Substation Standard

Standard for CVT Monitoring

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Abstract: The aim of this document is to outline the considerations and requirements for the design of capacitor voltage transformer monitoring inside an Energy Queensland substation.

Keywords: Capacitor voltage transformer, CVT Monitor, waveform, sequence component, voltage magnitude and voltage phase angle

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1 Overview

1.1 Purpose

Energy Queensland has identified capacitor voltage transformers within substations as plant with an increased risk of explosive failures and the potential to reduce network reliability. Multiple incidences of capacitor voltage transformer component failures have been investigated across many manufacturers with differing hazards and inherent levels of risk. Considering the number of incipient and terminal failures of capacitor voltage transformers a method of detecting each of the failure modes and managing the risks is considered high importance.

This document describes the considerations and requirements for the design of a capacitor voltage transformer monitor within high voltage brownfield and greenfield substations.

1.2 Scope

This standard shall be applied to all new and existing installations where high voltage CVT's occur in a bay within Energy Queensland fixed and mobile substations.

Excluded from this standard are:

High voltage CVT's owned by others

Coupling capacitors

CVT's in 2-phase applications (contact substation standards for further information)

Managing CVT maintenance

Managing operational requirements such as NAR implementation

2 References

2.1 Legislation, Regulations, Rules, and Codes

Document	Type
Electricity Act 1994 (Qld)	Legislation
Electricity Regulation 2006 (Qld)	Regulation
Electrical Safety Act 2002 (Qld)	Legislation
Electrical Safety Code of Practice – Works, 2020 (Queensland Government)	Code
Electrical Safety Regulation 2013 (Qld)	Regulation
Environmental Protection Act, 1994 (Queensland Government)	Legislation
National Electricity Rules	Regulation
Queensland WH&S Regulation 2011	Legislation

2.2 Controlled Documents

Document	Alternative Doc ID
Standard for Novatech M871 CVT Monitor IED (STNW1077AV3) - 39012118	STNW1077AV3
Standard for GE L90 Dual CB Communicating Distance Protection (STNW1094AV1) - 14400183	STNW1094AV1
Standard for GE L90 Line Differential Protection (STNW1071CV1) - 19745197	STNW1071CV1
Standard for GE T60 Short Interconnector Differential Protection (STNW1083AV1) - 3056500	STNW1083
STNW3106 - SCADA Standard Point List - 24558649	STNW3106
Standard for Maintenance Acceptance Criteria - 2928929	STNW1160

2.3 Other Documents

CVT Diagnostic Testing Reference - SP0508R02

2.4 Other Sources

AS 61869.1:2021, Instrument transformers, Part 1: General requirements

AS 61869.5 2021, Instrument transformers, Part 5: Additional requirements for capacitor voltage transformers

3 Definitions and Abbreviations

3.1 Definitions

For the purposes of this standard, the following definitions apply.

Brownfield project	A project at a location that has existing infrastructure
Coupling capacitor	AC capacitor connected to the high voltage network for the transmission of signals in a power system, e.g., PLC's.
CVT's	3-phase application of capacitor voltage transformers
CVT monitoring	Continuous on-line monitoring of 3-phase high voltage capacitor voltage transformers
Energy Queensland substation	Refers to bulk supply, zone or C&I substations owned by Ergon Energy or Energex DNSP's. Excludes assets owned by Yurika.
Greenfield project	A project at a location that has no existing infrastructure
Incipient failure	A component failure or partial failure that doesn't involve complete failure of a CVT. The CVT will still function but with reduced efficacy.
IVT's	3-phase application of inductive voltage transformers

Master station	A SCADA station that controls and/or coordinates the activities of other stations in a system i.e., GE or ABB SCADA systems.
SCIOD	For the purpose of this standard SCIOD is a device inside the substation that can provide CVT monitoring other than a protection relay or stand-alone CVT monitoring relay. e.g., Foxboro RTU, SACS, CGI RTU
Terminal failure	The complete failure of a CVT. This may include explosive failure or substantial reduction in voltage output.
Shall	Means mandatory
Should	Means advisory

3.2 Abbreviations

The following acronyms and abbreviations appear in this standard.

AER	Australian Energy Regulator
ARI	Average recurrence interval
CVT	Capacitor voltage transformer
DNP	Distributed network protocol
EMU	Electro-magnetic Unit
EQL	Energy Queensland Limited
HMI	Human-machine interface
IED	Intelligent external device
IVT	Inductive voltage transformer
NAR	Network access restriction
PLC	Power line carrier
p.u.	per-unit – way of expressing a quantity in terms of a base
RPEQ	Registered Professional Engineer of Queensland
RTU	Remote terminal unit
SACS	Substation automated control system
SCADA	Supervisory control and data acquisition
SCIOD	Substation configurable input output device
SICM	Serial interface control module

4 Authorities and Responsibilities

The responsibility for the management of CVT monitoring at EQL is as follows:

Table 4-1: List of Teams and Associated Responsibilities

Authority	Responsibilities
Asset Standards	Substation Standard for CVT monitoring
Asset Maintenance	Performance and maintenance of existing devices, including management of CVT's without monitoring
Protection Group	Protection RPEQ Site-specific application of this standard and design settings for each relay
SCADA Group	Control Systems RPEQ Site-specific applications of this standard and design of some SCIOD's and master station code
Substation Design	Substation Design RPEQ Site-specific application of this standard

5 Design principles

The principle of a substation high voltage CVT monitor is to detect incipient failures before major degradation can lead to a terminal failure. Early detection of a CVT component failure allows implementation of suitable control measures within an appropriate time frame, hence reducing the risk.

All new CVT EQL installations shall include CVT monitoring (refer to Table 6-1).

All existing CVT's within EQL that don't currently have continuous on-line monitoring shall have CVT monitoring implemented (refer to Table 6-1).

Consideration should be given during primary network upgrades in bays containing CVT's to their replacement with IVT's. At this point in time IVT's do not require monitoring for safety which may reduce planning and construction costs.

IVT's should replace all CVTs in a bay where there have been one or more CVT failures to eliminate the risks associated with CVT's and the need for CVT monitoring.

Consideration should be given during secondary systems upgrades where the voltage source is a CVT to the installation of a current period of contract relay with on-board CVT monitoring if the installation of IVT's is not feasible.

6 CVT monitoring solutions

6.1 General

Selection of a CVT monitor shall be to best practice based on site-specific details and the risks associated with each application.

An EQL CVT monitoring solution shall include the following features as a minimum:

- System frequency voltage measurement inputs from each phase
- Voltage measurement inputs with a suitable precision and accuracy to detect changes less than setting thresholds
- Continuous measurement of voltage magnitude or with scan rates as low as practical
- Alarm generation that is available to operations when the monitoring system detects a CVT problem
- Ability to differentiate between a genuine CVT alarm and normal operating condition

Provision for analysis of all three voltages at the detection of a disturbance. Analysis of the three voltages should be a waveform where possible. However, an absolute RMS voltage of each phase is acceptable if a waveform is not available.

Where possible, CVT monitor should generate alarms based on voltage sequence components.

A voltage waveform is desired when analysing the disturbance because of the extra details provided for the engineering assessment after an event.

The following CVT monitoring solutions in table 6-1 are methods for implementation on high voltage CVT's in EQL applications. Each of the CVT monitoring solutions has a different level of hierarchy which must be considered for each CVT monitoring application. The level of hierarchy is represented by preferences with 1 being the best option.

Table 6-1: CVT Monitoring Solution

<table>
<tr><th>CVT Monitor</th><th>Preference</th><th>Voltage Measurement</th><th>Greenfield Applications</th><th>Brownfield Applications</th></tr>
<tr><td>Protection relay</td><td>1</td><td>Magnitude and phase angle</td><td rowspan="2">Shall include one CVT monitor (more than one CVT monitor can be implemented)</td><td rowspan="6">Shall include one CVT monitor (more than one CVT monitor can be implemented)</td></tr>
<tr><td>Stand-alone relay</td><td>2</td><td>Magnitude and phase angle</td></tr>
<tr><td>SCIOD (direct voltage input)</td><td>3</td><td>Magnitude OR magnitude and phase angle</td><td rowspan="4">Available as backup only</td></tr>
<tr><td>SCIOD (transducer input)</td><td>4</td><td>Magnitude only</td></tr>
<tr><td>SCIOD (communication input)</td><td>5</td><td>Magnitude (with possibility of being sent sequence voltages)</td></tr>
<tr><td>Master station code</td><td>6</td><td>Magnitude (with possibility of being sent sequence voltage)</td></tr>
</table>

6.2 Protection Relay

The preferred method for CVT monitoring is a current period contract protection relay with on-board CVT monitoring built into the relay application.

Protection relays with on-board CVT monitoring have the following advantages:

- Are a permanent solution with a managed maintenance cycle
- Confirmed accuracy for implementation as a CVT monitor by protection standards
- Ability to monitor sequence components which increases setting sensitivity with the ability to identify all CVT component failure modes.
- Settings and logic for use as a CVT monitor by protection standards
- The ability to monitor a fourth CVT through comparison to the matching phase (system check or check synchronising CVT)
- Cost effective use of a multi-purpose device which may improve the existing protection in a brownfield site
- High accuracy waveform capture built into the application
- Standard alarming and SCADA points
- A communication failure will not impact the CVT monitor
- Inbuilt watchdog monitors the protection relay and hence the CVT monitoring function

The main disadvantage with using a protection relay is the time and effort to make setting changes. Extracting the disturbance is limited to employees with software and access.

The protection relay CVT monitoring settings shall be designed by the protection group or an equivalent person.

6.3 Stand-Alone Relay

The second preference is to install a current period contract stand-alone CVT monitoring relay. This option is available if installing a current period contract protection relay with on-board CVT monitoring is not feasible.

The advantages of using a stand-alone relay are:

- A permanent solution with a managed maintenance cycle
- Confirmed accuracy for implementation as a CVT monitor by protection standards
- Ability to monitor sequence components which increases setting sensitivity with the ability to identify all CVT component failure modes.
- Settings and logic for use as a CVT monitor by protection standards
- High accuracy waveform capture built into the application
- Standard alarming and SCADA points (stand-alone relays often have no alarm indication on their front face)
- A watchdog monitors the relay

The main disadvantage with using a stand-alone relay is the time and effort to make setting adjustments. A stand-alone relay is often less cost efficient compared to current period contract protection relay with on-board CVT monitoring because it is single purpose. Consideration will also need to be given to the costs involved with the removal of a stand-alone relay if a new protection relay with on-board CVT monitoring is installed or the CVT's removed at a later stage.

The protection relay CVT monitoring settings shall be designed by protection group or an equivalent person.

6.4 SCIOD

A SCIOD such as an RTU or SACS with standard code for use as a CVT monitor is an acceptable option. The SCIOD may utilise one of the following voltage inputs:

- Direct voltage input from CVT (i.e. Foxboro alternating current transducer card)
- Communication input containing the voltages measured by another device (i.e., SICM to SACS or protection relay to RTU)
- Voltage transducers input

The SCIOD option is cheap and easy to implement if one already exists on site. The SCIOD option is not susceptible to communication failures between the site and master station, assuming there is a HMI on-site providing the CVT monitor alarm.

The disadvantages of using a SCIOD are:

- There may not be a watchdog or indication of a problem to advise that the CVT monitor is no longer active
- Some SCIOD's are unable to calculate sequence components
- Accuracy of voltage measurement inputs must be confirmed
- Scan rate of the voltage input may reduce the visibility of a failure
- Reliance on master station and data capture historian to display the voltage disturbance

A CVT monitor built into an SCIOD shall implement standard code . If the SCIOD is provided with or can calculate negative or zero-sequence voltage this will provide a greater sensitivity for incipient failures.

6.5 Master Station Code

A CVT monitor incorporated within a master station is cheap and easy to implement if it has three phase voltage visibility, however it may rely on many external field devices to function which increases the exposure to interruptions.

The disadvantages of using master station code are:

- May not be able to monitor sequence components without magnitude and phase angle information on all three phases
- Accuracy of voltage measurement device inputs must be confirmed
- Scan rate of the voltage input may reduce visibility of a failure
- Failure of any device in the process of delivering data to the master station will stop the CVT monitoring, alarming and voltage disturbance capture
- Substations with poor communication may have increased exposure to extended periods without CVT monitoring

The devices used in the process of delivering information to the master station may not have watchdogs or indicate that when they are failed the CVT monitor is not operational.

A CVT monitor built into the master station shall implement standard code. If the master station is provided negative or zero-sequence voltages this will deliver a greater sensitivity for incipient failures.

7 Monitor Parameters

7.1 Logic

The CVT monitor shall include logic to ensure normal operating conditions and contingency scenarios do not cause any nuisance alarms. The logic shall be capable of detecting one or more CVT incipient failures. The logic shall account for the following as a minimum without reducing the sensitivity of the CVT monitor fault identification:

- De-energisation of the high voltage bay containing the CVT
- Switching of secondary voltage changeover relays
- Boot cycle of any devices used by the CVT monitor
- Voltage unbalance caused by temporary network earth faults

7.2 Voltage Settings

Considering the possible CVT failure modes and impact secondary burden has on the secondary voltage presented to a CVT monitor, the best option selecting alarm settings is to work back from the maximum expected voltage unbalance seen on a high voltage network.

The NER (National Electricity Rules) provide voltage unbalance tolerances for all high voltage networks in Australia under various conditions (Table 7-1). The unbalance tolerances provided in the NER is a negative-sequence voltage as a percentage of the nominal voltage.

Table 7-1: Voltage Unbalance Tolerances (NER Table S5.1a.1)

Nominal Supply Voltage	No Contingency Event (30-minute average)	Credible Contingency Event or Protected Event (30-minute average)	General (10-minute average)	Once Per Hour (1-minute average)
High voltage network > 100kV	0.5%	0.7%	1.0%	2.0%
10kV < High voltage network < 100kV	1.3%	1.3%	2.0%	2.5%
High voltage network < 10kV	2.0%	2.0%	2.5%	3.0%

A trade-off will need to occur between the CVT monitor voltage settings and the alarm time frame based on the NER tolerances. Increasing the average period in the NER tolerances improves the setting sensitivity but decreases the alarm time. Under “general” operating conditions the NER allows a tolerance over a ten-minute period which is a compromise between sensitivity and a suitable alarm period.

CVT monitor settings and alarms that base their calculations on measured system voltages must consider that the NER tolerances are based on the nominal voltage.

7.2.1 Voltage Difference Method

This method compares the voltage magnitudes of all 3-phases and triggers an alarm if any one calculation is outside the setting threshold for a time delay. Voltage phase angles are not considered.

The voltage difference method shall use one of the following comparators:

- Measured voltage difference – Measured 3-phase voltages are used in a calculation to a establish voltage difference and are compared to a voltage setting.

[$V_A – V_B$ > setting = alarm starter] for each phase combination or two-phase combination.

- Percentage voltage difference – Measured 3-phase voltages are used in a calculation to convert the voltage difference to a percentage of the measured voltage. This is then compared to a percentage setting.

[(1 - (2 * V_A / (V_B + V_C))) * 100 > setting = alarm starter] for each phase combination.

All CVT monitors using the voltage difference method shall implement settings that can identify incipient failures with a low as reasonably practical risk of terminal failure.

7.2.2 Sequence Component Method

This method calculates negative-sequence or zero-sequence component from the 3-phase voltages and alarms once it increases above a setting threshold for the time delay.

The sequence component method should use a negative-sequence voltage. If a negative-sequence voltage is unavailable, then a zero-sequence voltage can be used.

The sequence component method shall use one of the following comparators:

- Negative-sequence voltage – Negative-sequence voltage is compared to a voltage setting.

[$1V_2$ > setting = alarm starter]

- Negative-sequence percentage – Negative-sequence voltage is used in a calculation to convert to a percentage of positive-sequence component or a measured voltage. This is compared to a percentage setting.

[3V2 / Vmax * 100 > setting = alarm starter]

- Zero-sequence voltage difference – Zero-sequence voltage is compared to a voltage setting.

[$1V_0$ > setting = alarm starter]

- Zero-sequence percentage – Zero-sequence voltage is used in a calculation to convert to a percentage of positive-sequence component or a measured voltage. This is compared to a percentage setting.

[$3V_0$ / V_{max} * 100 > setting = alarm starter]

All CVT monitors implementing the sequence component method shall implement settings that can identify incipient failures with a low as reasonably practical risk of terminal failure.

7.3 Indications

Upon trigger of CVT monitoring alarm, indication shall advise operations of the problem. The standard naming convention for CVT monitoring alarms shall include and match the following details (exceptions to the naming convention will be allowed if character limitation is encountered).

Table 7-2: CVT Monitoring Alarm Naming Convention

CVT Monitoring Alarm Naming and Layout					
Substation	Voltage	Bay	Device	"CVT Supply"	Urgency

The "substation", "voltage" and "bay" identify the problem and direct the response crew to the location. The "device" tells the response crew what device generated the alarm. The "CVT supply" and "urgency" parts of the alarm naming indicates the problem and triggers a standard response from operations.

The CVT monitor should include two levels of alarms to trigger an urgent and non-urgent response. The first level is a non-urgent alarm that will provide indication to the operators after a time delay.

Non-urgent CVT monitoring alarm name example,

"Black River 66kV Bohle 1 Fdr (P90) CVT supply Non Urg Alm"

The second level is an urgent alarm that will provide indication to the operators after a time delay.

Urgent CVT monitoring alarm name example,

E.g. "Bundaberg 132kV 7328 Fdr (J11M) CVT supply Urg Alm"

A watchdog should be included to provide an alarm to the operators when the CVT monitor is no longer functioning.

7.4 Disturbance Record

Analysis of all three phase voltages at the time of the disturbance is crucial to establishing the possible failure mode and the level of risk. A stand-alone relay or protection relay with on-board CVT monitoring shall have a disturbance recorder incorporated that captures all voltages before, during and after the event. A SCIOD or master station should provide as a minimum the voltages used by the CVT monitor to a data capture historian for analysis. Each CVT should provide voltage waveform to a data capture historian for analysis even if not used directly by the CVT monitor. If a voltage waveform is not available, an absolute RMS voltage should be provided.

A stand-alone relay or protection relay with on-board CVT monitoring should have remote engineering access to extract the disturbance.

Annex A

Informative

Background Information

A.1 History

Several incipient and terminal CVT failures within the Energy Queensland high voltage network triggered the implementation of control systems for monitoring CVT's. CVT monitoring is used to detect unexpected changes in the secondary voltage to enable fault rectification with the lowest possible exposure to failures. This allows suitable control measures to be implemented for improved risk management on site and to the high voltage network. Monitoring has been successfully implemented on high voltage CVT's to:

- Detect unexpected changes in secondary voltage over a set threshold
- Trigger an investigation into the secondary voltage change
- Trigger field crews to investigate the secondary voltage change
- Manage the short-term risk based on the change in secondary voltage
- Implement NAR's where there is an increased risk of explosive failure
- Apply changes to voltage-based protection schemes
- Manage the CVT until the plant can be replaced
- Implement new voltage thresholds to detect any further changes in CVT secondary output
- Establish contingency plans

A.2 Failure Modes

CVT monitoring should be capable of identifying incipient failure modes that increase the risk of an explosive failure beyond an acceptable level. The risk of explosive failure increases when voltage stresses are transferred to components outside the steady-state or transient operating range.

CVT monitoring should also be capable of identifying failure modes that pose a risk to network reliability where possible.

All CVT failure modes have different impacts on the secondary output voltage magnitude and phase angle. The secondary load on a CVT at the time of an incipient or terminal component failure will impact the change in secondary voltage magnitude and phase angle.

A CVT monitor that compares the difference between 3-phase voltage magnitudes alone may not identify the same failure modes as a CVT monitor that uses sequence components. Therefore, consideration should be given to the failure modes of each application and whether a CVT requires the monitoring of sequence components.

CVT failure modes include:

- High voltage capacitor stack C1 – A failure of one or more capacitor elements in the C1 stack causes an increase in voltage across all healthy capacitor elements and the secondary voltage will increase with a small voltage phase angle shift
- Intermediate voltage capacitor stack C2 – A failure of one or more capacitor elements in the C2 stack causes an increase in voltage across all healthy capacitor elements and the secondary voltage will decrease with a small voltage phase angle shift
- Series reactor – Shorted turns in the series reactor will cause a secondary voltage phase angle shift with a small change in voltage magnitude
- Intermediate transformer – Shorted turns in the intermediate transformer will cause a secondary voltage phase angle shift with a small change in voltage magnitude
- Ferro resonant suppression circuit – A failure of one or more passive filter devices can cause a steady-state secondary voltage change in any combination of magnitude, phase angle and transient response
- Surge arrester – A failed surge arrestor may significantly increase the CVT burden or fail open circuit
- C1 and C2 capacitor stacks – A failure of one or more C1 and C2 elements can cause many different secondary voltages depending on the combination. The secondary voltage phase angle will continue to shift with each C1 and C2 capacitor element failure. The secondary voltage change will depend on the number of C1 and C2 capacitor element failures.

A.3 CVT Monitor Preferences

A1.1 Preference 1 (Protection Relay Example)

A protection relay provides CVT monitoring using a direct voltage input. The protection relay will send an alarm to operations and trigger a disturbance. In some instances, data capture historian can provide the disturbance as well as the protection relay if 3-phase visibility is available.

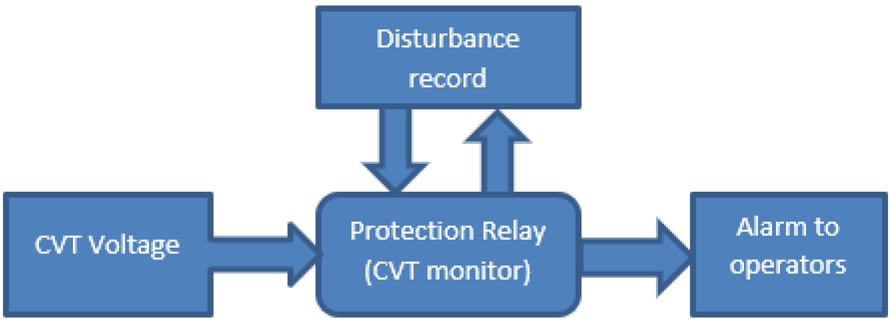

Figure 1: CVT Monitoring via Protection Relay

A1.2 Preference 2 (Stand-Alone Relay Example)

A stand-alone relay provides CVT monitoring using a direct voltage input. The stand-alone relay will send an alarm to operations and trigger a disturbance. In some instances, data capture historian can provide the disturbance as well as the stand-alone relay if 3-phase visibility is available.

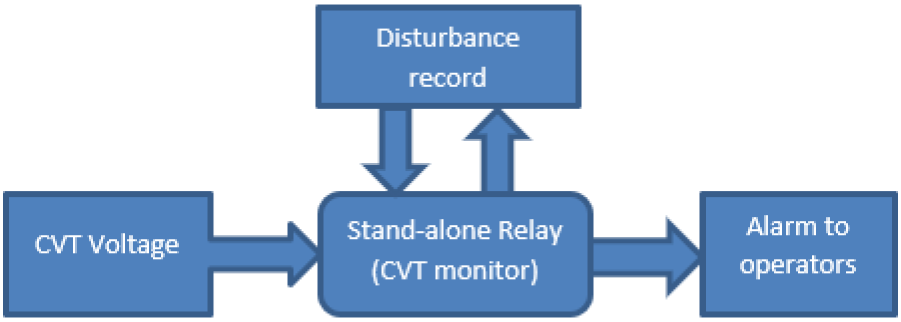

Figure 2: CVT Monitoring by Stand-Alone Relay

A1.3 Preference 3 (SCIOD Direct Voltage Input Example)

An SCIOD could be an RTU or some other device capable of monitoring a direct voltage input. In most cases the SCIOD would not be capable of providing a disturbance for the event. If the SCIOD is not capable of providing a disturbance, there would be a reliance on 3-phase visibility in data capture historian as shown in the example below. The data capture historian may get 3-phase visibility from a protection relay, transducers, SACS, RTU or any other device that has a communication link to SCADA.

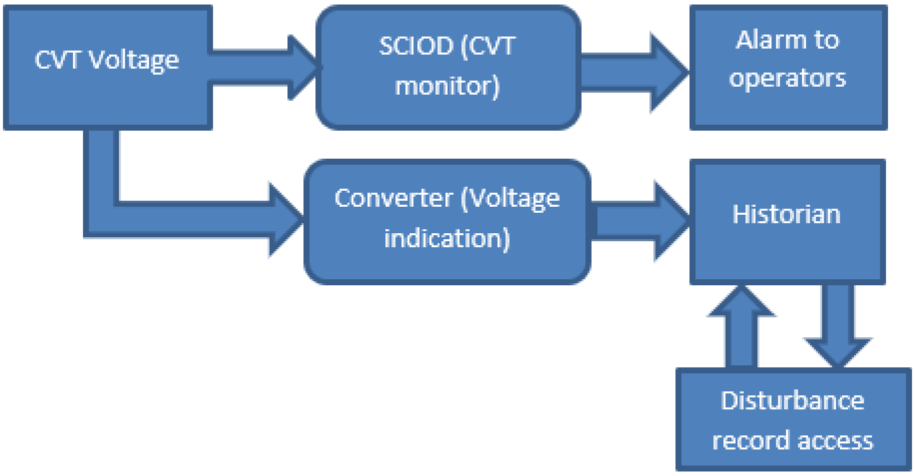

Figure 3: CVT Monitoring by SCIOD Direct Voltage Input

A1.4 Preference 4 (SCIOD Transducer Input Example)

An SCIOD could be an RTU or some other device capable of monitoring a transducer output. In most cases the SCIOD would not be capable of providing a disturbance for the event. If the SCIOD is not capable of providing a disturbance, there would be a reliance on 3-phase visibility in data capture historian as shown in the example below. The data capture historian may get 3-phase visibility from a protection relay, transducers, SACS, RTU or any other device that has a communication link to SCADA.

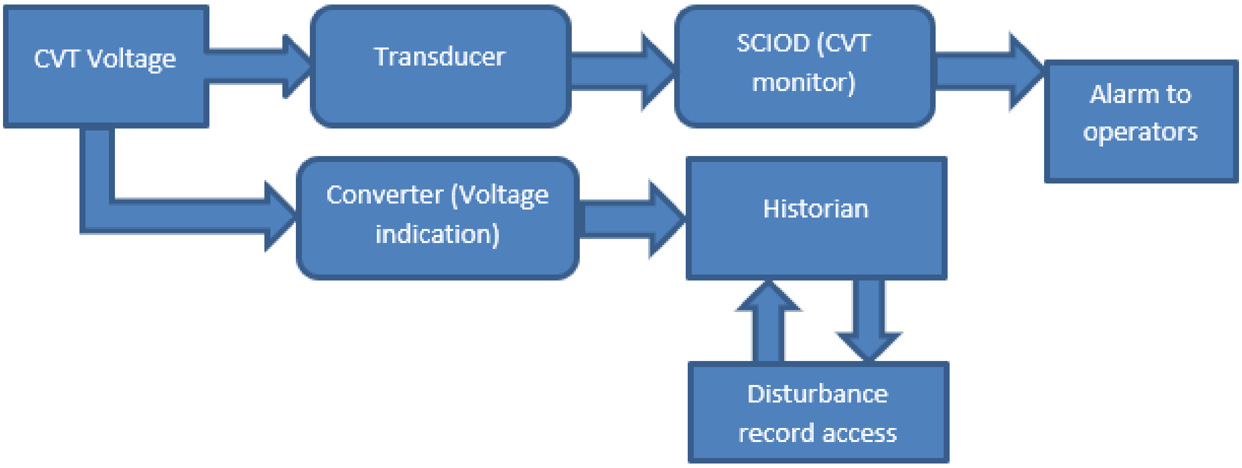

Figure 4: CVT Monitoring by Transducer Input to SCIOD

A1.5 Preference 5 (SCIOD Communication Input Example)

An SCIOD could be an RTU, SACS or some other device capable of monitoring a voltage through an external device such as a protection relay or SICM via a communication path. In most cases the SCIOD would not be capable of providing a disturbance for the event. If the SCIOD is not capable of providing a disturbance, there would be a reliance on 3-phase visibility in data capture historian as shown in the example below. The data capture historian may get 3-phase visibility from a protection relay, transducers, SACS, RTU or any other device that has a communication link to SCADA.

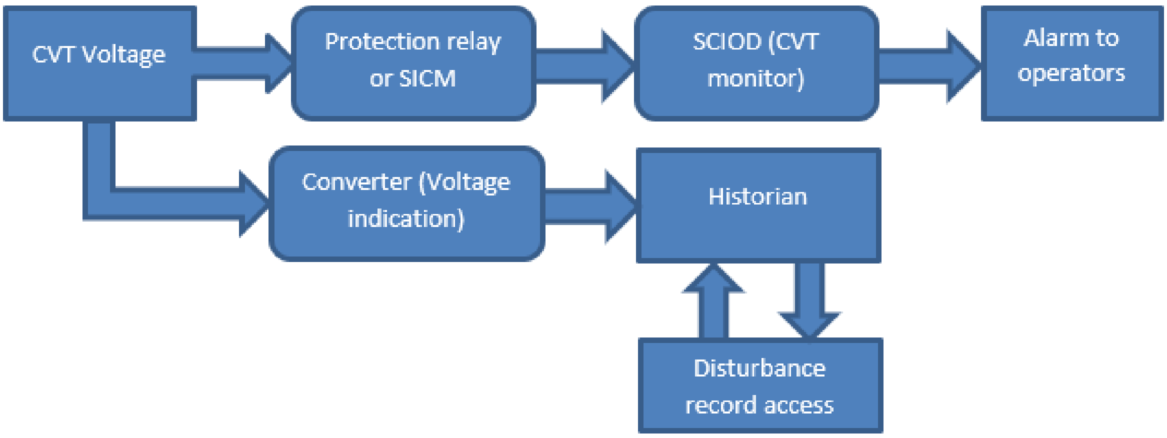

Figure 5: SCIOD Communications Input

A1.6 Preference 6 (Master Station Code Example)

A master station controls and coordinates the activities of all field SCADA stations or devices. The master station may be ABB or GE SCADA system which has visibility of the CVT voltages. The master station will receive 3-phase voltages from a device in the field via a communication path. Code in the master station will provide the CVT monitoring and send an alarm to operations. The disturbance record will most likely only be available from data capture historian.

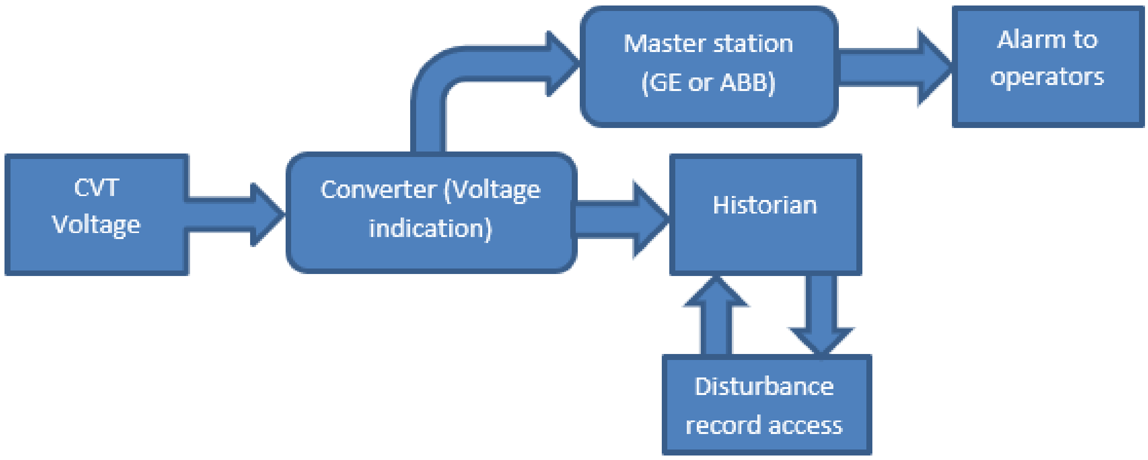

Figure 6: Master Station Code

Annex B Revision History

Revision Date	Release Number	Author	Description of Change/Revision
April 2026	6	John Lansley	Update links, correct formatting