Improving Protection System Reliability With Automatic NERC PRC-005 Testing and Reporting

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***Abstract*—This paper is a case study of the design process and validation of a hydroelectric generating station protection system monitoring (PSM) application that provides an automated system to meet many of the requirements of NERC PRC-005. This system communicates with intelligent electronic devices (IEDs) to perform real-time validation and status reporting. Critical protection system components, including potential transformers, current transformers, relays, and communications channels, are automatically monitored for function and accuracy. The system includes automatic collection of event reports and disturbance records to provide enterprise-level event storage and analysis. A discussion of future enhancements, such as trip circuit validation, is also included. Isolation of the PSM of relay health and settings from the protection, control, and monitoring (PCM) IED network operation is discussed to address system security.**

The system design was tested using the design of an actual hydroelectric generating station. This paper includes lessons learned from a full test simulation of the system.

Two major distinctions between traditional protection system maintenance and the testing performed by the PSM system are the automatic and continuous natures of the reporting. Traditional protection system maintenance is performed by technicians when returning equipment to service following infrequent and expensive tests or repairs. The PSM system instead constantly monitors the condition and performance of in-service equipment, evaluating and reporting the overall health of the system. In doing so, the PSM system not only improves the overall reliability of the bulk electric system by performing continuous real-time evaluations of critical protection system components but also reduces or eliminates the exposure to fines due to a missed test.

I. Introduction

The North American Electric Reliability Corporation (NERC), under the direction of the Federal Energy Regulatory Commission (FERC), is responsible for improving the reliability of the North American bulk electric system (BES). This includes creating a compliance program to improve the protection system reliability of generation and transmission facilities that can impact the BES. This program is designed to ensure that the right protection system testing and maintenance practices are implemented to minimize the severity of a future system disturbance.

This paper references the NERC PRC-005-1 definitions of maintenance and testing reliability standard requirements in place at the time of publication, but these requirements are in the process of being updated with PRC-005-2. Under PRC-005-2, the definition of "protection systems" includes protective relays, associated communications systems, voltage- and current-sensing devices (including their circuits), dc control circuitry, and station dc supplies associated with protection functions [1].

Although it is not yet approved, there is a consensus that many of the changes defined in the PRC-005-2 draft for protection systems will be included when the standard update is official. These changes include a comprehensive protection system maintenance program (PSMP) and the approval to deploy maintenance based on condition or performance monitoring to help reduce or eliminate manual testing procedures. These changes will allow generation and transmission owners to utilize the inherent capabilities of microprocessor-based protective relays and real-time automation systems to automatically test and validate many critical protection system components while also avoiding the downfalls of manual testing [2].

The California Department of Water Resources (CDWR) recognized this shift in testing procedures and initiated a program to design an integrated system that continuously monitors, tests, and validates many of the critical protection components identified in the PRC-005-1 reliability standard. An equal motivator was the desire to incorporate a system that could significantly enhance the awareness of the CDWR generation protection system and the many valuable assets CDWR protects via remote communications from their offices in Sacramento, California. This was critical to the small staff of protection engineers responsible for generation plant protection spread across numerous plants over a large geographic area.

This paper focuses on the CDWR design process and the development of a protection system monitoring (PSM) application using protective relays, a real-time automation controller, and reporting software to monitor, test, validate, and report many of the PRC-005-1-defined critical protection system components.

II. CDWR Generation

The CDWR State Water Project (SWP) is the largest publicly built and operated water and power development and conveyance system in the world. The SWP was designed and is operated by CDWR. It includes a system of dams, reservoirs, and a main aqueduct that stretches across 700 miles of California, as shown in Fig. 1.

Fig. 1. CDWR State Water Project

The SWP includes a total of seven generation facilities. Three of these power plants are in the process of a relay replacement program, which includes upgrading from electromechanical relays to microprocessor-based relays. All three plants are required to meet the PRC-005-1 reliability standard.

Recognizing the inherent self-test and communications capabilities of microprocessor-based relays and the advancements in real-time automation controllers, CDWR protection engineers investigated the potential of implementing a system to perform real-time monitoring and reporting of CDWR critical protection system components.

III. NERC PRC-005-1

NERC defines protection systems as including the following components:

- Protective relays, which respond to electrical quantities.
- Communications systems, which are necessary for the correct operation of protection functions.
- Voltage- and current-sensing devices and their circuits, which provide inputs to protective relays.
- Station dc supply, which is associated with protection functions.
- Control circuitry, which is associated with protection functions through the trip coil(s) of the circuit breakers and other interrupting devices.

As part of the PRC-005-1 reliability standard, NERC requires generation and transmission owners to maintain a PSMP, which includes maintenance testing procedures, testing intervals, and documented test results for each of these components. Its purpose is to verify that all critical components are in working order and that the proper operation of malfunctioning components is restored [3].

IV. PSM Design Overview

Using these requirements as guidelines, CDWR designed the PSM system to improve the overall reliability of their generation protection systems via the performance of real-time evaluations of numerous critical protection components. The results are automatically communicated to a centralized server, and maintenance reports are generated that are visualized for protection engineer review and then archived as component test documentation. Critical to the design is the availability of an existing secure communications infrastructure, which allows the small number of plant maintenance protection engineers to monitor the daily performance of remotely located generation protection systems. These capabilities help supplement manual protection system testing with an automated process that compensates for the lack of available qualified test technicians while also reducing maintenance outages and eliminating the difficulties of manually organizing and centralizing test result documentation over a large geographic area.

The system performs real-time validation and reporting of critical protection system components, including current transformers (CTs), potential transformers (PTs) and their circuits, protection communications, relay health, firmware, and settings.

The plant PSM system incorporates a real-time automation controller that acts as the PSM controller to poll connected generator protection relays for digital and analog values. The standalone PSM controller manages communications to all the intelligent electronic devices (IEDs) via a completely secure and isolated communications network that is separate from the protection, control, and monitoring (PCM) communications network. The standalone nature of the PSM communications network ensures that no new settings are required in the PCM system and that the PSM processes will not impact the performance of the PCM processes. The PSM controller evaluates component health by collecting and processing PSM data via preprogrammed component-specific evaluation criteria. The health of all monitored protection system components is documented in a single plant-level automated report that is sent to a centralized PSM server. This report serves the following purposes:

- Improves protection system awareness through daily reports that help identify potential failed components that may otherwise go unnoticed.
- Supports PRC-005-1 maintenance testing and documentation requirements, where the daily reports are used to reset the maintenance intervals for each of the monitored critical protection system components.
- Documents the occurrence and behavior of power system apparatus operations.
- Provides time-stamped information and evaluation for instant or periodic PSM audits.

The system also includes automatic enterprise-level relay event report retrieval and storage capabilities, which are used to determine the reason an event occurred and to support documentation for PRC-005-1 component validation.

V. Thermalito Power Plant

The three CDWR generation plants that fall under the PRC-005-1 reliability standard as "key generating facilities" with transmission voltages above 100 kV are the Edward Hyatt Power Plant, Thermalito Power Plant, and Devil Canyon Power Plant. The development of the PSM system was based on the Thermalito Power Plant and designed for easy adaption to the other two plants. If successful, CDWR will consider installing PSM systems at the remaining four plants.

The Thermalito Power Plant, shown in Fig. 2, is part of the Oroville-Thermalito Complex, located 70 miles north of Sacramento, California. The plant includes three 28 MVA units and one 36 MVA unit.

Fig. 2. Thermalito Power Plant

Each of the four generating units incorporates dual primary generator and transformer protection relays and one motor relay to monitor the unit pump-back function. Each generator relay connects to CTs on both sides of the generator and shares a PT. Each transformer relay connects to CTs on the high and low sides of the transformer (see Fig. 3). The motor relay connects to separate CTs and PTs. With five relays protecting each generating unit, the PSM system monitors a total of 20 relays.

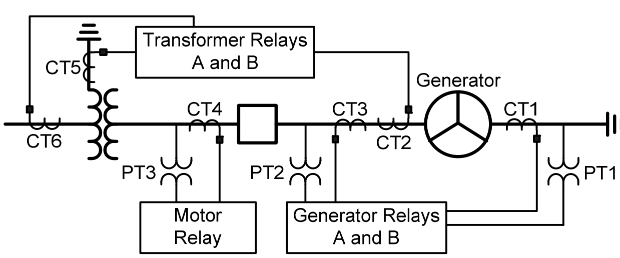

Fig. 3. Thermalito Power Plant one-line diagram

VI. Thermalito PSM System

The Thermalito plant PSM system utilizes the PSM controller to communicate with each of the generator protection relays via a serial interface. Each relay is polled to collect the data required to test and validate each of the monitored critical protection system components. Preprogrammed test and validation logic is used to determine the current status of each component, with the results included in a daily report sent to the remote PSM server.

The plant PSM system communicates to the protective relays within the PCM network. These relays also act as nodes in the supervisory control and data acquisition (SCADA) system for the sole purpose of performing real-time validation and status reporting of critical protection system components. As mentioned, conversations with the relays use a dedicated communications interface for data acquisition only and cannot influence the operation of the SCADA network. PSM data exchanges with critical protection system components are completely isolated from SCADA conversations that may include automatic and commanded controls. Advantages to this design include system security and the ability to perform PSM maintenance without affecting SCADA operations (see Fig. 4).

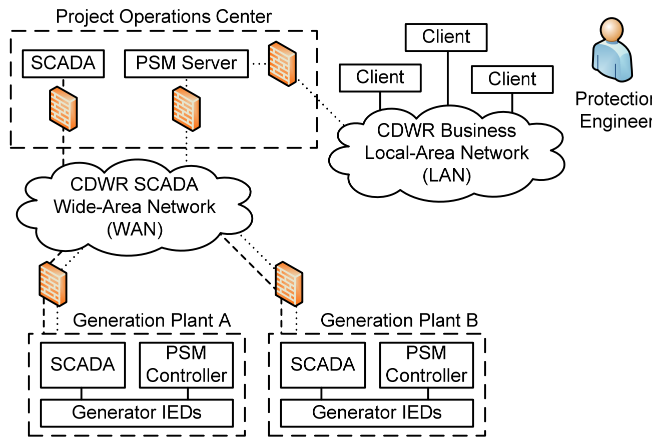

Fig. 4. PSM controller system architecture

VII. PSM Controller

The design and development of the PSM system were made possible because of the advanced functionality of the PSM controller, which provides the tools required for developing and testing this application. Equally important is the controller reliability, which meets or exceeds protective relay standards and IEEE 1613, IEEE Standard Environmental and Testing Requirements for Communications Networking Devices in Electric Power Substations [4].

Only one software tool is required to build and test the PSM application, which provides easy configuration of relay integration, including data collection, data management, and data verification. The PSM controller also includes an integrated IEC 61131 logic engine to perform component validation logic through the use of graphical continuous function charts and function blocks via internationally standardized methods. The PSM controller tag processor builds daily validation reports and securely communicates them to the remote PSM server for viewing by the plant protection engineering staff [5].

The PSM controller is also responsible for collecting relay event reports, which, upon detection, are automatically forwarded to the PSM server and used to analyze system events and support PRC-005-1 documentation.

For accurate event analysis and validation reporting, the PSM controller uses a satellite clock to automatically synchronize the system clock of each connected relay by distributing an IRIG-B signal via the EIA-232 interface cable.

The PSM controller application includes the tasks discussed in the following subsections. Together, these tasks verify, test, validate, and report each monitored critical system component.

A. Data Collection and Verification

The PSM controller uses EIA-232 serial communications operating at 19,200 bps to poll the required data from each connected relay once per second. This serial interface is completely isolated from the relay SCADA connection.

When the data are received, the PSM controller determines the quality of the requested data and attaches a quality attribute to the polled value. This attribute is included as an input to the component validation logic. The PSM controller verification process includes the following data quality checks:

- Valid communications exist between the relay and the PSM controller.
- The collected data value is within the defined reasonability range.

Table I is an example of the available PSM controller data quality flags.

TABLE I
PSM CONTROLLER DATA QUALITY ATTRIBUTES USED IN VALIDATION LOGIC

Attributes	**Type**	**Default Value Enumerations**
q	quality_t	
validity	validity_t	Good, invalid, reserved, questionable
detailQual	detailQual_t	
overflow	BOOL	TRUE, FALSE
outOfRange	BOOL	TRUE, FALSE
badReference	BOOL	TRUE, FALSE
oscillatory	BOOL	TRUE, FALSE
failure	BOOL	TRUE, FALSE
oldData	BOOL	TRUE, FALSE
inconsistent	BOOL	TRUE, FALSE
inaccurate	BOOL	TRUE, FALSE

B. Self-Test Diagnostics

Each relay runs continuous self-tests to monitor the internal health of its major components. If an out-of-tolerance condition is detected, the relay generates a warning or a failure alarm. When a self-test determines that one or more internal components have exceeded an expected limit but have not compromised the relay operation, a warning alarm is generated. For a severe out-of-tolerance condition, a failure alarm is issued and the relay enters a protection disabled state.

Both the relay warning and failure alarms are monitored by the PSM controller. These alarms, along with specific PSM controller self-test statuses, are used as inputs to the component validation logic. All of these alarms are also monitored by the SCADA system to quickly notify operations personnel of a potential component failure.

C. IEC 61131 Programs and Function Blocks

The PSM controller-integrated IEC 61131 logic engine is preconfigured to access all the data and data attributes required to perform the PSM validation logic. It also provides capabilities to create function blocks, which are routines that a program can use as definitions for multiple instances to perform a specific task. Because many of the validation tests are repeated for each relay, preconfigured functions and PSM-developed function blocks are applied to reduce and simplify the validation programs [5].

D. Validation Programs

PSM validation logic determines if a critical system component is operating as designed. Validation testing results are monitored and reported daily. A test failure could be associated with data quality, a relay or PSM controller self-test, bad CT and/or PT data values, or a relay firmware or settings change. If a component fails its validation test, the PSM controller identifies which of the test parameter(s) failed, logs the failure time, and includes the status of the failed component in the next validation report sent to the PSM server. This is accomplished by continually monitoring and processing the data required to accurately identify when a component passes or fails its validation test. The PSM controller includes validation tests for the following protection system components:

- Relay and PSM controller diagnostics
- CTs
- PTs
- CT circuits, PT circuits, and relay analog-to-digital (A/D) converters
- Protection communications
- Relay firmware
- Relay settings

1) Relay and PSM Controller Diagnostics

The PSM controller includes validation logic for self-test diagnostics both within the relay and PSM controller. If any relay or PSM controller warning or failure alarm is detected, the logic identifies the failure, logs the time and the specific alarm, and transmits a failed validation report to the remote PSM server.

2) CTs

CT validation compares the instantaneous A-, B-, and C-phase measured values of each relay with the A-, B-, and C-phase currents of a selected reference relay. If a phase from any one of the five relays deviates from the defined dead band, it is logged and a failed validation result is generated. This methodology allows the use of multiple instances of the same function block to simplify the validation program.

Each Thermalito generating unit has five protective relays connected to five sets of CTs (see Fig. 3). The dual primary generator relays monitor CT1 (IA, IB, IC) and CT3 (IA87, IB87, IC87), the dual primary transformer relays monitor CT2 (IAW2, IBW2, ICW2) and CT6 (IAW1, IBW1, ICW1), and the motor relay monitors CT4 (IA, IB, IC). These instantaneous measured values are polled once per second by the PSM controller and programmed as inputs to the CT validation logic. The logic output is either pass or fail and is used to report the current status of this critical protection system component.

The CT validation logic includes the following inputs:

- Unit current output
- Instantaneous measured values
- Measured value comparison dead band
- Data quality
- Time of poll

To initiate a qualifying validation report, the logic first determines if the unit is generating a minimum output. CDWR engineers determined that the unit output current must exceed 5 percent of nominal to qualify for a valid online report. For the Thermalito generating units, this is calculated by multiplying 0.5 by the CT ratio and comparing the result with the A-phase measured value. If the unit output is below this predetermined parameter, the unit is considered offline.

If the unit meets its minimum output, the measured values for each phase from all five relays are compared with each other to determine if they are all reading values that fall within a calculated dead band. The measured values may not be exactly the same for each comparison cycle, so a reasonable dead band is applied. For the Thermalito generating units, CDWR engineers set the dead band at 2 percent of the measured value, which is based on the accuracy of the installed CTs.

Because the transformer relay measured values from CT6 (IAW1, IBW1, ICW1) are located on the high side of the transformer, a scale factor is applied before the values are compared with the other current inputs. The CT scaling parameter is based on the Thermalito transformer winding ratio and is set to 17.42.

As previously mentioned, the PSM controller determines the data quality for each of the measured values read from the relays. These quality statuses from all current readings are included in the CT validation logic. The PSM controller also assigns a time attribute each time it receives a CT measured value from a relay. This attribute is used by the CT validation logic to ensure that the 1-second comparison cycle of the CT measured values occurs within that cycle time of ±1 second. This is accomplished by assigning a 1-second time dead band when comparing CT measurements.

The CT validation logic is designed to monitor and compare two sets of phase currents (A, B, C) from each generator and transformer relay and one set from the motor relay. If implemented in a single program, this logic becomes difficult to troubleshoot and maintain. To simplify this potential problem, the CT validation program uses one generic function block that is applied to all phases from each relay. Fig. 5 is a screenshot of the function block logic used by the CT validation program to compare and validate all phase currents.

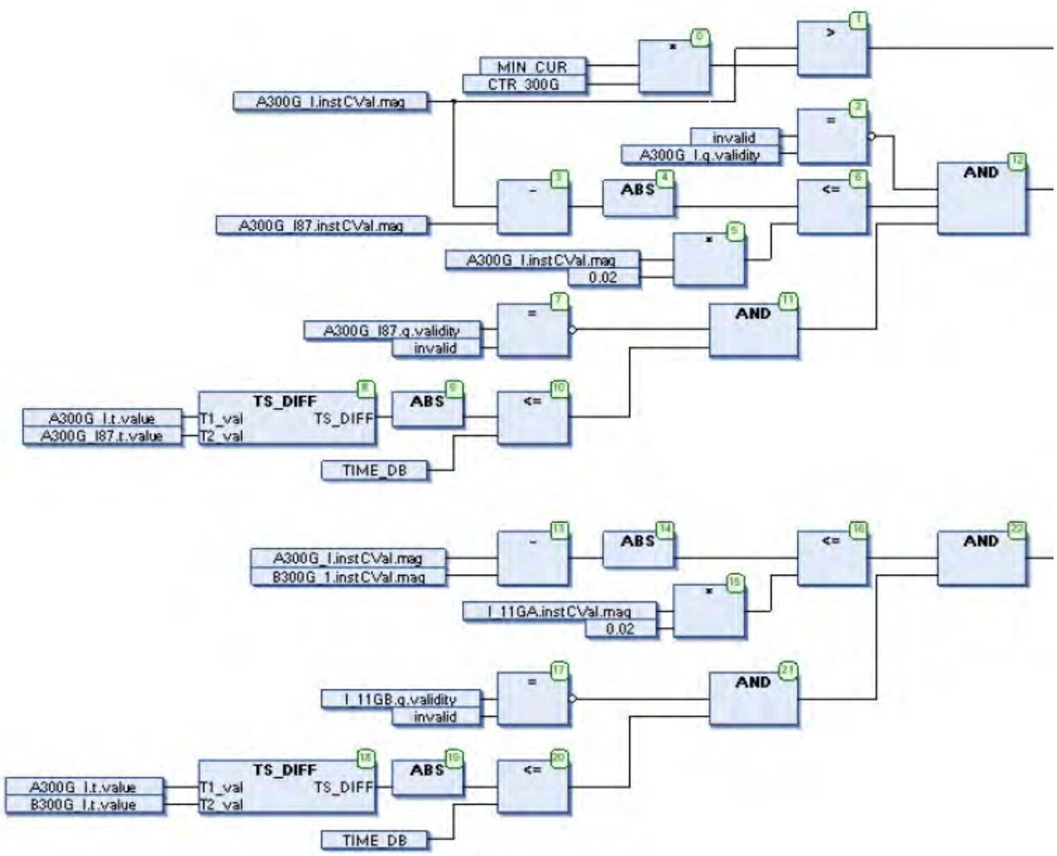

Fig. 5. CT validation function block logic

Because the IEC 61131 logic engine allows the use of multiple instances of one function block in one program, the CT validation program includes 12 instances (one for each phase) for each generator. Fig. 6 shows the Thermalito Unit 1 function block UNIT_1_IA instance comparing all the A-phase currents from five relays. The UNIT_1_IA_STATUS output is included in the validation report sent to the remote PSM server.

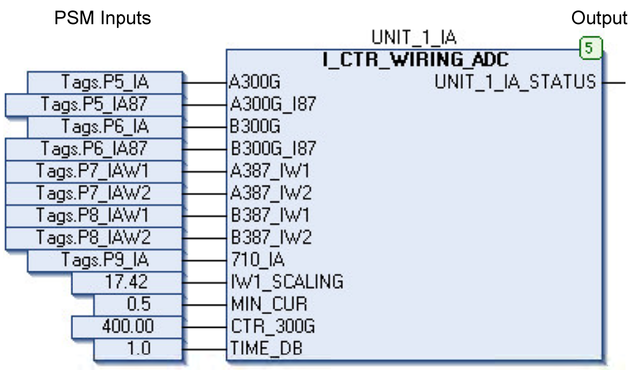

Fig. 6. CT validation function block

3) PTs

PT validation logic implements the same approach as that used for CTs, except that the voltages are compared instead of currents. The motor relay and each generator relay are connected to a set of PTs, which are monitored by the PSM controller. The motor relay (see Fig. 3) monitors PT3 (VA, VB, VC), and both generator relays monitor PT2 (VA, VB, VC).

The PT validation logic is similar to the CT logic, with the following exceptions:

- The unit voltage output determines an online PT validation report. CDWR set the minimum voltage limit at 2 percent of unit nominal voltage, which calculates to 7,967 Vdc.
- The generator relay loss-of-potential (LOP) target is included in the logic as an additional identifier of a failed component.

Fig. 7 is an example of the A-phase function block used by the PT validation logic program.

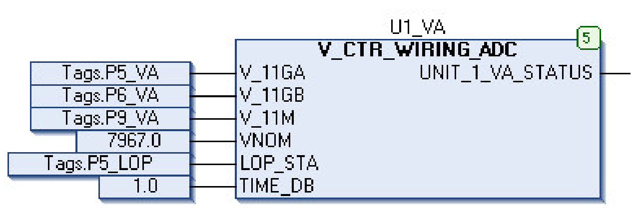

Fig. 7. PT validation function block

4) CT Circuits, PT Circuits, and Relay A/D Converters

A positive result from CT and PT testing provides validation for additional critical protection system components, including the CT and PT circuits and relay A/D converters. Comparing and validating PT and CT measured values from multiple independent sources test and validate not only the CTs and PTs but also the circuits connecting them to each relay. When measured values from multiple sources pass the associated validation test, this also validates the components responsible for calculating the value, which, in this case, is the relay A/D converter.

5) Protection Communications

Each generator relay incorporates a field ground module to calculate the isolation resistance between the generator field winding and ground. This measurement is used by the relay protection settings when determining a unit trip condition. Because communication to the module is necessary for the correct operation of the protection function, it is monitored by the PSM controller and included in the relay self-test diagnostic validation report.

6) Relay Firmware

Relay firmware changes are usually implemented to correct an existing issue that affects the correct operation of a relay or to add a new feature. CDWR protection engineers document installed relay firmware as part of the commissioning process and record any changes when they occur. The PSM controller includes capabilities to automatically monitor the present firmware revision and alarm changes to the relay installed firmware. Each relay includes the revision of its currently installed firmware, which is continuously monitored by the PSM controller. If new firmware is installed, the PSM controller logs the new version with the date and time of installation and the firmware validation logic issues a firmware validation report to the remote PSM server.

7) Relay Settings

CDWR documents their commissioned settings for all installed relays. If a change is required, it is the responsibility of the assigned protection engineer to install, test, commission, and record the new settings. To avoid a possible settings change issue, the installed settings are continuously monitored by the PSM controller. If new settings are installed, the PSM controller logs the change time and date and the relay settings validation logic issues a relay settings validation report to the remote PSM server.

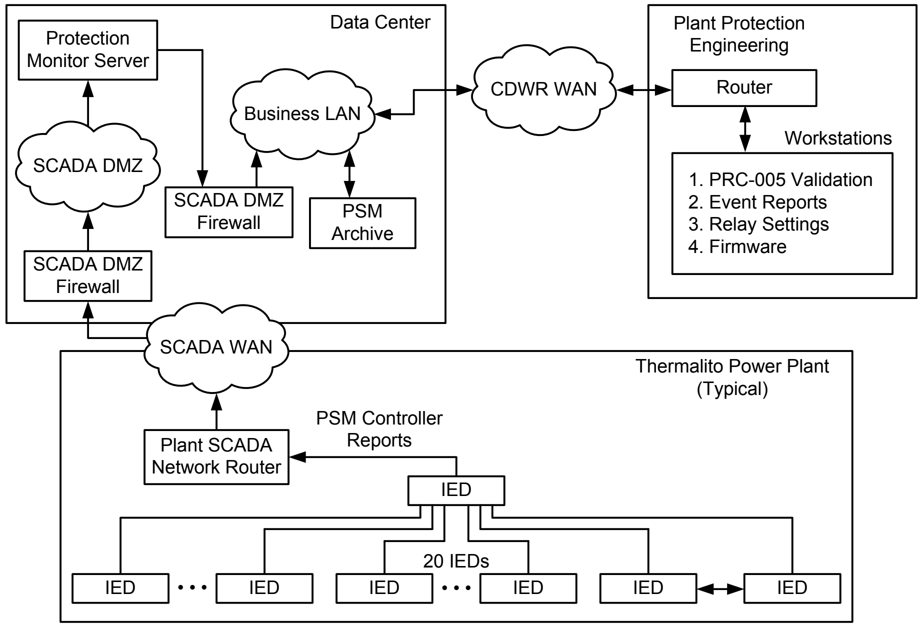

Fig. 8. System communications architecture

VIII. PSM LAN/WAN Communications

The PSM controller continuously monitors, tests, and validates each critical protection system component. At the end of each 24-hour period, the PSM controller transmits a plant validation report to the remote PSM server. Communications from each plant to the PSM server utilize the existing CDWR SCADA network, which provides a secure LAN/WAN connection from each PSM controller to the centrally located server (see Fig. 8).

Plant protection engineers access the daily validation reports via PSM clients located in the plant maintenance engineering office.

IX. System Security

The PSM system is designed to provide secure communications across the CDWR SCADA LAN/WAN with existing firewalls and a demilitarized zone (DMZ) already in place. The PSM system adds additional security by initiating all report conversations from the PSM controller, thus reducing the potential of a rogue or accidental attempt to compromise the system. PSM controller security features perform the following actions:

- Block any accidental or rogue attempt to implement a remote control action to the connected relays.
- Block any accidental or rogue attempt to remotely change the relay or PSM settings.
- Permit relay and PSM controller settings changes only through the front serial port using the secure authentication and password process.
- Initiate all validation and relay event report conversations from the PSM controller to prevent a remote accidental or rogue interaction.

X. Validation Reports and Logs

Validation reports, as shown in Fig. 9, provide CDWR protection engineers with a simple view of how the remote protection systems are performing on a daily basis. Using the PSM client, the system can be quickly inspected for a potential critical protection system component failure. Daily results are viewed, acknowledged, and archived to support the CDWR PSMP.

If a validation report fails, the plant protection engineer is notified and corrective action is initiated. To identify where a validation test fails, the protection engineer accesses the PSM controller log via its web-based interface and inspects the logged data associated with the critical protection system component of each relay. The system uses both the PSM client displays and email to notify the protection engineering staff of a failed validation report.

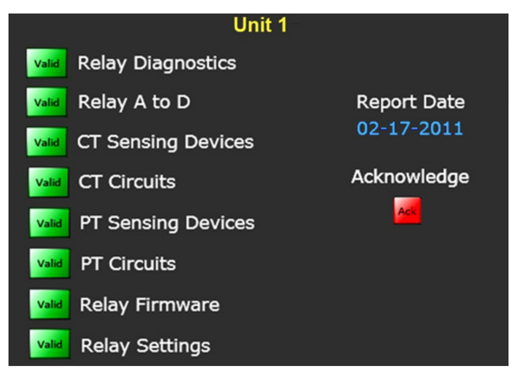

Fig. 9. Validation report

The result of each validation test is recorded by the PSM controller to determine if a failed test qualifies as a countable event. A countable event occurs when a protection system component has failed and requires repair or has contributed to a protection system misoperation. Because each test occurs on a once-per-second cycle, it is possible to have an isolated negative result due to an anomaly that generates a negative validation test. To determine if an intermittent failure is a countable event, the PSM controller tracks all failures and calculates if the monitored component should be included in the daily validation report.

Server data archives are organized to access all recorded validation reports. This is accomplished with a file system that stores events by year, month, and day. The results of the daily validation reports are filed under one of three categories: *G_Report* (pass), *NG_Report* (fail), or *OL_Report* (offline because of a shutdown or maintenance), as shown in Fig. 10.

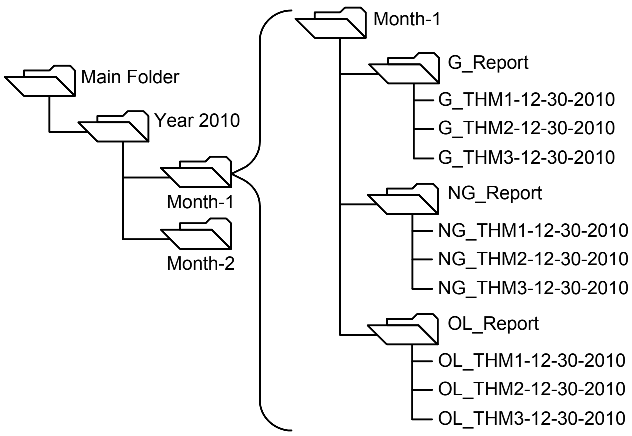

Fig. 10. PSM folder and file structure

XI. Event Reports

Each relay includes settings to generate a 30-cycle event report, including 1 cycle of prefault data, in response to a fault or other disturbance. The report includes current and voltage data, relay element states, and I/O statuses. When an event occurs, the following steps happen:

- Relays automatically inform the PSM controller of the new event.
- The PSM controller collects the event report and notifies the remote PSM server.
- The PSM controller pushes the event report across the SCADA network to the server, where it is time-tagged, displayed, and archived.

If a generator breaker trips as a result of its commissioned settings, the event report is used to validate the relay breaker control output contact, breaker control circuit, and breaker apparatus. If the recorded event includes information that identifies a critical system component failure, it is logged, protection engineers are notified of a potential misoperation, and the event report is included in the PSMP support documentation.

An important feature for this system is the ability of the PSM controller to perform continuous monitoring of the critical components of each relay while also supporting automatic event retrieval. This is accomplished by deploying a serial protocol capable of interleaving these two conversations at the same time.

XII. Future Additions

CDWR protection engineers are considering expanding the system to include additional monitoring by installing trip coil monitors (TCMs). TCMs provide output contacts that indicate the present status of breaker or lockout relay trip coil or trip circuit connection continuity. Although they do not provide continuous validation for the dc trip circuits and other interrupting devices, TCMs do contribute to their validation when combined with the normal operation of the breaker. The TCM outputs would be wired directly to the PSM controller inputs and mapped to additional validation logic. Each time the breaker operated, the PSM system would record the event and generate a validation report verifying the relay input and output contacts, dc trip circuit, and breaker operation.

XIII. Conclusion

Generator and transmission protection relays can be described as silent sentinels that only demonstrate their designed function when a protection event occurs. Typically, an event may not happen for an extended period of time. This can increase the possibility of a false operation or a failure to operate on a protection event due to an undetected critical protection system component failure, noncommissioned settings, or other potential issues. The PSM system helps mitigate these possibilities by continuously monitoring many of the generation plant critical protection system components, updating their statuses through daily reports, and increasing protection system engineering awareness through the use of visualization and logging tools. Additional PSM features include isolating the system from SCADA (to minimize security and operational outage requirements) and archiving validation and event reports (to support the PRC-005-1 PSMP). CDWR continues to investigate the development of additional monitoring capabilities, including the installation of TCMs, which would enhance awareness of the breaker and dc trip circuits while adding additional PSMP support documentation.

XIV. References

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[5] IEC 61131-3, Programmable Controllers – Part 3: Programming Languages.

XV. Biography

Robin Jenkins has a BSET degree from California State University, Chico. From 1984 to 1988, he was employed as a systems integration engineer for Atkinson System Technologies. From 1988 to 1999, he was with the California Department of Water Resources, where he worked as an associate and then senior control system engineer. From 1999 to 2007, he worked for Schweitzer Engineering Laboratories, Inc. (SEL) as a senior integration application engineer. From 2007 to 2009, he rejoined the California Department of Water Resources as the control systems branch chief. He is currently employed by SEL, where he holds the position of integration application engineer and is responsible for technical support, application assistance, and training for SEL customers in Northern California.

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