

PacifiCorp's Jim Bridger RAS: A Dual Triple Modular Redundant Case Study

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Abstract—The Jim Bridger Power Plant, located near Rock Springs, Wyoming, is a mine-mouth, coal-fired generation station jointly owned by PacifiCorp and Idaho Power Company. Jim Bridger operates four 530 MW units that transmit the majority of their power through three 345 kV lines west through the Borah West Corridor in southern Idaho. Two 230 kV lines connect to the Wyoming transmission system as well. A subcycle remedial action scheme (RAS) allows system operators to push more power through their existing transmission infrastructure, meanwhile protecting against several known dynamic stability problems.

The existing RAS consists of two systems, one a triple modular redundant (TMR) programmable logic controller (PLC) and the other a hard-wired relay panel. Both systems are obsolete and at the limit of maintainability. They are also difficult to expand in terms of improving logic and adding I/O for new transmission.

PacifiCorp contracted with a supplier to implement a dual TMR RAS system to satisfy PacifiCorp and WECC (Western Electricity Coordinating Council) requirements. The system utilizes proven substation-grade, IEC 61131-3-compatible programmable controllers and high-speed I/O. Each TMR system consists of three identical systems gathering I/O, performing two-out-of-three voting on the data, and performing calculations to decide if an action is necessary. Total loop timing from input assertion to output contact conduction is less than 17 milliseconds. An action (generator trip or capacitor insert/bypass) cannot be executed unless two of the three systems in a TMR RAS agree. The two fully independent TMR RAS systems have dual supervisory units to ensure that a different action can never be taken by the two independent RAS systems. Due to the dual TMR nature of the RAS, a total of four very specific device failures is necessary before the RAS is incapable of reaching a decision.

I. BACKGROUND

A. Power System

The Jim Bridger Power Plant is located 22.7 miles east of Rock Springs in southwestern Wyoming. The coal-fired electrical generating plant with its four 530 MW units is adjacent to a coal mine from which most of the fuel for the plant is obtained. The plant, which is jointly owned by PacifiCorp and Idaho Power Company, is operated by PacifiCorp. The transmission system that connects the Jim Bridger Power Plant to the transmission grid consists of three 345 kV lines and three 230 kV lines. Although the plant is in Wyoming, it is an energy resource for the PacifiCorp and Idaho Power loads in Idaho, Oregon, and Washington. The power from the plant is transported over three 345 kV and two 230 kV transmission lines that radiate out to the west. Those transmission lines and the critical parts of the transmission

system across the states of Wyoming, Utah, Idaho, and Oregon are parts of the transmission system monitored by a remedial action scheme (RAS) located at the Jim Bridger Substation. Since the plant was built in the early 1970s, a RAS has been required to achieve the transmission path rating needed to move the energy from the plant to the loads. When the transmission path is being operated at the path limit and a transmission line in the path is lost, the generation at Jim Bridger must be reduced to maintain the transient stability of the power grid.

The complete loss of the RAS for any reason requires that the Jim Bridger Power Plant be reduced to 1,300 MW. The full capacity of the Jim Bridger Power Plant is greater than 2,200 MW.

B. History

There have been three generations of Jim Bridger RAS control systems, and each successive system has increased in complexity. The reason for the additional complexity has been to reduce the number of times that generator units must be tripped. Each generation of Jim Bridger RAS has monitored additional statuses of the power system. With the additional information, the arming levels for tripping generator units for different line faults were raised. The worst-case scenario must be assumed for any condition that is not being actively monitored by the RAS. The less complex, older systems have therefore caused unnecessary tripping of generator units for the loss of transmission lines. The system being described in this paper has more inputs, a more complex algorithm, and therefore will shed less generation than any of the preceding systems used for the Jim Bridger RAS.

C. Description of Dynamic Problem

When a fault occurs on the transmission system, the power flow, as a result of the fault, is predominantly reactive power, since the impedances of the transformers and lines are predominantly inductive. During the fault, the voltage at the fault is zero, and the voltage at the terminals of the generators is significantly reduced. The low voltage restricts the real power flow from the generators. Since the turbines driving the generators are continuing to pour real power into the generators, the units start to accelerate. This acceleration continues until the faulted transmission line is disconnected from the system. With the fault removed, the real power starts moving from the generators to the load, and the generators decelerate. With the removal of the faulted transmission line from the power system, the transmission path impedance is increased.

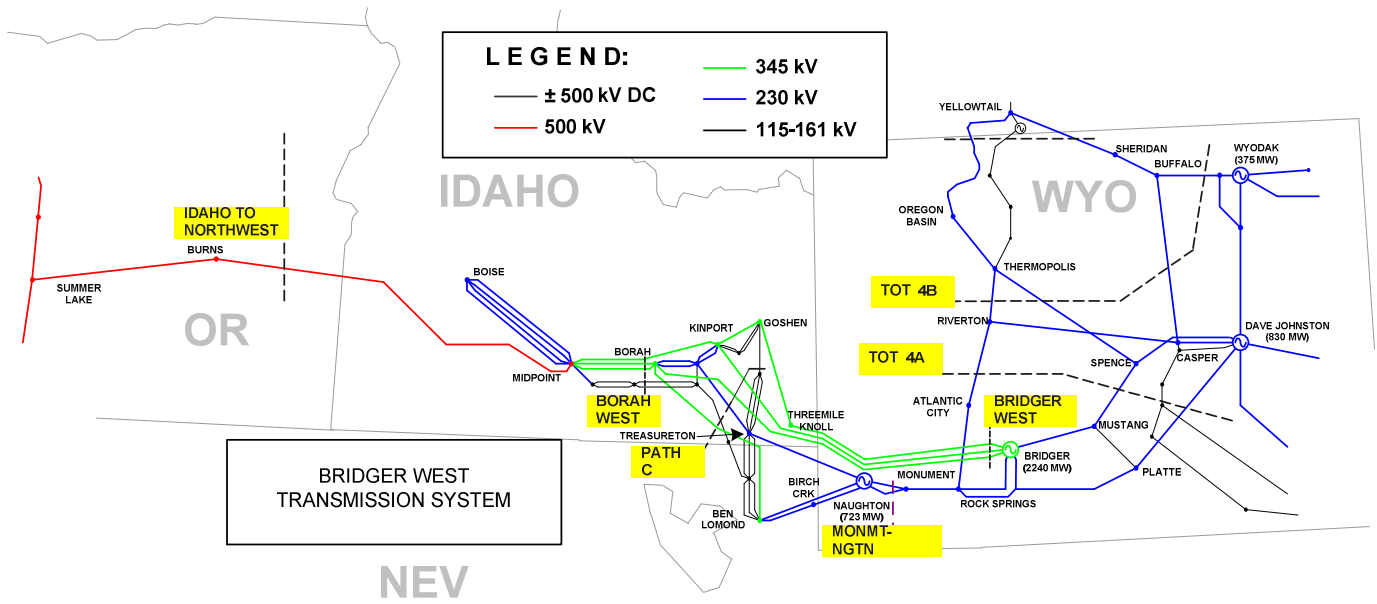


Fig. 1. Map of Transmission System

The increase of the transmission path impedance combined with the generator acceleration during the fault results in an oscillation between the generator rotors and the power system. If the real power flow is low enough and the increase in transmission path impedance small enough, the oscillations will dampen, and a new equilibrium state will be reached. If the new conditions are too extreme, the oscillations will not dampen, and the Jim Bridger generators will go out of step with the PacifiCorp power system.

The generation oscillations will cause the voltage at Jim Bridger to swing in magnitude. The voltage magnitude on the first swing after the fault is cleared is an indicator of the stability of the system. The Western Electricity Coordinating Council (WECC) requires that the voltage on the first swing not drop more than 30 percent from the pre-fault value. The Jim Bridger RAS action is needed to prevent the voltage at Jim Bridger from dropping more than the 30 percent limit following the loss of a transmission line when the plant is operating near the transmission path limit. To arrest the voltage dip, the power output from the plant must be reduced and, in the most severe cases, within 5 cycles on a 60 Hz base. The 5 cycles are measured from the inception of the fault until the generator breaker disconnects the generator.

II. RAS CONTROLLER REQUIREMENTS

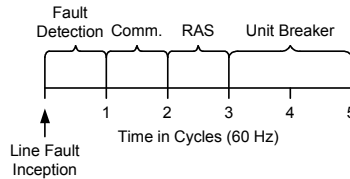
A. Timing Requirements

Based on stability studies for the most severe fault case (a multiphase fault on a 345 kV line close to Jim Bridger), the total time from event to resulting action must not exceed 5 cycles. Fig. 2A1 shows the time allocation for this case. Zone 1 faults (faults close to Jim Bridger) are the most severe N events; for these events, the overall reaction time is 3.7 cycles. (See Section VI, “RAS Design,” for a further explanation of N events.) The breakdown for Zone 1 events includes 16 milliseconds for the line relays, no communica-

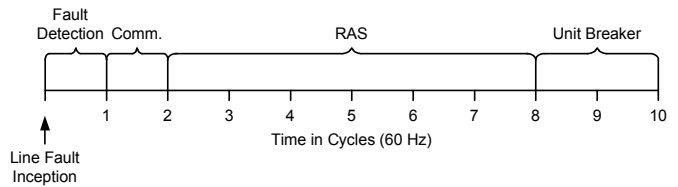
tions time, 20-millisecond RAS processing time, and 25-millisecond unit breaker clearing time. When the typical fault detection, communications time, and unit breaker opening time are excluded from the total time budget, the RAS is left with 20 milliseconds of operating time. The RAS operating time is the total measured time from an input voltage asserting to 90 percent to an output (trip contact) fully conducting.

A: For Jim Bridger Area Line Loss

A1: For Multiphase Line Faults



A2: For Nonmultiphase Line Faults (Single-Line-to-Ground or Nonfault Line Opening)



B: For Non-Jim Bridger Area Line Loss

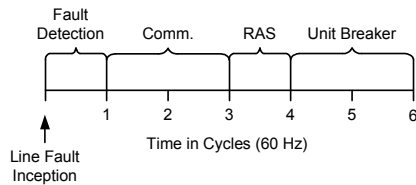


Fig. 2. Timing Charts

For less severe fault cases, less speed is required. Fig. 2A2 shows the time allocation for a single-line-to-ground fault on a 345 kV line. Although the Jim Bridger RAS has the capability to process the signals in the time needed for the most severe

case, the process is deliberately delayed for single-line-to-ground faults. Since a single-line-to-ground fault can evolve to a multiphase fault in the time it takes to detect and clear the fault, delaying the RAS response is beneficial. If the processing for the initial event is not delayed, excessive generator tripping could result. If, due to system conditions, a small amount of generation tripping was required for the single-line-to-ground fault but the output of the selected generator for tripping was inadequate for a multiphase fault event, multiple generators could be tripped when the fault evolved to a multiphase fault. By delaying the RAS to see if the fault condition will worsen, the minimum amount of generation will be tripped.

For the loss of a transmission line at a great distance from Jim Bridger, the line loss status needs to be communicated to Jim Bridger. This communication over several hundred kilometers adds additional delay, but studies have shown that the delayed response will not have an adverse effect on the stability of the power system. Fig. 2B shows the time allocation for the loss of a remote transmission line, such as the Three Mile Knoll – Goshen line.

B. Triple Modular Redundant Requirement

With the correct and timely response of the Jim Bridger RAS being critical to the stability of the power grid, the dependability of the Jim Bridger RAS is important. For this reason, the Jim Bridger RAS must be a system containing redundant inputs, outputs, and processing units. Transmission line fault incidents are unusually high for this transmission system due to the following factors:

- The 240-mile length of the transmission lines
- The rugged terrain the lines cross
- The 8,300-foot elevation of the lines
- Difficult grounding conditions
- Many unknown factors

The average incidence of faults on this transmission system is 0.8 faults per week. The plant is base loaded 24 hours a day. Between the plant's loading and the transmission line fault incidents, the Jim Bridger RAS is often called on to react. Most of these events do not require generator unit tripping, because the plant is operated at loading levels below the arming level for the most common transmission line faults, single-line-to-ground faults. The consequence of tripping a 530 MW coal-fired unit involves significant costs and reduces the reliability of the unit. For these reasons, balancing dependability with security against false operations is very important. This is why the Jim Bridger RAS is a triple modular redundant (TMR) voting control system. Two out of three identical systems must agree on the status of the inputs and the resulting outputs for the system to cause a generator unit to trip.

This triple modular redundancy is extended to the power transducers feeding the RAS data. Due to cost and complexity, the triple redundancy was not extended to two of the major

subsystems of the Jim Bridger RAS: the communications systems from remote locations and the fault severity units. These subsystems are only redundant. To accommodate the limitations of these subsystems and TMR system maintenance, dual TMR systems were specified and installed. The transmitters and receivers that use one communications network and one set of fault severity units, which are associated with each transmission line terminating at the Jim Bridger Substation, are connected to one TMR system. The communications equipment using the alternative communications network and fault severity units is connected to the second TMR system. Both TMR systems are normally in service, and either system can trip the generator units.

Due to the speed at which the Jim Bridger RAS must operate, the accuracy of the power transducers, and the scanning nature of a programmable logic controller (PLC), there are several predictable circumstances where the two TMR systems will not select the same generator unit to trip for the same event. The most likely circumstance would be when a unit's power output is near an analog threshold; in this case, one of the TMR systems could select one unit and the other select a different unit as the apparent level of the unit operating at the edge moves in and out of selection. This condition would result in tripping two generators rather than one. Since this is an unacceptable event, provisions were designed into the Jim Bridger RAS to prevent this type of event from happening. Two independent processors review what each of the TMR systems is planning to do if an event were to occur. This is possible because of the way the TMR systems predetermine their action for each of the possible line loss events based on current system conditions. Statuses as to the health of the subsystems are communicated to the monitoring systems. If the predetermined actions of the two TMR systems do not agree, the system with the healthier subsystems is permitted to take the action if the event takes place. If the health of all systems is equal and the two TMR systems will perform different actions for the event, a predetermined TMR system will be permitted to perform the action.

The other important issue is that the previous TMR systems were not designed to tolerate and perform correctly in the substation environment. Most TMR systems on the market are designed for industrial applications, and the substation introduces different environmental issues. The previous TMR system was designed with external protection elements on the inputs and outputs of the system that brought the overall system up to meeting the IEEE relay equipment environmental standards. These auxiliary systems performed well in protecting the TMR system, but later in the life of the RAS, these auxiliary systems began failing at a higher rate than the TMR primary systems. The new systems meet the IEEE relay equipment environmental standards out of the box, which should provide longer trouble-free life to the overall RAS.

C. Events and Actions

The following is the list of transmission lines for which the statuses are monitored in a real-time, high-speed manner. The single or combined loss of multiples of these lines is an event that could trigger an action from the Jim Bridger RAS.

- Jim Bridger – Borah 345 kV line
- Jim Bridger – Kinport 345 kV line
- Jim Bridger – Three Mile Knoll 345 kV line
- Jim Bridger – Rock Springs 230 kV line*
- Jim Bridger – Rock Springs via Point of Rocks 230 kV line*
- Three Mile Knoll – Goshen 345 kV line
- Goshen – Kinport 345 kV line*
- Midpoint – Borah #1 345 kV line*
- Midpoint – Borah #2 345 kV line*
- Midpoint – Kinport 345 kV line*
- Midpoint – Summer Lake 525 kV line

The loss of a transmission line marked with an asterisk will not, as a lone condition, cause generation tripping at Jim Bridger, regardless of the plant loading. However, closely timed or simultaneous successive combinations of line outages will cause generation to trip. The RAS was designed to respond to closely timed or simultaneous events; this functionality is key to a successful RAS control strategy.

The cause of the transmission line loss is taken into consideration for the loss of the lines that radiate out from the Jim Bridger Substation. The severity of the fault will impact the action to be taken. Relays throughout the PacifiCorp system are set up for fault detection and discrimination; the relays categorize each detected fault into one of the following:

- No fault or single-line-to-ground fault
- Phase-to-phase close-in fault
- Phase-to-phase remote fault
- Three-phase close-in fault
- Three-phase remote fault

The following is the list of the Jim Bridger RAS actions:

- Jim Bridger Unit 1 trip
- Jim Bridger Unit 2 trip
- Jim Bridger Unit 3 trip
- Jim Bridger Unit 4 trip
- Burns series capacitor bypass transmitter signal
- Goshen shunt capacitor transmitter signal
- Kinport shunt capacitor transmitter signal

The Jim Bridger RAS evaluates the pre-fault conditions and determines which of the above actions needs to be executed for each contingency. The primary conditions used to determine whether generator units need to be tripped for the different line loss events are the real power output of the plant or the real power flow on the three Jim Bridger 345 kV transmission lines and the impedance of the remaining lines. The 345 kV lines are series compensated with multisegment series capacitor banks. The number of series capacitor segments that are bypassed in the remaining lines prior to the line loss reduces the stability of the system and lowers the arming levels in the RAS. In addition to the power flows and compensation levels, an extensive number of critical power

network elements are also monitored. The status of those critical power network elements as well as the prior outage of transmission lines for which the loss of the lines has triggered an event are considered preexisting states for the RAS. The pre-event state of the power system establishes the arming levels for RAS action.

III. ANCILLARY CONTROL FUNCTIONS

There were two functionalities added to the RAS controllers that were not part of the core Jim Bridger RAS. These are described in the following subsections.

A. Subsynchronous Resonance Avoidance

The three 345 kV transmission lines that terminate at the Jim Bridger Substation are series compensated with multisegment series capacitor banks at the remote substation terminals. Each series capacitor has a bypass breaker. When a fault or switching event (N event disturbance) occurs on the local transmission system with the series capacitors bypassed, the system currents change from the previous operating state to the new state with less than a quarter cycle of high-frequency transients. In contrast, when a fault or switching event occurs on a system with series capacitors, the currents change from one state to another with a low-frequency transient characteristic.

The low-frequency switching transient forces an exchange of stored energy in the series capacitors (electrical field) and the stored energy in the inductance (magnetic fields) of the transmission system. During normal operation (prior to an event), the energy in these two systems is in a state of equilibrium. The frequency of this electromagnetic oscillation is dependent on the natural frequency associated with the value of the inductive and capacitive reactance of the power system.

Unfortunately, several turbine generators in the local system have mechanical resonance frequencies that coincide with the electromagnetic natural frequency of the electrical power system. Because of this, the fault or switching event that initiated the low-frequency transients in the electric power system will also initiate mechanical oscillations on the turbine generator. Because the electromagnetic and mechanical natural frequencies are so close, they exchange energy at the frequency of oscillation. Unfortunately, there is not sufficient damping in the combined electrical and mechanical system; this causes the amplitude of the natural frequency oscillation to be maintained or grow indefinitely. This phenomenon is called subsynchronous resonance (SSR). SSR events place additional stress on the shaft of the mechanically oscillating turbine-generator units. The cumulative effect of multiple SSR events has caused shaft fatigue and failures at power plants in the PacifiCorp system.

Several control systems are applied on the Jim Bridger power system to prevent SSR. One of these systems is implemented in the same hardware as the RAS. The RAS controllers monitor status points from the plant to determine when it is permissible to insert the last stages of the series capacitors on all three transmission lines. This prevents series

capacitor compensation from increasing to levels known to cause SSR. The plant status signals monitor generator conditions known to promote SSR.

The RAS controllers send the series capacitor insertion permit signals when the following four conditions are met:

- The protective relays used for SSR detection must be in service.
- The generator excitation systems must be in service (they damp out low-frequency oscillations on the turbine generators by varying the generator field current).
- All the on-line generators must be operating above a critical power threshold.
- The total plant power output must be above another threshold.

If these conditions are met, the RAS controllers communicate the signal to the remote terminals to permit the final segments of series capacitors to be inserted at each location. The permit insert signal must be maintained to keep the capacitors in service.

B. Scheduling Limit Functionality

Corridor capacity limits are dynamically changing and are often difficult for PacifiCorp Operations to track. The state of the power system (lines in or out of service) strongly impacts corridor capacity limitations.

The RAS controllers use the known line and equipment outages (J states) to first come up with the system state. The system state is then used to derive the scheduling limit for the Jim Bridger West Corridor. This is done in a fashion similar to

arming level calculations, by using a weighted equation of gains to evaluate the system state and come up with a single scheduling limit number for the Jim Bridger West Corridor.

IV. RAS ARCHITECTURE

Fig. 3 is an overview of the major systems in the Jim Bridger RAS. RAS Systems C and D are identical, triple redundant systems with full two-out-of-three voting. Each input/output (I/O) point to the field is wired to three independent I/O points on both systems. Each half of the RAS I/O is separately wired to terminal blocks, and all RAS controllers and whetting voltages are powered by separate dc battery systems. This creates a system of two completely autonomous control systems, hence the system is considered “dual primary.”

Within each RAS system (C and D), there are three autonomous IEC logic controllers with fully independent I/O modules. These three controllers perform two-out-of-three voting via high-speed communications links. A single substation-hardened computer provides a user interface (human-machine interface, HMI), sequence of events viewing (SERviewer Software), and event report viewing (oscillography). Another hardened computer is used as an engineering workstation and contains the development environment for all hardware (IEC 61131-compliant programming).

Each RAS system (C and D) has its own protocol gateway for communication to the PacifiCorp energy management system (EMS). These gateways communicate the necessary status, metering, and controls to and from the SCADA (supervisory control and data acquisition) masters via serial DNP3.

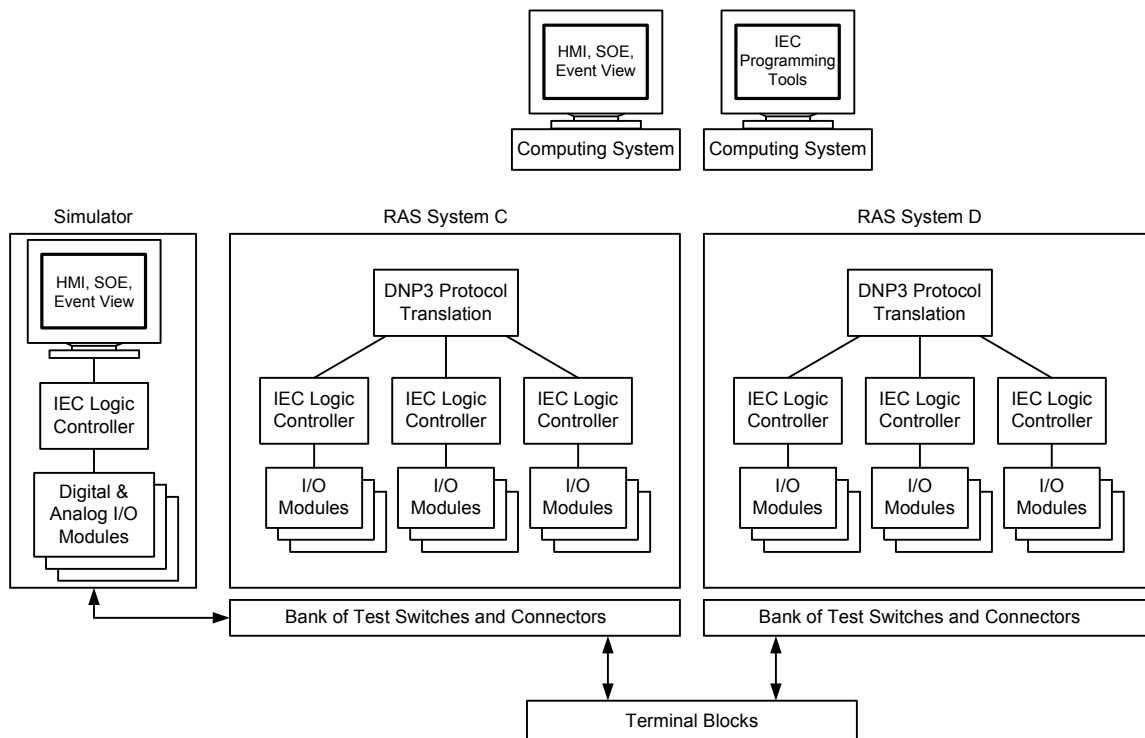


Fig. 3. System Architecture Overview

RAS Systems C and D are completely isolated on separate networks, and all logic on each system runs without any knowledge of the other system. The router between the two systems is configured to prohibit all traffic between the two RAS systems. The router limits communication from the RAS systems only to the HMI, engineering workstation, and supervision systems.

A. SCADA Communication

The SCADA gateway systems function as the intermediary for receiving data from the PacifiCorp EMS that will be used in the RAS system calculation algorithms. These gateways are also used for providing data to the EMS regarding the status and operating characteristics of the RAS system. The tasks performed by the gateways are as follows:

- Receive status and analog values from PacifiCorp and Idaho Power and make them available to the IEC controllers.
- Validate that each redundant data stream contains identical data (status and analog values) that are returned from the three controllers. Select the data source (controller) that represents the best quality data, and pass this on to the EMS.
- Flag and alarm any and all data not consistent within each redundant data stream.
- Identify and alarm any and all communications path failures via a watchdog routine.
- Code using the IEC 61131-3 programming system in a library that can be accessed from any program.

Each IEC controller performs integrity comparisons of data set points coming from the two PacifiCorp EMS front-end processors. One front-end processor is located in Casper, Wyoming, and the other is located in Salt Lake City, Utah. Based upon quality indicators, the controllers select which data source (gateway) to use. Because the code (library) running in each controller is identical, the decisions will be identical. The quality indicators used to decide data source selection include:

- Loss of communications watchdog to the EMS.
- Loss of communication between the gateway and controller.
- Alarm contact assertion on the gateway.
- Unchanging or high latency data from the EMS.

B. Simulator Design

The test simulator for the RAS control system simulates all RAS external inputs, including digital status, control inputs, analog data, and DNP3 data streams. The test simulator contains a user interface (HMI) from which an operator can perform all system tests. All systems run autonomously from the RAS.

The test simulator has the following two operating modes:

- Static simulator. This mode provides the operator the ability to drive each individual input to the RAS to a desired value. For example, the system is used to set EMS set points, set breaker status conditions, and detect generator trips from the RAS. This is extremely

useful for testing all I/O points and creating any desired power system scenarios for presentation to the RAS controls.

- Playback simulator. In this mode, the simulator is used to replay one or more event report files to the RAS system. There are two types of playback files:
 - Playback of RAS system recordings of actual events. This is identically analogous to replaying an event report created by a relay back to that very same relay. The only difference is that the response of the RAS in the recorded event is deleted for the playback, and the test simulator emulates the power system response to the output of the in-test RAS, changing the inputs to the in-test RAS.
 - Playback of recordings created by the engineers. These test records are similar to the RAS report records but are for events that the RAS has never seen before. The records cover a series of events over a period of time. The test simulator again emulates the power system changes that would occur as a result of the RAS unit tripping.

Both RAS subsystems have separate disconnect equipment (test switches) for all status, control, and low-level analog signals. The test simulator plugs into either RAS C or D for testing purposes. When under test, the RAS will not receive any inputs other than the conditions supplied by the test simulator.

The test simulator was used extensively during factory acceptance testing and on-site commissioning and will be used for future verification and maintenance testing.

C. Rugged Design Characteristics

All hardware in the Jim Bridger RAS is protective relay-class, substation-hardened equipment with extended temperature range, physical shock resistance, electromagnetic immunity, and static discharge capabilities.

The control algorithm resides on a substation-hardened controller running an embedded real-time controller engine. This engine is programmable in all IEC 61131 programming languages. There are no fans and no spinning hard drives in any equipment. All components run off of the substation battery (dc). No ac power is used in the RAS panels.

All outputs are Form A, trip-rated dry contacts; there are no interposing relays in the system. These outputs are therefore failsafe (i.e., they remain open unless a tripping scenario has occurred).

Additionally, every zone of the RAS hardware, firmware, and software contains continuous self-diagnostics. This guarantees the detection of catastrophic failures of any component(s) in the system. Every device in the RAS design has a normally closed, watchdog alarm contact that will assert if any device is powered down or has a hardware or firmware failure. These contacts are crosswired to other devices for monitoring, which guarantees that a failure in one device will not propagate further.

The logic, settings, and configurations installed on each hardware system are developed and tested to be fault tolerant,

meaning that bad computations are intentionally rejected. For example, if a line metered value is out of range or coming from a failed device, an alarm will be asserted, and the logic will declare that specific data as bad. All logic, settings, and configurations are set up to automatically reject bad data and reselect available (good) data. Bad data will not be used to make decisions.

A dual Ethernet communications network completely replaces the need for failure-prone, backplane technologies present in most industrial PLCs. The traditional technique for TMR systems is to use three central processing unit (CPU) controller modules on a single backplane, making the backplane the inherently weak point of the design. The Jim Bridger RAS TMR system uses dual redundant Ethernet hardware and redundant communications lines to eliminate this single point of failure.

The result of these design decisions is a RAS that requires four carefully selected, simultaneous hardware failures to prevent RAS operation.

V. COORDINATION WITH NEIGHBORING RAS

The Jim Bridger RAS is tightly integrated with a neighboring RAS system on the Idaho Power transmission system. These two RASs are designed to complement each other with intertripping and coordination, a nontrivial task for any RAS crossing company boundaries.

The Jim Bridger RAS receives two digital inputs (Level 1 and Level 2 trips) from the RAS located at the Idaho Power Midpoint Substation. For Level 1 and Level 2 trips, the Jim Bridger RAS is expected to trip two selectable levels of generation (Level 1 and Level 2). Based on the loss of key facilities in Idaho and pre-fault conditions, the Idaho Power Borah West RAS will send transfer trip signals to the Jim Bridger RAS for the processing and tripping of predetermined generation amounts. Idaho Power can trip up to two units (Level 2) within a 30-minute window; further trips are blocked during this time to prevent Idaho Power from tripping more power than necessary from the PacifiCorp Jim Bridger Power Plant. The transfer trip signals are sent via high-speed, protective relay communications channels. The Jim Bridger RAS also monitors some key facilities in Idaho. Some data required for monitoring these facilities are sent from the Idaho Power Borah West RAS to the Idaho Power EMS system. These data are shared between the Idaho Power and PacifiCorp EMS systems.

VI. RAS DESIGN

The RAS scheme implemented at Jim Bridger dynamically calculates the generation needed to be shed for each of the pre-identified events and then selects generators to shed, based on a generation selection algorithm. The main requirements of the RAS are as follows:

- Available
- Reliable
- Deterministic
- Fast (operation must be less than 20 milliseconds)

The RAS should be available under all circumstances. Having dual primary systems (RAS C and D) satisfies this requirement. The two systems are independent of each other, which gives the flexibility to disable RAS C or D for testing or maintenance and keep at least one RAS available at all times. Having a triple modular system, two-out-of-three voting, and independent communications paths in each RAS greatly increase system availability. The other two concerns are speed and determinism. Once a contingency is detected, the RAS is required to process the inputs, perform two-out-of-three voting, and trigger remedial action in less than 20 milliseconds. It has to be deterministic under all circumstances. Failure of the RAS to respond within 20 milliseconds may lead to blackouts. To make the RAS fast and deterministic, the RAS logic needs to be efficient. The RAS logic has two parts: data acquisition and processing of the RAS algorithm.

A. Data Acquisition

The RAS needs to gather analog and digital information from the field. Both high-speed and low-speed serial lines are used to gather the data. The dual TMR RAS implemented at Jim Bridger is replacing an existing RAS scheme, so a portion of the I/O required for the RAS was already available. Of the remaining I/O, some had to be wired from the field, and some had to be brought in from remote locations.

Not all data need to be fast. Some of the data are needed in detecting contingencies and some to calculate the RAS actions. This leads to the classification of the required data into two categories: high-speed and low-speed data.

1) High-Speed Data

The communication and input voting logic required to detect contingencies (N events) are accomplished in less than 8 milliseconds. The output voting logic, communication, and contact closure required to energize the trip coils are accomplished in less than 9 milliseconds. The total loop time of the system is therefore less than 17 milliseconds. If the detection of a contingency is delayed, the power system may collapse into a blackout. A proprietary communications protocol was used for high-speed data communication. This protocol provides data with deterministic, 2-millisecond updates of digital I/O to the logic processing units.

2) Low-Speed Data

Low-speed data are processed every 200 milliseconds. These data are used in determining the power system state (J states), determining the appropriate arming levels, and calculating the remedial actions for all the predefined contingencies. Data from the EMS system, analog data, breaker statuses, and out-of-service conditions fall under this category. Once the arming levels and actions for each contingency are calculated, they are fed into a crosspoint switch (CPS). The high-speed input data are then cross-multiplied with the CPS to issue digital output signals (trips).

B. RAS Algorithm and Logic Processing

The RAS algorithm is shown in the flow chart in Fig. 4. The following subsections discuss the different sections of the RAS algorithm.

1) Two-out-of-Three Voting

All data inputs, control outputs, and internal data in each RAS go through two-out-of-three voting. Specifically, all input data (slow and fast) are voted, all internal computations are voted (slow and fast), and all outputs are voted (fast).

For example, in RAS C, there are three logic processors that run similar logic. The data are fed to all the processors, and the processors share the data between them. Processor 1 now has three sets of data, and it performs two-out-of-three voting. At least two sets of data need to agree for the data to be considered valid. Fig. 5 shows the two-out-of-three voting logic.

2) N Events

Any event in the power system that may require a RAS action is identified as an N event (contingency). The following

is the digital information (in order of preference) required to identify an N event:

- Line relay trip signals
- Fault severity signals (single-line-to-ground, phase-to-phase severe and nonsevere, and three-phase severe and nonsevere)
- Breaker auxiliary contact status
- Breaker disconnect switch status
- Lockout relay status
- Transfer trip receiver outputs

Not all of the above data are required for every N event. It all depends on what the end user can provide. Trip signals come first, because they are fast. The line loss status is then maintained for the breaker auxiliary contact status. All of the data required to detect N events must be high-speed data.

3) J State

Any event that changes the configuration of the power system is identified as a J state. Most N events become J states in the RAS after a fixed amount of time. For example, a

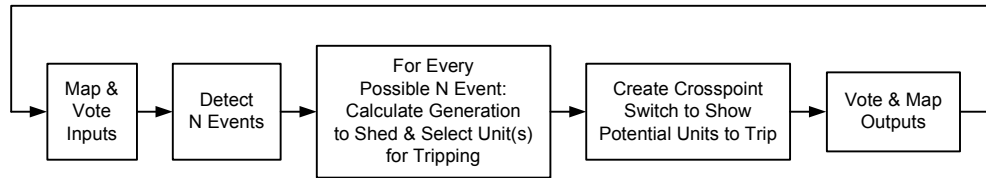


Fig. 4. Basic RAS Algorithm

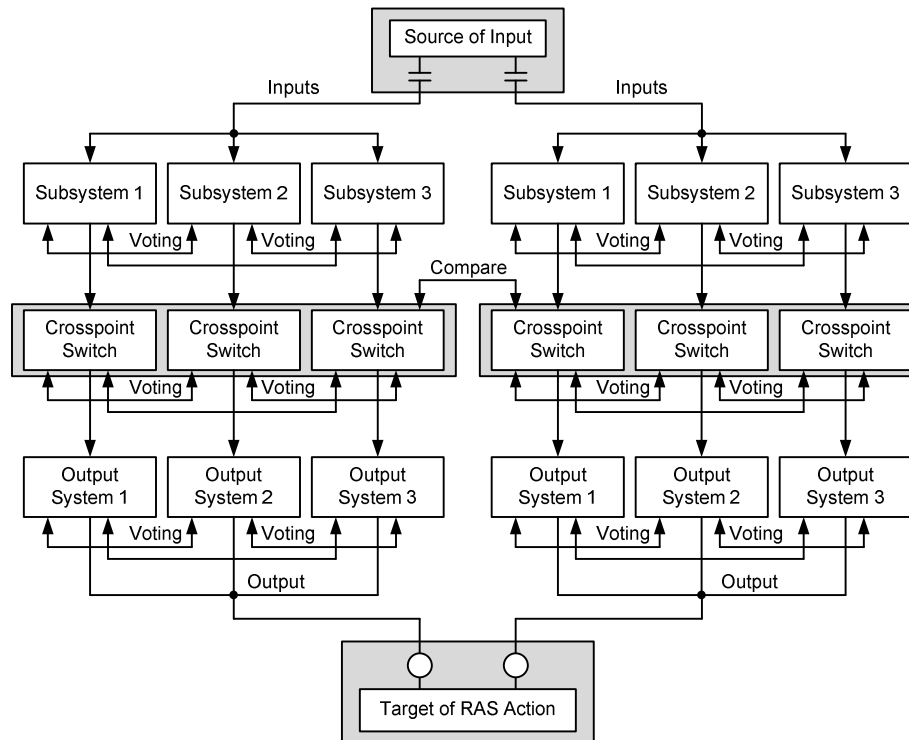


Fig. 5. Two-out-of-Three Voting on All Data

remote phase-to-phase fault on the Jim Bridger – Borah line is an N event. This N event becomes the J state that the Jim Bridger – Borah line is out of service. But J states are not limited to just N events. The outage of each power network element that is critical to the flow of power from the Jim Bridger Power Plant to the west is a J state.

A change of a J state will not require a RAS action but will change the configuration of the power system. Other examples of J states are the outages of synchronous condensers, transformers, shunt capacitors, and transmission lines. J state data do not need to be high speed.

4) *System State*

The combination of J states is called a system state. For example, in an instance when there are two lines open and a capacitor is out of service, three J states are identified in the system. These three states converge to a system state, and this system state determines the limits of the system. In other words, the system state actually mimics the present condition of the power system. The RAS uses the system state to determine which gain constants need to be used in the action-determining calculation.

5) *Arming Level and Generation-to-Shed Calculation*

The RAS uses the arming level equation and calculates up to 64 arming levels every 200 milliseconds. The arming level equation is basically a polynomial equation that uses measured real and reactive power generation (local inputs), compensation level of the 345 kV lines (remote inputs), several path flows (local and remote inputs), and eight gain factors that define system sensitivity. Data are gathered from local and remote systems, and all the J states that are active in the system are identified. The identified J states are mapped to a new system state. This system state identifies which gain factors need to be used in the arming level calculation equation. A total of eight gain factors can be loaded from a lookup table, and there are four lookup tables that represent each season (spring, summer, autumn, winter). These gain factors define the system sensitivity to each component in the arming equation and are developed from system studies.

6) *Generator Selection Algorithm*

The arming level calculation logic calculates an arming level for each contingency. This arming level will be used in the generation-to-shed calculation equation (1) for each contingency, which results in a generation-to-shed value for each contingency. The values will be zero if no generation needs to be shed. For all values greater than zero, the generator selection algorithm will determine which of the four generators needs to be shed. Operators are given preference in selecting units to shed. If no unit is selected by the operators, the algorithm will select the optimum units. At any point of time in one scan, the RAS is allowed to trip only two units. This restriction prevents the RAS from tripping all the units for contingencies detected in one scan.

The following is the generation-to-shed calculation equation:

$$G = K_{nj} \cdot (F_{nj} - AL_{nj}) - X \tag{1}$$

where:

AL_{nj} = calculated arming levels from previous logic.

K_{nj} = coefficient that changes with facility outage and fault type. These are predetermined values that reside in a lookup table. In most cases, the value equals 1.

F_{nj} = either net Jim Bridger generation or net Jim Bridger flow, which depends on the preexisting outage combination j and fault type n . The selection of Jim Bridger generation or Jim Bridger flow is predetermined by system planning.

X = generation dropped by the RAS in the last 5 seconds.

7) *Crosspoint Switch*

The CPS is the final result of the RAS algorithm. The CPS shows the N event and the actions. The results from the generator selection algorithm are used to populate the CPS. The CPS is preloaded and will give operators information on how the RAS is going to respond for each contingency. As soon as an N event is detected, the RAS knows which actions it needs to take and triggers the actions. Fig. 6 shows a typical CPS.

Actions		Ns															
		N ₁	N ₂	N ₃	N ₄	•	•	•	•	•	•	•	•	•	•	N ₆₄	
Trip Gen1	I_1	X			X										X		
Trip Gen2	I_2		X		X									X			
Trip Gen3	I_3							X		X							
Trip Gen4	I_4		X					X									
•		X			X												
•			X										X				
	I_{16}		X					X									

Fig. 6. Crosspoint Switch

8) *RAS Logic Processing*

The logic processing in the RAS controllers is done as multithread processing, which provides flexibility in dividing the tasks into groups, based on how fast they need to be computed. This also makes the RAS algorithm deterministic and prevents time-consuming tasks from delaying the RAS actions. The RAS algorithm is arranged into three schedulers: 1-millisecond, 8-millisecond, and 1-second tasks.

The Jim Bridger RAS has dual primary systems running in parallel. The two systems are independent of each other and come up with their own trip remedial actions. Theoretically, both systems are running the same logic, and if all communications paths are good and the data fed to both systems are the same, the decisions of both systems will

match. However, in foreseeable situations, the decisions made by the RAS Systems C and D may be different due to the following reasons:

- The analogs are fed from different transducers and have measuring discrepancies.
- There can be failed communications paths or equipment that may force a RAS to make a different decision.

VII. SUPERVISION SYSTEM

The analog differences seen in each RAS can cause each RAS to come up with different decisions for a contingency. This is especially dangerous because different decisions increase the chance of shedding more generators than required. To overcome this problem, a supervision system was designed to monitor the crosspoint discrepancies between the systems. In the case of discrepancies, the supervision system will assess the overall quality indicators of the system and decide which RAS should be allowed to operate. The quality indicators are the weighted average of the system communications and hardware alarms. Primary and backup supervision units are designed for redundancy and use different technology hardware, software, and communications protocols to further ensure reliability.

Testing has shown that the RAS systems quite often come up with different decisions, caused primarily by analog transducer scaling discrepancies. This is especially frequent as analogs create arming levels around preset tripping thresholds. Note that direct digital communication to the power measurement devices eliminates many of these problems.

VIII. MULTIPLE N EVENTS AND CLOSELY TIMED EVENTS

There are two special logic timers used in the RAS logic. Any contingency that happens in the power system creates a disturbance. For example, a line is tripped. Due to this line loss, the power is redistributed across different paths, or there are power swings, causing the gathered analog data to fluctuate as the power system settles towards a steady-state condition. During this time, if the gathered analog data are used in the arming level calculation, it may result in poor-quality decisions. To prevent these disturbances from affecting RAS decisions, all generation-to-shed values calculated prior to this event are frozen for a certain period of time, in this case, 5 seconds. At the end of the analog freeze, the N events are transitioned to J states. If a second event happens during this time, the timer is reset, and the 5-second counter starts again.

If the CPSs in RAS C and D are different, the supervision system decides which system is allowed to operate for the next contingency. However, it takes around 12 milliseconds to send the CPS to the supervision unit and receive a decision from it. During the 12 milliseconds after the first contingency, the RASs can have different CPSs, which may lead to different decisions if a second contingency happens in this 12-millisecond window. The closely timed event logic is used to prevent these cases. Once a first contingency (that sheds

generation) happens, a 16-millisecond timer is started. During this timer duration, if a second or additional events happen, all of these events are queued and evaluated at the expiration of the timer. This gives the supervision unit enough time to evaluate the CPSs, make a decision, and prevent the RASs from making different decisions for closely timed events.

IX. FAST RECALCULATE ALGORITHM

If an event happens and a line is tripped, the RAS detects the contingency, verifies the generation-to-shed values, and trips a generator. The 5-second timer starts, and the generation-to-shed values are frozen. If, after some time (e.g., 100 milliseconds), the RAS detects another contingency, it will overtrip if it does not take into account the loss of line and generator tripping that happened during the last scan. This is because the generation-to-shed values are frozen and have not yet updated. They are waiting for the 5-second timer to expire. The fast recalculate code is designed to address these issues.

As soon as a contingency is detected, if the RAS detects another contingency in the next 5 seconds, the fast recalculate code is run, which modifies the generation-to-shed values based on how much generation was shed for the previous contingency. X in (1) serves this purpose. It deletes the generation shed by the RAS in the last 5 seconds, yields fewer generation-to-shed values, and prevents overtripping.

X. GRAPHIC INTERFACES

A. RAS HMI

The RAS HMI runs on a substation-grade computer. Although it is designed to run continuously, it is not necessary for the RAS to operate. The HMI is only necessary for changing the settings used for the RAS computations. These settings are stored in nonvolatile memory in the individual RAS controllers, making the RAS operations independent of the HMI.

The RAS HMI station serves as the user interface to all RAS controllers and subsystems. The functionality includes:

- Status display of live power system data on a summarized one-line screen.
- Status display for every system input and output, including data shared through the EMS system.
- Ability to change and view adjustable settings and gains loaded in the RAS controllers.
- Real-time view of the CPS matrix that shows the action to be taken for every contingency.
- Communications and alarm screens that reflect current device and communications alarms.
- Sequence of events (SOE) gathering, archiving, and viewing.
- Historical alarm and event viewing. The event files can be played back to the RAS through the test simulator.

The HMI collects data from all six RAS controllers and the four EMS interfaces. Screens exist to view the data individually for verification that they agree and to view the one-line screen that reflects the system status as determined by the

two-out-of-three voting logic. The data set for the one-line screen is picked by the same algorithm that is present in the supervision logic. The one-line and I/O screens are critical for factory acceptance testing, site acceptance testing, and commissioning purposes, because they provide visual verification of what occurs during each test.

Due to the immense amount of data required to fill the system adjustable gains, a database file was created to hold these large matrices. There are eight matrices that are of the dimensions 64 x 1,000 x 4 (256,000 gains) and several other matrices of smaller sizes. When edits are made to any one of the 256,000 gains, the controllers detect that new settings are available and issue a signal that the loaded settings are old. At this point, the database file is compacted into several binary files; these files are then transferred to the RAS controllers at the operator's request. These binary files are stored in non-volatile memory on the RAS controllers and are viewable in tables through the HMI.

Each RAS controller creates SOE logs, event report logs (oscillography), and OPC (Object Linking and Embedding [OLE] for Process Control) alarm tags. There are two main ways to view alarms on the HMI: through the communications and alarm screens (OPC point) and through the SERviewer Software (SOE logs). The communications and alarm screens show the active state of major device, communications, and diagnostic alarms. If an alarm clears but was not acknowledged, there is still an indication that the alarm was not viewed by an operator. The SERviewer shows all alarm points time-stamped as to when any changes occurred. All data in the SERviewer are time-stamped with 1-millisecond accurate resolution.

Event reports are in a flat file format, similar to COMTRADE format. Event report viewing on the HMI is performed using special software that displays all digital and analog information before and after each event. The event report logs contain the status of every I/O point in the RAS, sampled at 2-millisecond intervals. The event report logs contain data for 2 seconds prior to each event and 4 seconds after every event. This allows for easy diagnostic evaluation of what occurred during the event. Also, the event file can be replayed to the RAS from the test simulator.

B. Simulator HMI

The simulator HMI has two modes of operation: operator controlled and file playback. The operator-controlled mode allows the user to interactively change any digital or analog system input from the default value. The user can then trigger a contingency and observe the results on the RAS connected to the simulator. File playback allows user-generated files or actual event reports from the RAS to be fully simulated. This allows the RAS gains to be easily adjusted for desired operation.

Additionally, the simulator has controls for biasing the analog values to test the voting logic. Discrepancies between the redundant analog inputs are the most likely source of differing inputs to the RAS, due to the maintenance required on transducers to keep them calibrated. The controls to bias

the inputs allow for skewing the analog inputs to each RAS subsystem. Running tests this way verifies that two out of three systems agree before an action is taken. Controls are also present to skew the analog signals between RAS C and D for verifying the supervision logic when testing both RAS systems.

C. Event and System Diagnostics

The RAS has complete diagnostic capability that automatically pinpoints any faults or errors within the system (hardware and software) to a failure location within a hardware device or a software module. Every N event, input, and output occurring in the RAS system is also tracked by these tools. All SOEs and event reports are saved as flat *.csv files and saved in nonvolatile, flash-type memory on the substation-hardened computers.

There are three types of diagnostic tools for these purposes:

- HMI displays. This is generally the first place to look. The HMI describes failures pictorially by color changes on the HMI screen. This provides a high-level view of the system. These data are provided through an OPC data link out of each controller.
- SOE logging and viewing. SOEs from both systems are simultaneously logged. These events are viewable with the SERviewer and are time-tagged at 1-millisecond accuracy. Alarms are given descriptions detailed enough to specify the faulted device or software module.
- Oscillography logging and viewing. These oscillography reports (event report logs) capture the system conditions monitored by the controllers. The reports are generated on the controllers and passed to the computers for long-term storage and viewing. These oscillography files have an identical structure to the event reports created by all of the protective relays used for fault discrimination in the RAS. For this reason, these log files are called event reports.

D. Sequence of Events Logger

The SOE logger contains raw, digital I/O, internal digital values of great interest in the controller, and all system alarms (e.g., data disparities, equipment failures). The SOE logger is responsible for detecting, identifying, and making available to file the SOEs of selected, critical variables. The main features of the logger include:

- Monitoring of up to 512 digital variables.
- Detection of up to 4,000 events per minute on a continuative basis with no data loss.
- Detection of up to 2,000 events over 160 milliseconds (simulation of a fault with clearance time of proximally 10 cycles) with no data loss.
- Visualization of the SOE file with the SERviewer or any text reader.
- Multiple SOE file creation when the end of the file is reached or problems are encountered during the writing process.
- Minimal CPU consumption.

E. Oscillography

Any N event contingency will cause an event report to be gathered. The event report records all control outputs, all digital inputs, all analog inputs (in engineering units), all data provided through the SCADA interface, the contents of the CPS, the J states, the current state, the arming levels, and the generation to shed. Some of the main features of the event report logger include:

- The event report library has the capability to store 320 Boolean values (10 DWORDS) and 64 analog (REAL) values.
- Each analog and Boolean quantity has a textual name associated with it. This name is saved in the event report file (*.csv). The analog and Boolean variable names are each limited to 15 characters.
- Each event stores up to 6 seconds of data. The 6-second time is a combination of the pre-event and post-event length.
- The CPU usage is minimal.
- The event report library is designed to log data every 2 milliseconds.
- The event report library has the capability to store at least five event reports triggered in a 2-millisecond time gap.
- The file written to the storage location is readable with off-the-shelf COMTRADE-viewing software.
- There is no limit to the number of files that can be stored on the substation computer. The limit is purely the maximum free space left on the compact flash.

XI. TESTING

A. Test Simulator

The test simulator was designed to play back power system events into one of the redundant RASs (C or D). Through a pair of interconnection panels and software interlocks, the test simulator can be isolated and connected to either RAS C or D. Because of the sensitivity of the RAS system to changes in gain files used in the RAS algorithm, it is necessary to test modifications in a fully functional, triple redundant system prior to applying them to a live system. The hardware and software designs implemented within the Jim Bridger RAS satisfy this requirement.

A playback simulator is used to easily simulate system conditions and events. This allows the creation of text files that contain analog and digital data reflecting specific scenarios to be sent to the RAS system. The files are sent through an algorithm that separates each value in time, thereby properly compensating for the communications delays of the various test simulator components. Several hundred playback files are then queued up for automatic playback, one after another. In this fashion, engineers can observe the reaction of the RAS algorithm to hundreds of different scenarios in a few hours.

The test simulator uses hard-wired analog and digital signals to communicate to the RAS. The test simulator also communicates to the RAS with serial links, emulating the

EMS DNP3 interface. All RAS and test signals are sent through an interconnect panel, which allows for easy insertion of the test simulator signals into the RAS. By using test paddles and isolation test blocks, the signals from the live power system are disconnected from the RAS while simultaneously inserting the test signals.

Once a contingency occurs, the RAS system records each event for a period of 2 seconds before and after the event, for a total of 4 seconds. By doing this, the RAS can capture key information within the event and place that data within a .cev file. This file is then sent to the main HMI, where it can be transferred back to the test simulator for playback. The file structure is exactly the same as those created by PacifiCorp engineers, as described earlier. In this way, each event recorded on the power system can quickly be played back into the RAS and observed with no interruption to the performance of the RAS. This allows PacifiCorp to quickly evaluate the control system response with new settings for all known and recorded events.

B. Project Execution

A primary design objective of the RAS was to allow future modifications to occur with little interruption to the performance of the RAS. The hardware design allows for interconnect panels so either RAS C or D can be disconnected from the live power system and reconnected to a series of simulated signals. This not only allows for quick changes to occur within the RAS but also for expansion and other maintenance corrections without taking the entire system out of service. With one of the two systems connected to the test simulator, there is still a triple redundant RAS operating normally.

The test simulator and dual RAS design proved very valuable during the validation phase of the project. Engineers were able to interact with both systems and observe all levels of performance within the RAS systems.

It was discovered during the design phase that a close working cooperation between PacifiCorp and the supplier's engineers was critical. Instant feedback for the specific requirements and performance of the RAS system proved to be valuable. It is important for the PacifiCorp engineers to have a full understanding of the algorithms and logic within the RAS. This understanding allows for timely analysis of events once the system is fully operable. Their understanding of the power system provided critical information that modified the design of the control system algorithms. It became possible to incorporate very specialized solutions to past problems with the existing system. It was necessary for PacifiCorp and the supplier's engineers to spend no less than two months working in close cooperation at one location during final software implementation of the RAS.

C. Quality Control

Several forms of testing were involved in maintaining a high level of quality and ensuring that the integrity of the complete RAS control system was upheld throughout the RAS development and implementation. Unit testing was completed within the software, hardware, and communications designs. This involved isolated testing to detect failures prior to

integrating the components into the system. Using a peer review process to fully inspect each other's designs allowed each component to assimilate into a compatible scheme.

A series of internal validation tests were then completed to ensure the integrity of the system as a whole. This involved pushing the system past the ordinary limits described by initial specifications and was effective at capturing potential failures that were unforeseen at the component level. This testing was immediately followed by external validation in the form of factory acceptance testing prior to delivery. This process was repeated several times throughout the project as problems and solutions were discovered.

D. Timing Results

The throughput time of the RAS system is less than 17 milliseconds; this is the measured total time from an input voltage asserting to 90 percent of full voltage to an output point fully conducting. This includes the time required to accomplish both I/O voting schemes. All output contacts are rated for tripping; therefore, interposing relays were not used. All contact outputs used are a high-speed, high-current interrupting design; this design closes an output in less than 10 microseconds and can interrupt up to a 30 A inductive current.

XII. COMMISSIONING

The process of commissioning a system of this magnitude is highly critical and involved many groups within PacifiCorp, including protection engineering, field service technicians, planning, operations, dispatch, communications, and technicians. Because of this dynamic, it was key to have a primary individual or small group of individuals responsible for the coordination of each independent group's efforts.

Once the system was delivered to the substation, the immediate task was to coordinate efforts from each group to allow the system to be integrated in parallel with the existing system. This had to be accomplished without interruption to the existing system.

A checklist was created prior to commissioning that systematically checks each input and output of the RAS. This ensures that each individual component is operable. Once this is completed, the previous functionality from the factory acceptance test will be preserved.

A one-time site acceptance test involving the test simulator connected to both RAS C and D was performed in order to again prove the functionality of the entire system. Because the system was designed with the test simulator flexibility discussed earlier, this was possible.

Careful steps were taken to avoid unnecessary generation shedding at Jim Bridger. Each and every item within the checklist contained a specific method for testing and was described within the commissioning documentation. By doing this, everyone involved could gain an understanding of the reasoning behind the process. Upon completion of the checklists, all parties signed their approval.

Communication between the RAS and the PacifiCorp EMS is another critical piece. Information regarding system alarms and history is provided to the EMS through four SCADA machines, and likewise, data from the EMS are passed to each of the four SCADA components. Commissioning these systems depends on first establishing reliable communications circuits between the source and destination of each circuit. It also relies heavily on any DNP3 protocol conversion and settings involved in the communication. There was a very high dependence on having a constant working relationship between the engineers and technicians out in the field and those involved with the DNP3 master.

XIII. IN-SERVICE PERFORMANCE

At the time of writing this paper, the Jim Bridger RAS was undergoing final site commissioning. Presenters will share their experiences on system performance during the presentation of this paper.

XIV. BIOGRAPHIES

Dean Miller is a principal engineer in Protection & Control Engineering at PacifiCorp and an adjunct professor at Portland State University, teaching a course on power system relaying. He received his Bachelors degree in Electrical Engineering from the University of Idaho. During his 36 years at PacifiCorp, Dean has held a variety of positions in the engineering and operations organizations. He holds a patent in the area of distribution automation. Dean is a senior member of IEEE, an active member of the Power System Relaying Committee of IEEE, and a registered professional engineer in the State of Oregon.

Robert Schloss is an automation engineer for the Engineering Services Division of Schweitzer Engineering Laboratories, Inc. (SEL). Robert received his Bachelor of Science degree in Electrical Engineering from the University of Idaho and has been with SEL since 2004. He has experience in power system automation, specifically with remedial action schemes, load shedding, voltage control, and generation control.

Scott Manson is a supervising engineer for the Engineering Services Division of Schweitzer Engineering Laboratories, Inc. (SEL). He received a Masters in Electrical Engineering from the University of Wisconsin-Madison and his Bachelors in Electrical Engineering from Washington State University. Scott worked at 3M Corporation as a control system engineer for six years prior to joining SEL in 2002. Scott has experience in designing and implementing control systems for electrical utility customers, high-speed web lines, multi-axis motion control systems, and precision machine tools. Scott is a registered professional engineer in Washington, Alaska, North Dakota, and Louisiana.

Sai Raghupathula is an automation engineer for the Engineering Services Division of Schweitzer Engineering Laboratories, Inc. (SEL). He received a Masters degree in Electrical Engineering from the University of Idaho. Sai has been employed with SEL since 2004 and has experience in designing and implementing control systems for utility and industrial customers.

Trent Maier is an automation engineer for the Engineering Services Division of Schweitzer Engineering Laboratories, Inc. (SEL). Trent received his Bachelor of Science degree from Michigan State University and spent five years within the automotive industry prior to joining SEL in 2007. He has experience in control system design and application within power systems, conveyor systems, and robotics.