW of load
- **October 3, 2013 – CCVT Circuit Failure** *Source: AEMO Incident report, 16 December 2013*
  - Loose Fuse on secondary circuit of 330 kV line CCV
  - Caused overvoltage and line outage
- **November 20, 2015 – CT Failure** *Source: AEMO Incident report, August 2016*
  - Explosive Failure of Current Transformer (CT) at 330 kV
  - 330 kV Line Outage
  - 125 MW customer load loss

Summary

iTAM Complements Utility Asset Monitoring Systems

- Utility substation asset monitoring focused on monitor large assets – bulk power transformers, breakers, etc.
- Techniques are based on monitoring physical quantities – temperature, dissolved gases, oil, noise, vibration etc.
- Substation equipment includes instrument transformers (Current transformers, Voltage transformers, CCVT's) that are critical to substation protection
- iTAM - first of its kind digital technology that utilizes high resolution synchrophasor (PMU data) to monitor electrical signatures and detect precursors to failure of instrument transformers and enable pro-active action to mitigate against catastrophic costly failures
- iTAM complements existing asset health monitoring approaches by providing intelligence on electric signature anomalies to prevent substation equipment catastrophic failures
- Substation equipment failures are costly – iTAM can help prevent outages, reduce equipment replacement cost, promote safety

Thank You!