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Applying Substation Linear State Estimator to Instrument Transformer Health Monitoring and Management: Roadmap

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SUMMARY

Instrument Transformers (ITs), including but not limited to Potential Transformers (PTs), Current Transformers (CTs) and Coupling Capacitor Voltage Transformers (CCVTs), play an essential role in power system operation, protection, and control engineering through transducing primary electric quantities to secondary electric quantities and eventually digital readings after Intelligent Electric Device (IED) processing. Heath management of ITs, together with the IEDs, especially the continuous output monitoring and diagnostic analysis, could reveal the health of a particular device to avoid potential failures of that equipment and eventually reduce forced outages caused by IT and/or IED failures. In this paper, American Electric Power (AEP) proposes a roadmap which would apply Synchrophasor based Substation Linear State Estimator (SLSE) technology to establish a real time IT/IED reading monitoring and health management system. This system would detect IT/IED output abnormalities and in real time alert utility personnel to diagnose the malfunctions and take appropriate actions for asset management to prevent equipment failures, relay mis-operations, and forced outages, while reducing possible field service safety hazards.

KEYWORDS

Synchrophasor, Instrument Transformer, CCVT, Asset Heath Management, Linear State Estimator, Substation Automation

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Introduction

In [1] aging CCVT failure, especially violent failure phenomenon, impacts and methods to monitor failing CCVTs were well introduced. The health management of the CCVTs, which is an essential part of the ITs health monitoring and management system, could be implemented by continuously monitoring the digital readings from IEDs, such as microprocessor based relays which take the CCVTs as their analog inputs. Moreover, with the development of IEC 61850-9-x, it becomes possible that CCVT outputs could be digitalized and monitored directly through merging units [2] which bypass the IED processing. However, even in the current state-of-the-art CCVT failing monitoring algorithm, only the reading from a particular CCVT itself is used to determine if it is failing or not. Discontinuations of the readings are used as the criteria to determine if a CCVT is experiencing a failure and numerous ways of experience based engineering expert systems are applied in the algorithm to conclude if a CCVT is failing.

With the deployments of Synchrophasor concepts and technologies, more and more IEDs in the substation, especially microprocessor based relays, could have the capability to stream out Synchrophasor measurements. Monitoring Synchrophasor measurements from those IEDs to diagnose ITs' malfunctions, especially CCVTs' and PTs', became an industrial trend as introduced in [2]. However, if only single Synchrophasor measurement is to be monitored, it is still difficult to address if the abnormalities are caused by IT malfunctioning or power system perturbation. In another way, if it is possible to align those redundant Synchrophasor measurements together, then state estimation functionality could be applied in the substation to "cross check" the ITs readings and the abnormalities caused by ITs malfunctioning could be reliably detected and identified as bad data by state estimator. This method then could distinguish any power system perturbation caused CCVT abnormal readings from CCVT malfunctioning caused abnormal readings. Eventually, through the bad data pattern analysis, malfunctioning and/or failing CCVTs could be identified, recorded, and reported automatically.

In this paper, American Electric Power (AEP) proposes a roadmap which would apply Synchrophasor based Substation Linear State Estimator (SLSE) technology to establish a real time IT/IED reading monitoring and health management system. This system would detect equipment malfunctions and alert utility personnel in real time to diagnose the malfunction and take appropriate actions to prevent equipment failures, relay mis-operations and forced outages. Moreover, this system would contribute to AEP's "Zero Harm" standards through eliminating CCVT violent failure caused field service safety hazards.

CCVT Violent Failure Types, Impacts, and Health Management

A. CCVT Violent Failure Types, Impacts, and Failure Rate Statistics in AEP

A CCVT is a sealed porcelain insulator with a voltage divider containing a stack of capacitive elements that is tapped near the bottom of the stack to supply a low voltage source. This low voltage source is reduced via a transformer to a voltage that can be used for relaying and metering. There are 3 main failure mechanisms for CCVTs: (1) Ferro-resonance, (2) Oil Leakage and (3) Capacitor Pack failures. In this paper, only the third mechanism is covered in the scope. Over years, the capacitive elements/pack of the CCVT will degrade and/or experience overvoltage and that would result in capacitor element failures and the secondary voltage progressively losing its integrity [1]. The CCVT can explode if sufficient numbers of capacitor elements fail, which is called a catastrophic or violent failure. Figure 1 is a failed

CCVT at one of AEP's substations showing the damage and potential safety risk to substation maintenance personnel of a CCVT violent failure. AEP's safety standards specify that when a possible CCVT in-failure condition is known, the equipment would be de-energized and isolated as soon as possible for further testing or replacement. This eliminates the risk of failure, reducing the risk of injury *and* damage to nearby equipment in the substation.

Figure 1. CCVT Violent Failure Caused Explosion Damage in one of AEP Substations

The overall CCVT failure rate was reasonably low when averaged over the past few years, about 0.3% per year. And, the failure data used for the statistical analysis was not complete because CCVTs are generally ancillary equipment tied to other equipment. So much of their data was keyed to other components or not recorded at all. Figure 2 shows the recorded AEP 765-kV CCVT failure rate from 1982 to 2004 as an example.

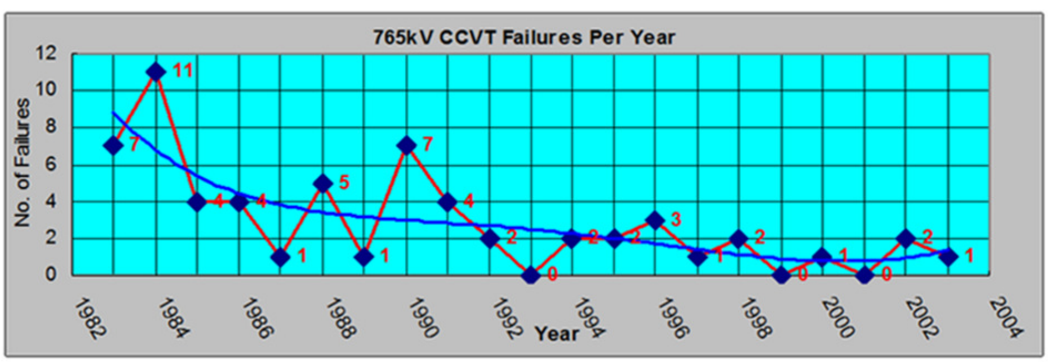

Figure 2. AEP 765kV CCVT Failure Rate

B. CCVT Health Management through Continuous Reading Monitoring

As shown in Figure 3, CCVT malfunctions caused by capacitor pack failures could cause indicated voltage drifting. Depending on whether the failed capacitor is above or below the tap, the indicated voltage would be raised or lowered, respectively. This indicated voltage drifting phenomenon becomes the criteria to evaluate if the CCVT has failed capacitors and would have the potential to explode. Currently one of AEP's approaches to detect a failing CCVT is through voltage measurement cross checking between double primary relay readings or primary/back up relay readings. This method would successfully detect the failing CCVTs, but would not identify them. Manual engineering work is necessary to trouble shoot both CCVTs involved in the cross-checking process and the relay which took those CCVTs as theirs transducers should be taken out of service to avoid mis-operations.

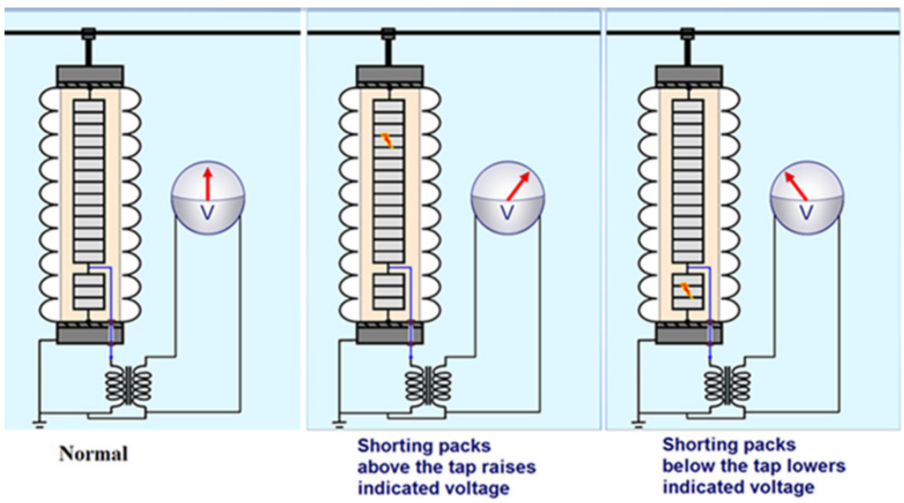

Figure 3. CCVT Capacitor Pack Failure Caused Voltage Drift

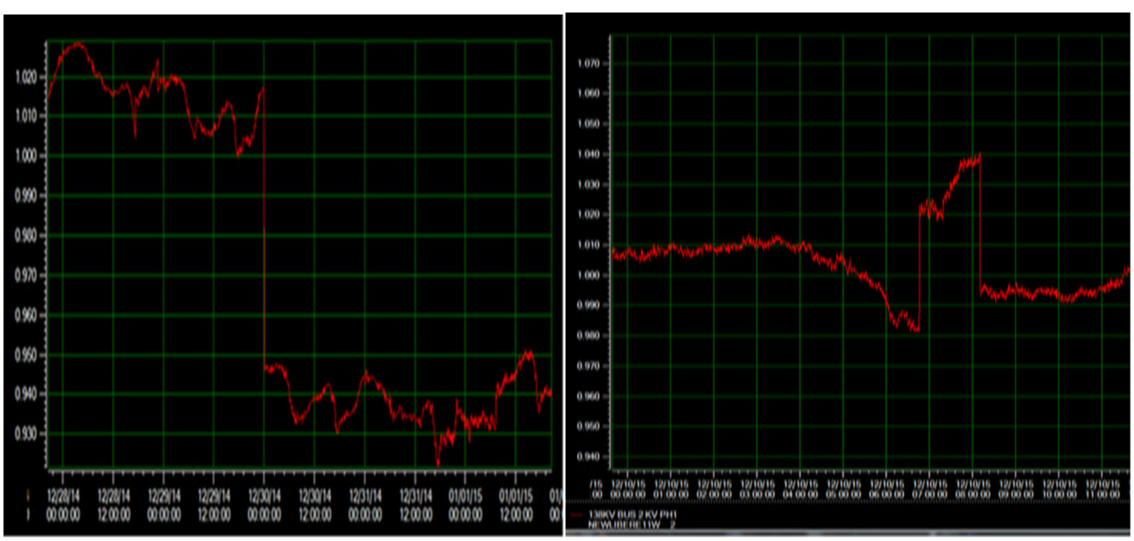

Figure4. Voltage Step Change Caused by CCVT Malfunctioning and Capbank Switching

Another method is to look for step change in SCADA voltage readings which is an offline process, and can only apply to RTU measurements. Furthermore, this approach is not very reliable by looking at the measurements data only. It is critical to distinguish bad data measurements from measurement change caused by power system perturbations. For example, the left part in Figure 4 shows an example of voltage step change caused by failing CCVT in a substation. It's extremely hard to distinguish this pattern from voltage step change caused by capacitor bank switching, as shown in the right part of Figure 4.

Applying SLSE to Identify failing CCVTs

It is well known that measurement monitoring and cross-checking is an effective way to detect failing CCVTs so naturally state estimation methodology would become the applicable solution to detecting and identifying failing instrument transformers, including CCVTs. Apparently, compared with the two methods now used by AEP, the state estimation methodology has two advantages: (1) it can not only detect but also identify the bad instrument transformers measurements; (2) it can eliminate any power system perturbation impacts to measurement abnormalities in the process of identifying bad instrument measurements. Since the purpose of state estimation is to identify and process bad measurements in the substation, the centralized state estimator may not be adaptive here. This is because, for the purpose of health managing health instrument transformers, as many instruments as possible would participate in the state estimation process, which is different from state estimation applied in the control center that only requires a certain amount of measurements to obtain the observability. So the data volume for a state estimator to handle is huge and the network model adopted should be a three phase model. In this case, substation state estimator, which is a cutting edge technology and the industrial trend, would be more appropriate and suitable.

A. Substation Linear State Estimation Overview

Phasor Measurement Units (PMUs) provide the complex voltage and current phasors the linearity between the phasor measurements and the system state, allowing a Linear State Estimator (LSE) to become feasible. Most developed LSEs are focused at the transmission system level to address system need. A two-level LSE has been developed at Washington State University (WSU) [4-5]. This LSE has the advantage of better solving system level LSE by running an LSE at the substation level for preconditioning. Different from the Supercalibrator introduced in [6] which is another applicable substation state estimator, this Substation LSE (SLSE) requires all the input measurements to be synchronized and enough current Synchrophasor measurements to fulfil the observability requirement in the substation to estimate the breaker status, instead of using digital breaker status to obtain the network topology in the substation. This prerequisite becomes more and more reasonable with the deployment of the microprocessor based relays. Moreover, the proposed SLSE system would use all three phase data from PMUs, Relays, DFR's, ITs, and other measuring devices in use at substations to monitor as many ITs as possible. This approach provides enough redundant data and full observability of the substation for SLSE to perform accurate state estimation and bad data detection.

B. Zero Impedance Current State Estimator and Voltage State Estimator

The SLSE flow chart is shown in Figure 5. The SLSE is solved in several parts. First, each voltage level in the substation is solved separately. The advantage is that the substation circuit at one voltage level has no impedances, thus simplifying the SE equations. Second, the current phasor measurements and the voltage phasor measurements are handled separately. This further simplifies the equations. Unlike the traditional SE, the topology is not constructed through the digital status of the breakers first. Instead, the current phasor measurements are used to solve a local SE for each voltage level. The resulting circuit breaker currents are then used to check whether the breaker/switch statuses are bad. Once the breaker/switch statuses are checked for bad data, the topology processor can be used to define the circuit topology at each voltage level. The voltage phasor measurements are then processed through a state estimator calculation at the substation. Finally, the set of injection current phasors and nodal voltage phasors from the substation form the analog measurement data that are sent to the downstream components of the system.

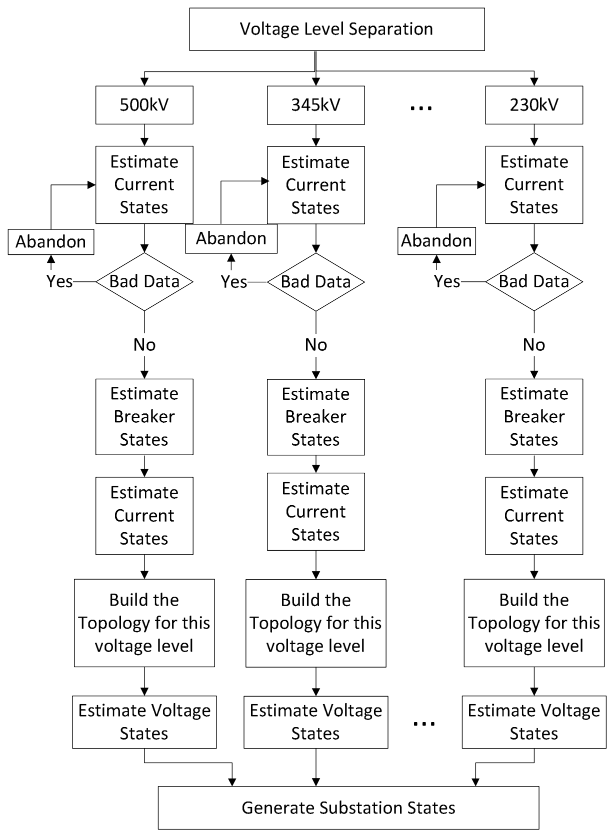

Figure 5. Flow Chart of SLSE

At the end, this calculation can output any analog values based on the estimated states at each substation, together with the substation topology. The bad data processing module will analyze the bad data pattern and trace back the root cause of problem. Suggested calibration of ITs and IEDs will also be included in this module. Once the problem is confirmed, for example, when there is continuous abnormal measurement from one or multiple pieces of equipment, an alarm is sent to the responsible operators, protection and control engineers, and transmission field service technicians.

Roadmap of Applying Synchrophasor and SLSE Technologies to CCVT Health Monitoring and Management

The overall software research and development approach is shown in Figure 6. The data input for the system will be provided by either laboratory generated Synchrophasor data and/or field PMU data streams as shown in the left box of the figure, including the three phase Synchrophasor voltage and current measurements; digitized samples of CT,PT, and CCVT waveform data from the merging unit; substation node-breaker model; signal mapping; and substation one-line diagrams. Several modules will be developed by AEP's collaborating vendor, Electric Power Group (EPG), to process the data through SLSE approach and visualize the bad data from SLSE to reveal the CCVT malfunctioning to the end users. The whole development would consist of three tasks shown below.

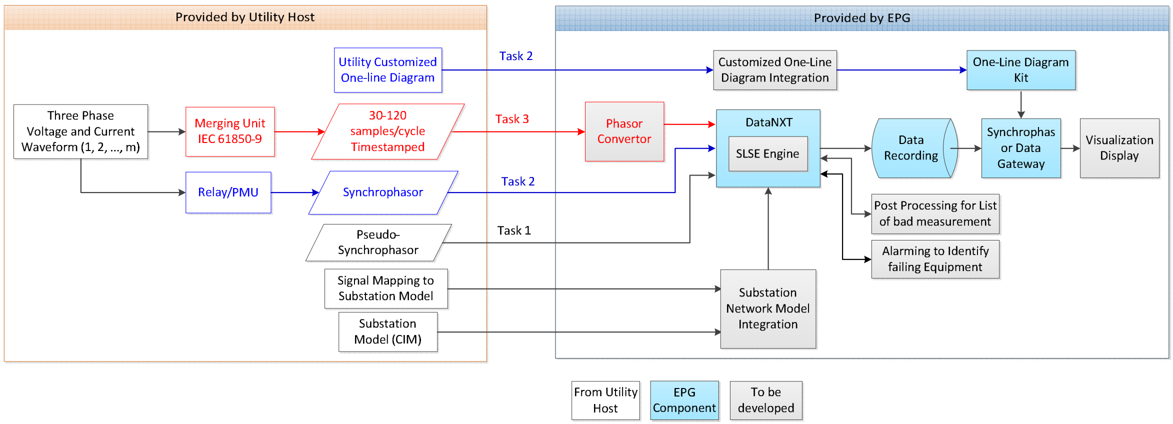

Figure 6. Overall SLSE and CCVT Health Management System R&D Approach

A. Task 1: Proof of Concept and Software Design

Task 1 is the software development and testing with pseudo-synchrophasor data from archived and simulated data. The software designed in this task includes all the functional modules in Figure 6, the input/output, and the user interface (GUI), except the Phasor Converter. Pseudo-synchrophasor data generated from RTDS simulation, which would include both system perturbations, caused abnormal data and manual data spoofing cases. Abnormal data, which mocks the CCVT malfunctions, would be benchmark inputs to the software.

B. Task 2: Centralized SLSE and CCVT Health Management System

Task 2 is the initial prototype testing and demonstration with recorded and real-time synchrophasor data sets from Relays and PMUs at two of AEP's substations selectively. This task also will include AEP's customized one-line diagram integration. The whole application will be installed at the AEP's data center for testing. At this step, the cost effective analysis also will be conducted to assess communication bandwidth needed for reliable and timely detection of failing equipment with this centralized infrastructure.

C. Task 3: Distributed SLSE and Centralized CCVT Health Management System

Task 3 is software development, testing and demonstration of a hardened PC box to distribute the SLSE functionality into substations, leaving the CCVT Health Management System still centralized as in task 2. Additional to data used in the second task, digital sampled voltage and current waveform data from ITs will also be used in the SLSE. In this task, software will be installed in a hardened PC box (commercially available) including the Phasor Converter, Substation PDC, and SLSE functionality, for installation in a substation. And only the bad data would be transferred from SLSE to the centralized CCVT Health Management System for bad data pattern analysis as records for CCVT health management.

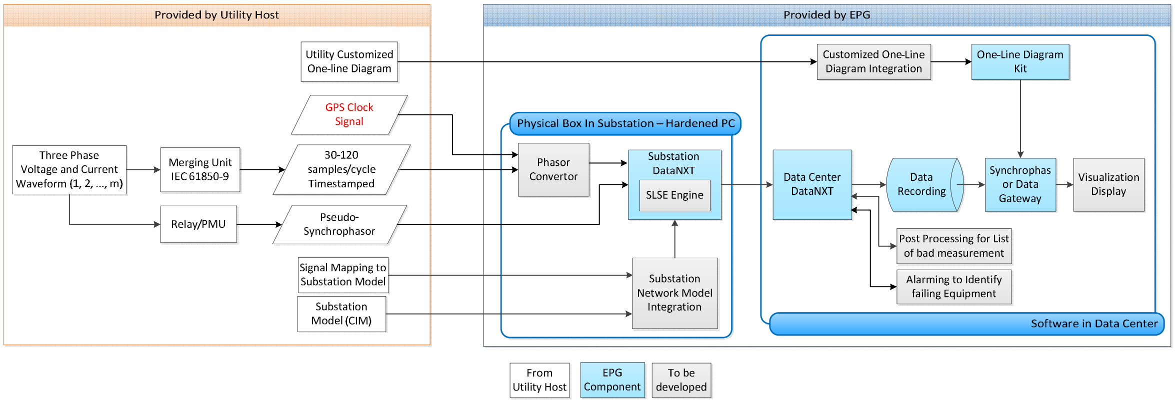

Figure 7. Implementation of SLSE Assisted CCVT Health Management System

Conclusions and Future work

This paper describs the roadmap to applying Synchrophasor based SLSE methodology to Instrument Transformers, especially CCVT and a health management system. The prospective solution will be a commercial, production grade application suitable for deployment at a enterprise level and installed in both control centers and substations. The project will deliver the following benefits to utilities:

(1) Offer a cost effective solution for instrument transformer health monitoring and management with synchrophasor technology.

(2) Provide enough early warning of a failing instrument transformer to take timely, proactive actions to reduce a utility's forced outages, operating and maintenance costs, and safety risks.

(3) Calibrate Instrument Transformers and Intelligent Electric Devices.

Even though this paper emphasized CCVT health management, the SLSE approach would also be able to provide continuous output monitoring and bad data pattern analysis of other instrument transformers. And eventually, all instrument transformer health management would be included.

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