CCVT Monitoring with Remote Diagnostics

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Abstract: A Coupling Capacitor Voltage Transformer, also called a CCVT, is one device used by utilities to transform high voltages to relaying levels. Historically, capacitors in CCVTs have been known to deteriorate over time. This deterioration can become significant enough to cause a catastrophic failure as the CCVT approaches the end of its expected life. PCS UtiliData (PCS) developed an approach to continuously monitor CCVT health using power meters and a Programmable Logic Controller (PLC). In addition, a remote Human Machine Interface (HMI) application at the engineering department enables an engineer to monitor the active data on demand and collect it for more in-depth study and analysis.

Keywords: CCVT, Coupling Capacitor Voltage Transformer, Monitoring, Potential Transformer, Substation, Human Machine Interface, SCADA, Electrical Power, Remote Diagnostics …

Customer Profile

The San Diego Gas & Electric (SDGE) division of Sempra Energy is an integrated natural gas and electric utility located in Southern California. With the electric deregulation in California, SDGE has moved into a position of being an electricity distributor. This makes their primary business delivering power in a reliable and cost effective manner.

Customer's Business Problems / Issues

About an hour away from their main engineering offices and maintenance shops, SDGE has a substation located adjacent to one of their sources of power. SDGE is in joint ownership of the substation with the utility that operates the power plant. The substation uses CCVTs to step down the 230 KV potential for local and remote voltage indication of the bus or tie-lines within the substation.

In order to prevent a potential sudden catastrophic failure of a CCVT while online and as a safety precaution to personnel working in the area, SDGE, together with the other utility, decided that a system was needed to continuously monitor the health of the CCVTs. The utilities independently requested proposals and evaluated them based on functionality and cost. Although the PLC-based system was not the lowest cost system proposed, it was selected by SDGE for their part of the substation due to its ability to provide trending capabilities and functionality not supported by some of the other proposed systems. Following discussions between SDGE and the supplier, the following system characteristics were defined:

- The PLC system continuously monitors the health of each CCVT, whether connected to an HMI type operator control center not.
  - A power monitor reads the three CCVT line-to-neutral voltages for each line or bus and communicates this information directly to the PLC.
  - The PLC communicates the phase voltages and alarms to SDGE's EMS SCADA system using a standard utility communications protocol.
  - Discrete PLC alarm outputs are connected to a local annunciator panel.
  - A FIFO style event log in the PLC stores recent events for later review.
- Multiple alarm levels provide progressive warnings prior to failure.
- The remote HMI applications use typical communication connections to access the PLC data on demand.
- System configuration and alarm threshold values are entered by an engineer remotely to maintain alarm configuration control.

It is always important to test a new system before installing it in the field. However, for this system testing was critical due to the logistics surrounding any installation or start-up activities in the shared substation compound.

Solution Description

Before developing a system for detecting changes in a CCVT, the design engineer needed a clear understanding of what was considered normal and suspect. A CCVT is a single phase potential transformer that is connected phase-to-ground. Three of these devices are used together for a three-phase line or bus. All three CCVTs have the same ratio when new or after servicing. Therefore, if two power line phases have the same voltage their CCVT outputs will also have the same voltage. In reality, power lines and buses often have a measurable phase-to-phase voltage imbalance which normally remains constant. Another typical characteristic is that the actual phase-to-ground voltage on all three phases varies throughout the day as the system generation and loading changes. Any system for monitoring CCVT health needs to compensate for these variations.

The CCVT potential transformer (PT) uses a series of capacitors as a phase-to-ground voltage divider. A tap point in the capacitor stack then provides a reduced voltage to the wound transformer section of the CCVT. Normally there are many more capacitors in the high voltage section of the divider (above the tap point) than there are in the low voltage section. This combination of capacitor voltage divider and transformer with a lower primary voltage is a competitive alternative to a wound PT designed to attach directly to the high voltage line or bus. Either type of PT can provide the desired potential for instrumentation or protective relays.

A CCVT has a typical life expectancy of twenty-five years. The capacitors are normally stable until close to the end of this expected life. Since three separate CCVTs are used for a three-phase line or bus, a deteriorating CCVT usually only affects one phase. Therefore, we are able to monitor and automatically evaluate a change in the voltage balance between the phases as a CCVT deterioration characteristic.

Capacitor deterioration causes the secondary CCVT voltage to change for a given primary voltage. Typical failure characteristics for a single capacitor are an initial impedance increase followed by a decrease as the device shorts out. Since the failure characteristic is an impedance change, the direction of the voltage change depends on whether the failing capacitor is above or below the tap point. Most of the failures observed by SDGE have been in the low voltage section of the CCVT located below the wound transformer tap. Under these conditions, the output voltage may increase slightly followed by a voltage decrease as capacitors short out. A single failing capacitor only makes a small change in the output voltage, so the voltage increase might not be significant. However, the voltage decrease gets progressively greater as capacitors fail, ensuring detection over time.

Utilities traditionally perform periodic tests on the CCVTs and increase the testing frequency for suspect units. At SDGE the tests are performed once a year and include powering down the line or bus to perform Doble testing. This provides a direct reading on the health of each CCVT. Differences from standard and historical test results can be evaluated and used to determine what service is needed. In at least one instance, SDGE saw evidence that a CCVT deteriorated rapidly between scheduled tests, causing an unscheduled outage. This initiated discussions that led to the addition of continuous monitoring systems for key units at this substation.

The heart of the monitoring system is a PLC which runs the CCVT monitoring algorithm and

handles the communications. While developing this system, the engineers evaluated two methods for continuous CCVT monitoring. Both approaches were based on using changes in the difference between adjacent single phase voltages to detect capacitor deterioration. Relatively inexpensive power monitors can read three phase voltages, scale them to engineering values, and then send this data to the PLC over a local communications network. Using this technology, the first approach we evaluated was to read in the three single phase voltages for a CCVT set, calculate the three differences, and use an algorithm to evaluate those voltage differences and identify changes. The second approach we considered was using the positive and negative sequence voltages as indications of the imbalance between phases. Changes in this imbalance can be interpreted to indicate which phase is changing. Our analysis indicated that the second approach could provide a more rigorous indication of changes in the relationship between adjacent phase voltages. However, more expensive power monitors would have been needed to get all the data required for the equations. Therefore, we chose the voltage difference approach as the most cost effective method of detecting a suspect CCVT.

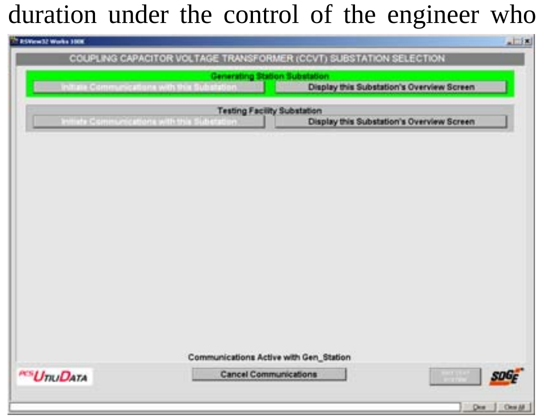
As stated above, the overall voltage on a power line changes regularly during the day depending on the load and generation characteristics. This variation is normally greater than the change in voltage caused by a single failed capacitor. However, the difference between adjacent phase-to-ground voltages generally remains constant through these changes. Two of the calculated differences will change when one phase has a failing CCVT. A person looking at the data can fairly easily interpret which phase is actually changing. Performing the same evaluation automatically proved to be a challenge.

In this CCVT monitoring system, values representing the normal differences between each pair of phase voltages are entered by an engineer to maintain control over the testing criteria. Then the PLC calculates the actual differences and compares these values to the standard. If the error between normal and actual differences exceeds one of the alarm thresholds then the differences are manipulated to identify which phase has changed. Based on these results, a bit is set and fed into status evaluation sequencing. This code checks to see whether the status has changed and, if so, whether the alarm just went active or was an existing alarm, whether it changed alarm levels, and even if it returned to the normal state. The PLC then stores changes in the event log and controls the alarm outputs to both the local annunciator and the utility's SCADA system.

SDGE defined three levels of concern based on their experience with CCVTs. The first is a monitoring alarm for engineering use. This indication is posted to the event log but is not alarmed to the SCADA or local annunciator. The monitoring threshold is set for a deviation between 0.75% and 1.5% from normal, depending on the current concerns, as an early warning that something might be changing. The next level is set for about 3% deviation. This is configured as a warning or minor alarm to the event log, the SCADA system, and the local annunciator. SDGE considers a CCVT deviation of 5% or greater an indication of a possible impending failure. This level is used as the threshold for detecting a major alarm. Like the minor ones, major alarms are reported on the local annunciator, the SCADA system, and into the event log. The HMI also includes active minor and major alarm status indications.

The CCVT monitoring system normally operates independently from any operator observation or control because this substation is not manned. One of the modules in the PLC chassis makes the phase voltages and CCVT alarms available on the standard utility communications protocol used by the SDGE EMS SCADA system for remote communications. Discrete outputs from the PLC for minor and major CCVT alarms and PLC failure are connected to a local annunciator panel. Alarms to this panel provide local indication and a remote alarm through the substation's Remote Terminal Unit (RTU). These interfaces provide immediate notification to operators from SDGE, who can then alert the power plant operators. In addition, SDGE engineering wanted visibility over the CCVT monitoring system to facilitate their analysis of the monitored data. This is provided by the remote HMI application. It was not practical for the engineering HMI application to remain connected to the CCVT monitoring system due to the distance between the locations. Therefore, communication modules were provided at the PLC to support the remote HMI software.

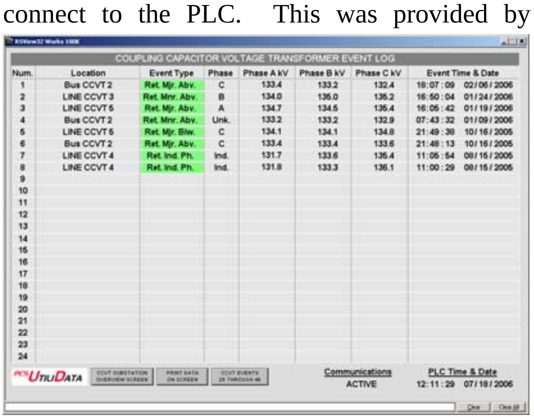
The PC-based HMI application uses a PC driver to connect into the CCVT monitoring system. The configuration puts the connection timing and duration under the control of the engineer who will be using the data. The HMI application is design provides for either automatic or manual connections. Engineering can configure an event within the HMI application to connect to a substation CCVT monitoring system at specific times each day. Therefore, anytime the HMI application is running at the configured time the code automatically connects to the station, waits for a period of time to allow the system to finish handling data, and then disconnects. The manual connection is initiated by an engineer or operator



clicking on the appropriate substation's button from the substation selection screen.

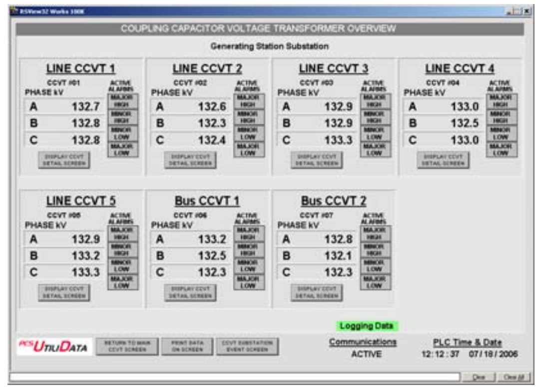
Once connected with one of the CCVT monitoring systems, the HMI application performs several automatic data handling tasks. First, it retrieves the communicated data from that station and refreshes the data used on the screens. Next, it stores a snapshot of the CCVT voltages and any new historical event log records to an Access database. The voltage snap shots in this database can be used for long term trending and historical evaluation. Finally, the HMI starts logging the voltages to its own native database for use on trend screens, allowing the engineer to perform a more in-depth study of the data while connected. Although SDGE operators can use the remote HMI as discussed below, the SCADA system provides independent CCVT alarm delivery to operations. An additional feature is configured on the engineering HMI application to give the SDGE engineering department a similar alert. The PLC sets an alert bit for any new alarm going active. If this bit is set when the engineering HMI application connects to the substation, the system sends an email to any preconfigured addresses, in this case one of the engineers. With this HMI application configured to automatically connect to the substation early each morning, an email will be waiting when the engineer arrives at work if any alarms went active during the previous day.

Since the system normally operates without the HMI connected, the users wanted the ability to review recent system activity when they did connect to the PLC. This was provided by

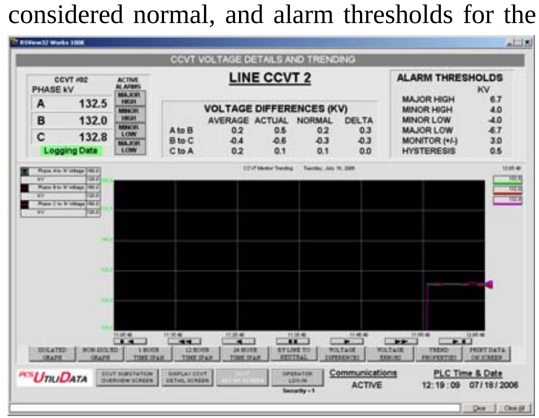


creating a FIFO style event log in the PLC for the forty-eight most recent events. Each entry includes the type of alarm going active or returning to normal, the phase it is associated with, the three phase-to-ground voltages, and the time and date stamp. By storing this information in the PLC it is available for review whenever the HMI is connected. This data remains in the FIFO until it is either shifted off the bottom by newer entries or the FIFO is manually cleared by an engineer. Because SDGE has not yet seen a CCVT capacitor fail while being monitored by this system, the actual failure event log entries have not been confirmed. However, we do have an idea of what to expect. Should the most common failure occur, failed capacitors below the tap, the event log should record a minor high alarm followed by its return to normal and then a major low alarm on the same phase.

When an engineer or operator establishes a manual connection to the CCVT monitoring system, the next step is to click on the button that displays the appropriate overview screen. This



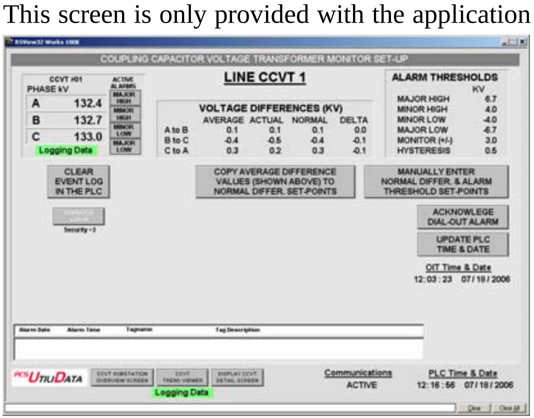
screen provides an overview of the phase voltages and active alarms. It also has navigation buttons to the event screen and a more detailed display of each CCVT set. The CCVT detail screen provides information on the average voltage differences over the last several hours, current voltage differences, values that are considered normal, and alarm thresholds for the



selected three-phase group. The trend display is an extension of the detail screen, adding a graphical display of native logged data. This CCVT monitoring system provides much more visibility over the CCVT health and other characteristics than previously available.

During the system scope definition process, the HMI functionality was discussed with the other utility. The generating station operators felt the visibility over the CCVT monitoring system provided by the HMI would be beneficial and requested a similar application. Otherwise their only information on CCVT health would come through SDGE operations. To support this additional monitoring, a second communication module was added to the PLC control and the monitoring system was tested with two simultaneous connections. While it was acceptable for the power plant operators to view the data and alarms, SDGE wanted to keep the alarm configuration control in their engineering group. A stripped down version of the HMI application was created by eliminating the set-up screen described below. This version was for use by the SDGE and power plant operators. The project scope included three copies of the OIT software operating system. These were located at SDGE engineering, SDGE operations, and the other utility's generating station operations. Only two of these HMI applications can connect to the CCVT monitoring system at a time; limited by having only two communication modules as discussed above. We anticipated that SDGE would use one of the connections while the generating station operator used the other.

All of the alarm configuration values are stored in the PLC data tables. These include the settings for normal voltage differences and the alarm threshold levels. Adjusting these settings using PLC programming software is possible but not very convenient. A screen included in the HMI application facilitates system configuration. This screen is only provided with the application



copy running at the SDGE engineering offices. Access is further limited by a password-secured login. In addition to alarm configuration, this screen includes a button to update the PLC time and date used for event log entries.

The CCVT monitoring system sequencing and HMI code were both configured using a modular approach. In the PLC code, the system for the testing facility was configured for one feeder while the actual substation has seven lines and buses. Since the data from up to seven power meters fits into the PLC's data table structure using a single address pointer, the controls were designed for easy configuration to accommodate between one and seven three-phase sets of CCVTs. The same PLC code can be configured for a new location by adjusting the value in one register. On the HMI side, the substation selection screen was designed to initiate communications with the two stations included in this project but with room to add additional stations if needed. Indirect address references are used to pass data into the subsidiary screens depending on the station selected. The number of units displayed on a particular substation's overview screen is controlled based on configuration data embedded in that station's data area. Therefore, adding a new station to the HMI entails copying a database area, configuring appropriate line or bus descriptions, copying the button group on the substation selection screen, and reconfiguring the copied buttons to link them to the new database area. This is more involved than adapting the PLC code, but the HMI has more complexity due to interfacing with multiple substations.

Testing was an integral part of this application. All of the hardware was connected in the supplier's shop to simulate the actual system. The HMI connection functionality was simulated using phone lines. For the Factory Acceptance Test, SDGE brought in a protocol test set to verify the SCADA communications. In addition, SDGE purchased two of these monitoring systems, one for the substation and the other for their testing facility. When SDGE received the equipment, their first step was to install the test system. This test unit proved to be a valuable tool. Although the HMI connection worked in the supplier's shop, the same code did not provide reliable connection sequencing to the system located in SDGE's testing facility. A difference between the communication lines such as line quality or the timing change related to the greater distance played havoc with the communication functions. During the time prior to the installation of the actual substation system, the supplier revised the communications driver and connection sequencing. This new approach was first tested extensively between the supplier's office and the SDGE testing facility, verifying the reliability of the new HMI connection code. All changes and testing were completed prior to commissioning the actual monitoring system at the substation.

Business Benefits

SDGE needed a system to continuously monitor CCVT health and alert operators when detecting suspect voltage differences. This CCVT monitoring system not only provides that functionality but also provides remote visibility over those alarms and the associated voltages through several paths, supporting simultaneous monitoring at three remote locations. When a utility gains visibility over a portion of their system, they also gain tools for improving their system's reliability.

When the monitoring system was first installed and before the "normal" voltage differences had been established, one CCVT voltage was about 15% above the expected value. This was significantly above the 5% threshold considered evidence of a possible failing CCVT. SDGE chose to change this CCVT out as a precaution. The voltage reported by the replacement CCVT matched expectations. This series of events shows the value of better visibility but says nothing about the monitoring system's ability to provide early detection of a failing CCVT. The early detection code is based on detecting voltage ratio changes over time. Therefore, time will be needed to prove the full worth of this CCVT monitoring system.

The value of raw information is always enhanced by automatic analysis and intelligent reporting. This CCVT monitoring system starts by gathering the secondary voltage data directly from the power monitors. Then it continuously evaluates this data to provide detection of suspect or failing capacitor sections. The CCVT monitoring system then adds the benefit of providing alarm status to the local annunciator panel and the remote SCADA operators. The SCADA operators also receive the monitored voltage data on a continuous basis. And finally, all of the key voltage data, event records, and system configuration data are provided remotely to engineering through the HMI application. This CCVT monitoring system combines data retrieval, event logging, and trend type data analysis with automatically generated alarm indications designed to make operators and engineers aware of the need to start watching the CCVT data more closely.

Post Article Follow-Up

Roughly two years after SDGE installed and put the CCVT monitoring system into operation, an incident occurred in which the PLC reported a major (> 5%) phase to phase voltage imbalance alarm on one of the monitored lines. As a precaution, the CCVT was brought off-line and removed for inspection by the appropriate maintenance personnel even though the unit was less than ten years old. The results showed that the CCVT had begun developing preliminary shorts due to deterioration within certain parts of the CCVT capacitor stack, causing the output voltage to go out of tolerance. A possible catastrophic CCVT failure was avoided because of the CCVT monitoring system.

Biography

Jim Michaelis grew up in Northern California. He is a member of IEEE (S' 1979, M' 1984) and

ISA (SR' 1994). Jim earned his BSEE from the University of Nevada - Reno in 1984. In 1990 he passed the Professional Engineers exam for Electrical Engineering in California while working as a Control Engineer for Reliance Electric Industrial Company. Jim joined Programmable Control Services, Inc. (now doing business as PCS UtiliData) in 1994 as a Control Engineer with a Drive Systems specialty. He has since moved up to a Senior Control Engineer position while expanding his expertise in PLC and OIT applications, communications, and systems for monitoring and controlling electric power. PCS UtiliData is a Spokane, Washington based control system integration firm specializing in power system automation and energy conservation using PLCs and power meters, with a secondary emphasis on systems for the metals industry. Jim can be contacted at jgm@pcsutilidata.com.

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