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***Abstract*—Adding generation assets to the power grid can create challenges for existing generation-dropping remedial action schemes (RASs) if the transmission capacity remains the same. An update to the control scheme is required to maintain the stability and reliability of the power system in the event of a contingency.**

Eastern Wyoming, with its abundant wind generation capabilities, has seen significant growth in wind farm operations, which are interconnecting with the eastern Wyoming transmission system. To transmit the power from these wind farms in addition to the existing power generation, new transmission from eastern Wyoming is being connected to the Jim Bridger Power Plant through a new 500 kV line. The power transmitted to the west of the Jim Bridger plant now includes the power produced from these wind farms along with the Jim Bridger generation, but the total path flow to the west of the plant is kept the same as before. With these additions, it is necessary to update the control algorithm that integrates the wind farms with the Jim Bridger RAS.

In this paper, we discuss the updates to the generation-dropping Jim Bridger RAS algorithm to integrate the additional wind generation assets with existing coal-fired generation. The updates to the RAS algorithm include monitoring the new 500 kV line and wind generation assets and using new criteria for selecting a combination of thermal and wind generation for tripping and new unit-selection logic. The updated RAS algorithm was tested using a test simulator system with actual RAS controllers and a simulator running test cases in playback fashion and providing the data to controllers. Test cases covered several system conditions involving various combinations of thermal and wind generation values. Using simulation and analysis, we show that tripping a combination of coal-fired and wind generation for transmission line contingencies helps to maintain system stability.

I. Introduction

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. 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 corridor 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 Jim Bridger RAS maintains the stability of the power system by shedding appropriate generation in the Jim Bridger plant for the loss of the lines in the transmission corridor and balancing the generation to the load. The complete loss of the RAS for any reason requires that the Jim Bridger Power Plant output to be reduced to 1,300 MW.

II. The Existing RAS System

The existing RAS for PacifiCorp's Jim Bridger Power Plant went into service in 2009 with an algorithm designed to trip excess generation in the case of a fault on the interconnecting lines going west [1]. This RAS allows operators to push more power through the transmission infrastructure by taking actions within the subcycle operating time to protect against disturbances. All actions initiated by the RAS scheme are preplanned based on studies of several predefined system operating conditions. Based on the current system outages, specific scaling factors are applied to arming level calculations for each credible fault type and location [2] [3]. The Jim Bridger RAS system quickly sheds generation to stabilize the plant and the transmission system. The existing RAS system is a dual triple modular redundant (TMR) scheme, and it has two RAS systems, RAS C & RAS D, with three controllers and three I/O modules in each of them. The system also has two redundant supervisory controllers to monitor the RAS controllers, so the actions taken by the RAS systems are consistent.

III. PacifiCorp's Eastern Wyoming Transmission System Changes

Eastern Wyoming, with its abundant wind generation capabilities, has existing and planned wind farms which are going to get connected to PacifiCorp's eastern Wyoming transmission system. Specifically, new wind farms at Windstar, Shirley Basin, and Aeolus are getting connected and integrated into PacifiCorp's eastern Wyoming transmission network. Three 230 kV transmission lines connect eastern Wyoming to the Jim Bridger substation through Point of Rocks and Mustang and 230/345 kV transformers at Jim Bridger, but the transmission lines do not have enough capacity to transfer all the power from the wind farms. Hence, a new 500 kV transmission line was constructed from Aeolus to the Anticline substation and then connected to the Jim Bridger substation through a 345 kV line. Fig. 1 shows the map of PacifiCorp's transmission system as described in this section. The power transmitted to the west of Jim Bridger now includes the power produced from the wind farms in eastern Wyoming, but the total transmission capacity to the west of the plant remains the same.

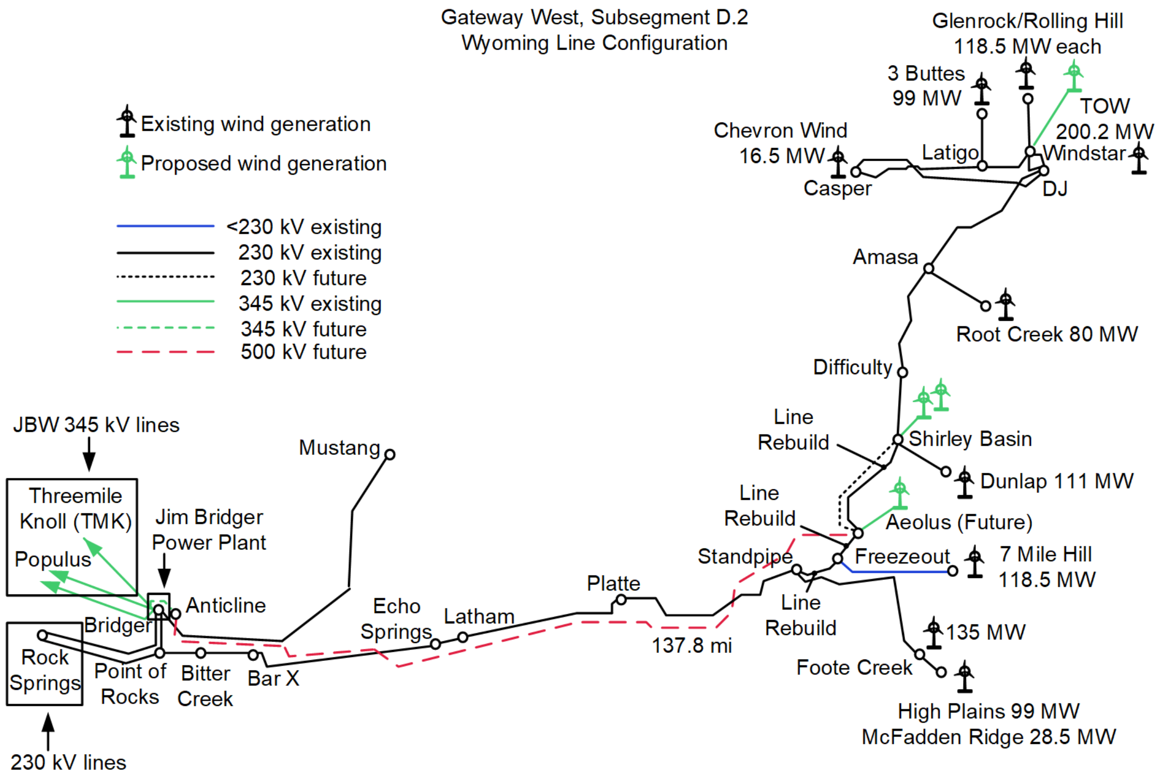

Fig. 1. Map of transmission system.

IV. Wind Generation Challenges to the Existing RAS

The primary function of the Jim Bridger RAS is to initiate fast remedial actions while minimizing generator tripping in response to power system disturbances, thereby maximizing power transfers and ensuring power system stability. The amount of generation to be dropped is calculated based on system configuration, fault type, and severity of the fault. The unit to be dropped is selected by the Jim Bridger RAS control system. With the wind generation coming available through the energization of the new 500 kV line from Aeolus to Anticline, there are several possible combinations of wind generation and Jim Bridger generation that could lead to heavy flows on the path to the west of Jim Bridger. Therefore, the Jim Bridger RAS logic was modified to integrate the newly installed wind generation as part of the transmission system upgrade. The Jim Bridger RAS algorithm has been modified to include tripping of the new wind generation in Wyoming to achieve the appropriate amount of tripping for each line outage contingency.

The transmission path rating to the west of Jim Bridger is being maintained at 2,400 MW so there are no physical transmission system changes and no additional J-states and N-states [1] are being added, but the generation selected for tripping must now include both Jim Bridger and wind generation units. The flows on the Anticline–Bridger 345 kV line, in combination with the three 345/230 kV transformers, are considered as a fifth Jim Bridger unit in the Jim Bridger RAS algorithms to calculate the appropriate trip amount to maintain reliability. Wind generation is located far away from Jim Bridger, which presented a dilemma about how to account for its effectiveness in tripping, so a parameter named effectiveness factor (Ef) was identified. The Ef factor is an empirical value based on studies used by operators to determine the equivalent amount of wind generation tripping for the RAS scheme; this factor can be provided by operators through supervisory control and data acquisition (SCADA) to give operational flexibility. The existing Jim Bridger bus configuration changed from four bays to five bays, which added another change in selecting the Jim Bridger units to trip to avoid a bus split condition. Fig. 2 shows the system overview with new wind generation along with the rest of the system under RAS control.

V. RAS System Design Updates

A. Remote Substation Devices

The critical system facilities that are monitored to support the new wind generation resources in Wyoming are:

- Aeolus 500/230 kV substation switch statuses and analog values.
- Anticline 500/345 kV substation.
- Aeolus–Anticline 500 kV new line.
- Anticline–Bridger 345 kV new line.
- Shirley Basin substation switch statuses and analog values.
- Foote Creek substation switch statuses and analog values for High Plains wind generation.

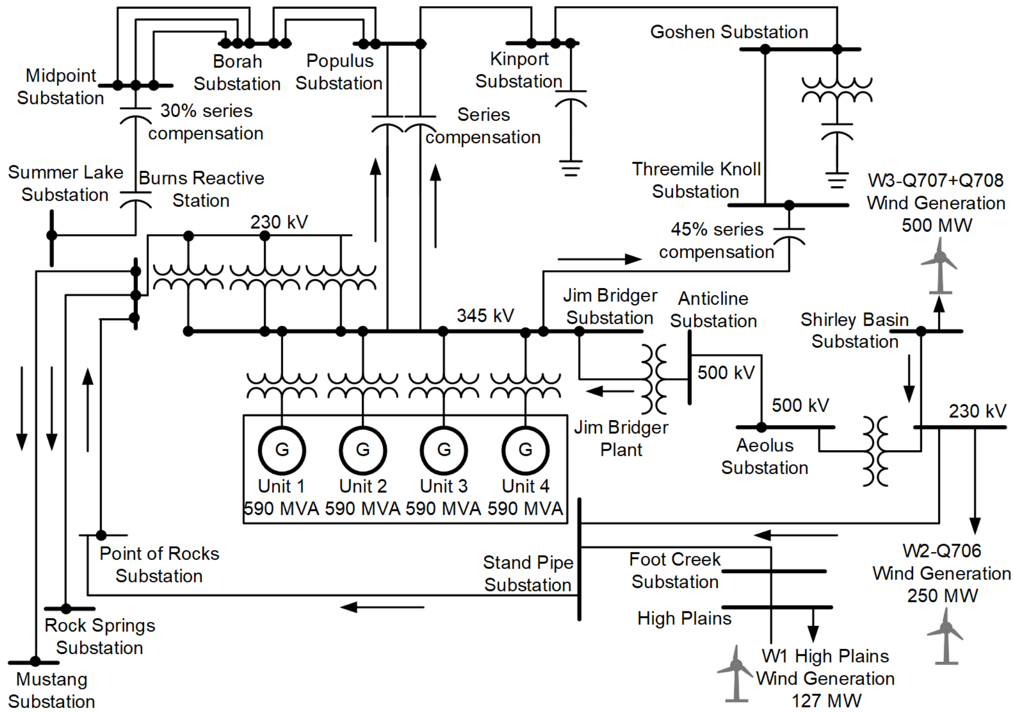

Fig. 2. System overview.

Input/output (I/O) devices are installed at the new substations to collect digital and analog data and send them to the RAS system through the existing front-end processor (FEP) in the Jim Bridger substation. Digital data are sent through high-speed channels and analog data through slow-speed channels; this segregation has been proven to yield good performance on both large-scale and small-scale RAS schemes [4] [5] [6] [7]. Digital data include breaker status and switch status, which are used to determine the wind generation connection to the substation and the 500 kV line status. Analog data include real and reactive power from the wind generation sources, real and reactive power flowing through the new 500 kV line, and power flowing through the three 230/345 kV transformers in the Jim Bridger substation. After the upgrade, the trip signals to the wind generation units are sent through a high-speed channel from the RAS system to the remote devices in the Aeolus, Shirley Basin, and Foote Creek substations where the wind generation units that the RAS trips are connected.

B. *Arming Level Calculation*

The RAS uses the arming level equation and calculates up to 64 arming levels every 200 milliseconds. The arming level equation is a polynomial equation (1) 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 [1]. 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). The gain factors (Kai_{nj}, Kc_{nj}, $KaConst_{nj}$) in (1) define the system sensitivity to each component in the arming equation and are developed from system studies.

$$AL_{nj} = \sum\left[Kai_{nj} \cdot \left(G_i - Rf_i\right)\right] + Kc_{nj} \cdot \left(\frac{Comp_{rem}}{135}\right) + KaConst_{nj} \quad (1)$$

where:

G_i is the various path flows of Jim Bridger real power and reactive power in the system.

Rf_i is the constant established in the gain files for Kai_{nj}.

Kai_{nj} is the sensitivity coefficient for each G_i.

Kc_{nj} is the coefficient that represents the relative sensitivity to the remaining series compensation level on the Jim Bridger lines following a Jim Bridger line outage.

$Comp_{rem}$ is the series compensation remaining after a line loss.

$KaConst_{nj}$ is a base coefficient.

The nj subscript indicates that there is a separate value of each possible combination of N-states and J-states. Each pre-existing facility outage is given a unique J-state number. Combinations of single J-states are given unique system-state numbers. Any combination of J-states forms a system state, i.e., system states are formed from J-state conditions within the system. Each fault event that is detected as a contingency by RAS is assigned a unique N-state.

The changes to the arming level calculation due to the additional wind generation are reflected in real power generation, as shown in (2) and Fig. 3.

$$\text{Gen} = \text{JBGen} + \text{Xt} \quad (2)$$

where:

JBGen is the measured Jim Bridger real power generation.

X is the MW of the Anticline–Bridger line plus the MW of the Bridger 345/230 kV transformers.

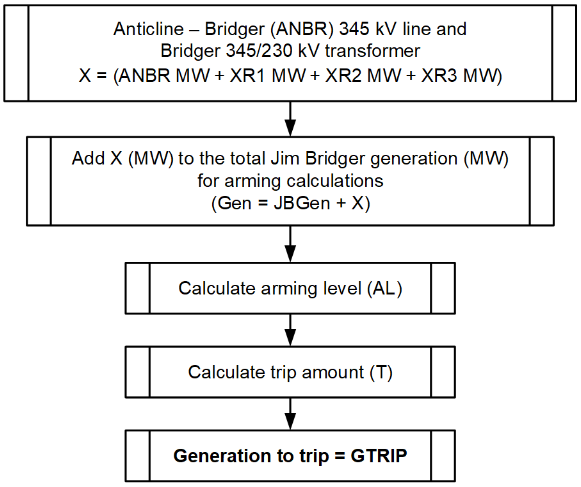

Fig. 3. Arming level and generation to shed calculation flow chart.

C. Generation-to-Shed Calculation

The arming level calculation logic calculates an arming level for each contingency. This arming level is used in the generation-to-shed calculation (3) for each contingency, which results in a generation-to-shed value for each contingency. The values are zero if no generation needs to be shed. For all values greater than zero, the generator selection algorithm determines which of the four generators in Jim Bridger and which of the three wind generation units needs to be shed. Operators are given the choice of selecting units to shed for Jim Bridger unit selections. If no unit is selected by the operators in the Jim Bridger plant, the algorithm selects the optimum units considering both Jim Bridger units and wind generation units. At any point of time in one scan, the RAS is allowed to trip only two Jim Bridger units and not more than a certain amount of wind generation. The limit on the wind generation is determined by system planning. This restriction prevents the RAS from tripping all the units for contingencies detected in one scan.

$$G = \text{Knj} * (\text{Fnj} - \text{ALnj}) - X \quad (3)$$

where:

Fnj is the net Jim Bridger west flow.

ALnj is the calculated arming levels.

Knj is the 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 one.

X is the generation dropped by the RAS in last five seconds.

D. Integrating Wind Generation to the Jim Bridger RAS

The flows coming on to the Jim Bridger 345 kV bus from the Aeolus–Anticline 500 kV line and the Jim Bridger 345/230 kV autotransformers are added to the Jim Bridger plant generation to accurately determine the arming level and generation-to-shed calculations as shown in Fig. 3.

Power values, along with the breaker status of the generator tie lines from the eastern Wyoming wind generation, are used to determine the different combinations of the wind generation units that can be tripped as shown in Fig. 4. The wind generation that is subject to tripping as part of the RAS logic includes the following:

- Ekola Flats (Pmax = 250 MW) interconnecting to the Aeolus 230 kV substation
- TB Flats (Pmax = 500 MW) interconnecting to the Shirley Basin 230 kV substation
- High Plains (Pmax = 127 MW) interconnecting to Foote Creek 230 kV substation

The new RAS logic uses the different combinations of the three wind farms that can be tripped. The criterion is that the wind generator tripping combinations should not exceed Wmax (627 MW).

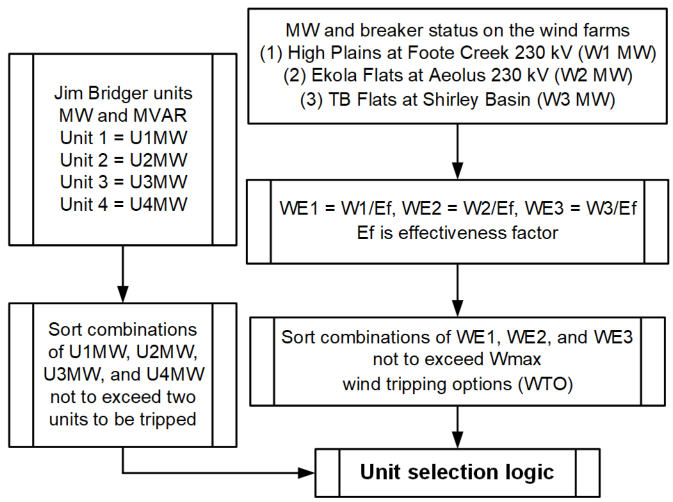

Fig. 4. Inputs to unit selection logic.

If the Anticline–Bridger 345 kV or Anticline–Aeolus 500 kV line is out of service, only Jim Bridger units are used to satisfy any trip call and tripping of wind generation is not required under Jim Bridger outage conditions. A specific path availability logic has been programmed into the RAS controllers to determine the 500 kV line status and the path availability of wind generation in each specific remote substation.

When tripping wind generation units, to achieve similar reliability performance compared to Jim Bridger generation, an effectiveness factor (Ef) has been applied to the wind generation. This factor is based on studies developed to determine how much wind generation needs to be tripped to have the same impact as tripping Jim Bridger generation. This is a user-provided input from the system operators to the RAS depending on the system conditions.

Table I describes the wind generation units and the effectiveness factor when applied to them. Table II shows the various Wind tripping options (WTO) available for the RAS based on the different combination of wind generation units.

TABLE I
WIND GENERATOR SELECTIVITY

Generator	Wind Farm	Effective Wind Power (WEx = Pmax/Ef)
W1	High Plains	WE1 = W1Pmax/Ef
W2	Ekola Flats	WE2 = W2Pmax/Ef
W3	TB Flats	WE3 = W3Pmax/Ef

TABLE II
WIND GENERATOR COMBINATION

WTO	Wind Generator Combination
WTO 1	WE1 = High Plains (W1Pmax/Ef)
WTO 2	WE2 = Ekola Flats (W2Pmax/Ef)
WTO 3	WE3 = TB Flats (W3Pmax/Ef)
WTO 4	WE1 + WE2 = High Plains + Ekola Flats (W1Pmax/Ef + W2Pmax/Ef)
WTO 5	WE1 + WE3 = High Plains + TB Flats (W1Pmax/Ef + W3Pmax/Ef)
WTO 6	WE2 + WE3 = Ekola Flats + TB Flats (W2Pmax/Ef + W3Pmax/Ef)
WTO 7	WE1 + WE2 + WE3 = High Plains + Ekola Flats + TB Flats (W1Pmax/Ef + W2Pmax/Ef + W3Pmax/Ef)

Any of the combinations of wind tripping options that are available to meet the trip call and are less than Wmax are considered in the unit selection logic. Wmax is the total maximum wind generation that can be tripped.

E. Human-Machine Interface (HMI) Screen Updates

RAS HMI screens were updated to show the 500 kV Aeolus–Anticline line, wind generation connected to the remote substations, and all the breaker and switch statuses associated with them. Separate screens showing the analog and digital data from each remote substation were added to the HMI. Communication points with energy management system (EMS)/SCADA were also updated to reflect the Aeolus substation, the Shirley Basin substation, and Foote Creek substation breaker and switch connection status. The HMI software was also upgraded to its latest version, which is compatible with new Microsoft Windows software, to keep the system operating on the latest software and operating system versions.

F. Simulator System Updates

The test simulator system for the RAS system simulates all the external inputs, both hardwired and communications-based signals. The simulator has an HMI screen that can initialize the system and run tests. The simulator can operate in both static and playback modes. The inputs related to the wind generation units, the new 500 kV line, and the wind units' connections to remote substations were added to the existing simulator system. The playback file structure was also modified to include the new inputs and system conditions. New test files were created by planners and the operation team for testing and validating the RAS system logic for integrating the wind generation units. The existing old test case files were modified to fit into the new file structure, so the playback feature can be used to simulate both existing test scenarios and new test scenarios. Both the simulator system logic and the simulator HMI were modified to reflect the new system changes.

VI. SIMULATION RESULTS

A study was conducted to find how a combination of wind and thermal generation tripping for line outages (contingencies) helps to maintain system stability. Critical clearing times for 345 kV line loss contingencies with and without the Jim Bridger RAS are analyzed. Further, the equivalent amount of wind generation which must be tripped in relative to the Jim Bridger generation is discussed.

A. Clearing Time Without the Jim Bridger RAS

Simulations were performed to determine the critical clearing time for the 3-ph faults near Jim Bridger and other critical contingencies. The critical contingencies selected are one 345 kV line loss (F1 in Fig. 5) and two 345 kV line loss (F1F2 in Fig. 5). The 345 kV line loss contingencies due to faults in the transmission corridor, limits the power transfer through them and hence generator-dropping due to RAS and its effectiveness are studied.

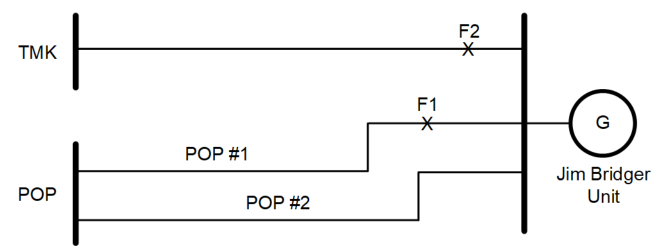

Fig. 5. Contingencies on Jim Bridger lines.

The following are the study results for clearing times without the RAS:

- For a three-phase fault at Jim Bridger for the loss of the Bridger–Populus 345 kV line
  - At low values of JB Generation (less than 50% with 4 units online), the critical fault clearing time is 6 cycles.
  - At high values of JB generation (greater than 90% with 4 units online), the critical fault clearing time is 4 cycles.
- For N–2 fault conditions (JB_POP12 or JBPOP_TMK), loss of two of the three 345 kV lines west of Jim Bridger
  - Irrespective of JB generation levels, the voltage profile is lot worse for clearing times of more than 4 cycles and without the Jim Bridger RAS the system does not meet Western Electrical Coordinating Council (WECC) requirements.
  - Further, the voltage at the Threemile Knoll side is much worse without the RAS system.

B. Clearing Time With the Jim Bridger RAS

The outages were also simulated with the Jim Bridger RAS in service. Using the arming level and the generation tripping level calculations, the generation that would be tripped was calculated. For cases with low Jim Bridger generation, a combination of both the Jim Bridger units (maximum of two out of four) and the new wind farms were tripped at different tripping times to evaluate the critical clearing time. Different times for tripping the generation were simulated, and the results did not show a significant difference in performance. There is not a significant difference in voltage performance when the Jim Bridger generation is lower.

However, the voltage performance is different when the Jim Bridger generation is high and wind generation that is loading the Jim Bridger west transmission path is low. The study demonstrated that the clearing time for a fault is as equally critical as the tripping of Jim Bridger units. Combinations of simulations with different tripping times and different clearing times were conducted to understand the timing requirements. The study demonstrated that irrespective of the Jim Bridger generation, it is necessary to trip Jim Bridger generation faster than wind generation. The study showed that Jim Bridger generation has to be tripped within 5 cycles of the fault inception in order to maintain stability of the system for some of the critical outages between Jim Bridger and Populus. The study also demonstrated that if the Jim Bridger units are tripped within 5 cycles of fault inception and the wind generation in eastern Wyoming at the latest by 8 cycles, the system stability is maintained for the N–2 outages west of Jim Bridger.

Fig. 6 and Fig. 7 show the voltages at the Jim Bridger 345 kV bus and Threemile Knoll 345 kV buses of the N–2 outages for the 345 kV lines west of Jim Bridger with the Bridger RAS tripping the Jim Bridger units at 5 cycles and the wind farm at 8 cycles. Both of the simulated N–2 outages met performance.

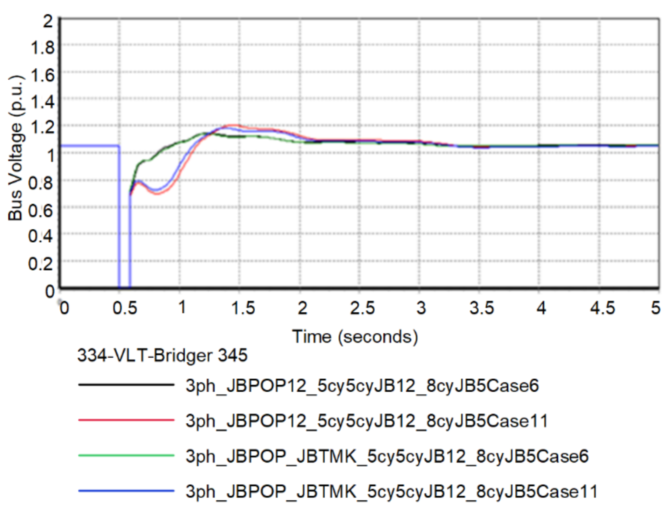

Fig. 6. Bridger 345 kV Voltage for N–2 outage of 345 kV lines west of Jim Bridger.

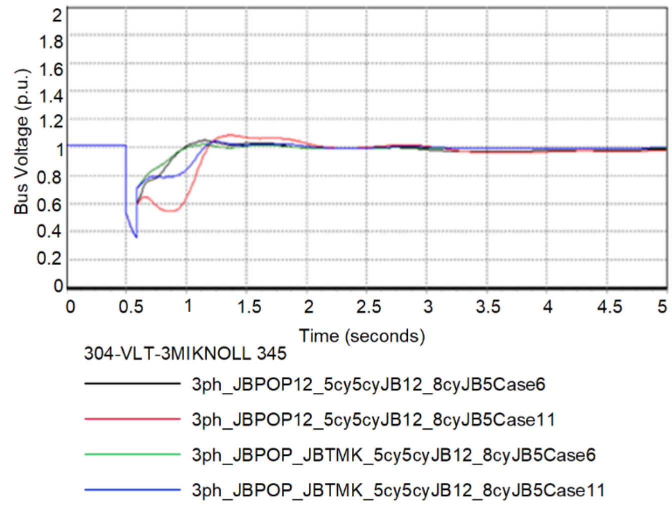

Fig. 7. Threemile Knoll 345 kV voltage for N–2 outage or 345 kV lines west of Jim Bridger.

The study also demonstrated that for close-in three-phase faults, the Jim Bridger units need to be tripped within 5 cycles and the wind generation in 8 cycles in order to maintain reliability of the system.

C. *Jim Bridger Generation vs Wind Generation Tripping (Effectiveness Factor)*

Electrically, the wind generation in eastern Wyoming is farther away than the Jim Bridger generators. Hence, the impact of tripping 1 MW of Jim Bridger generation is not the same as tripping 1 MW of wind generation in eastern Wyoming. The effectiveness factor ratio was calculated to determine how much wind generation needs to be tripped in order to have the same impact as tripping Jim Bridger generation.

Both power flow and transient stability analyses were performed to determine the effectiveness factor for the eastern Wyoming wind generation. For the case with lower Jim Bridger generation and high wind generation transfers, the RAS needs to trip 498 MW for a severe three-phase fault at Jim Bridger, losing any one of the 345 kV lines west of Jim Bridger.

This tripping can be achieved either by tripping Jim Bridger units or tripping an appropriate portion of wind generation that yields similar results. Different levels of wind generation tripping were simulated to determine how much more wind needed to be tripped instead of Jim Bridger generation.

Fig. 8 illustrates the comparison of the voltage performance at the Jim Bridger 345 kV bus and Threemile Knoll 345 kV bus for a three-phase fault at Jim Bridger resulting in loss of the Jim Bridger–Populus 1 line. Based on the model, the RAS requires a tripping of 497 MW at Jim Bridger for this outage. One simulation was performed by tripping 497 MW of Jim Bridger generation and another one by tripping 627 MW of wind generation. The 627 MW of tripped wind generation is 1.3 times higher than the actual Jim Bridger generation required to trip. As seen in the plot, the yellow and red curves represent the voltage at the Threemile Knoll 345 kV bus, and the green and blue curves represent the voltage at the Bridger 345 kV bus. The voltage performance is very similar.

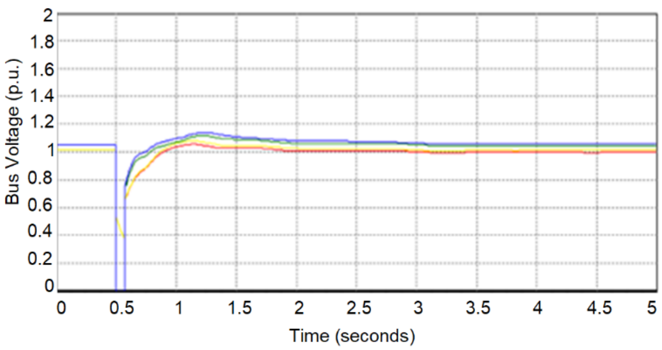

Fig. 8. Voltage performance of tripping wind versus Jim Bridger units to determine effectiveness factor.

The voltage performance for the simulation that trips the Jim Bridger generation is little worse than the simulation in which the eastern Wyoming wind generation is dropped, as the reactive support provided by each Jim Bridger unit is reduced when the Jim Bridger units are tripped. The Aeolus voltage performance is also better when the wind generation is dropped as compared to Jim Bridger units.

The study concluded that in order to achieve similar reliability performance by tripping wind generation instead of Jim Bridger generation, an effectiveness factor of 1.30 should be applied to the wind generation. For example, if the RAS requires tripping 100 MW of Jim Bridger generation, then a total of 130 MW of wind generation tripping is required to achieve similar results.

VII. Tripping Logic

A. Optimal Unit Selection Algorithm

This study has shown that under rare but critical outage conditions such as N–2 outage of Jim Bridger–Populus 1 and 2 345 kV lines or other N–2 outage conditions, the Jim Bridger RAS may call for tripping higher generation levels that require tripping the combination of both thermal and wind generation. Under these conditions, a maximum of two Jim Bridger units should be allowed to trip, and the rest of the tripping should be achieved by tripping wind generation. The study also has shown that the most effective system performance is achieved by tripping a combination of both the Jim Bridger generators and the wind generators.

The following steps are necessary to properly select a unit for tripping. The Fig. 9 flow chart also shows how the RAS controller calculates generation to trip.

1. Check to see which generators (both thermal and wind generation) are online and if the Anticline–Bridger line is connected.
2. Predict for each generator whether it will be taken offline due to an N-state and consider their combined generation output.
3. Based on the shedding requirement, if GTrip is less than lowflow MW (~200 MW), then verify if any of the wind combination (WTO) can satisfy the requirement; if not, move to single Jim Bridger unit selection.
4. Determine for each unit whether it will split the bus if tripped. Calculate the single unit that best satisfies the shedding requirement.
5. If it is determined that a single unit does not satisfy the power-shedding requirement, then multiple-unit (one Bridger unit plus wind combination) selection logic is used.
6. If the largest Jim Bridger unit and a combination of wind generation units (WTO) is less than Wmax MW and satisfies the shedding requirement, it is selected. If the largest Jim Bridger unit and wind combination does not satisfy the requirement, then jump to pair of units logic.
7. First, calculate all the power generation associated with each pair by adding the generation of the units together. Then determine if there is at least one pair of units that satisfies the power requirements.
8. Next, determine if a pair of units satisfies the power requirements and prevents splitting the bus. If so, select that pair and move to the end of the logic.
9. If none of the unit pairs satisfy the shedding requirement, then check if a combination of pairs of units (which does not split the bus) and wind combination (WTO) less than Wmax MW will satisfy the power requirements. If a combination does and if the pair of units does not split the bus, then select those units and move to the end of logic.
10. If a combination of a pair of Jim Bridger units and wind combination (WTO) less than Wmax MW does not meet the shedding requirements (the shedding requirement is more than this combination), then select the largest pair of Jim Bridger units (which do not split the bus) and largest wind combination greater than Wmax MW and trip them.

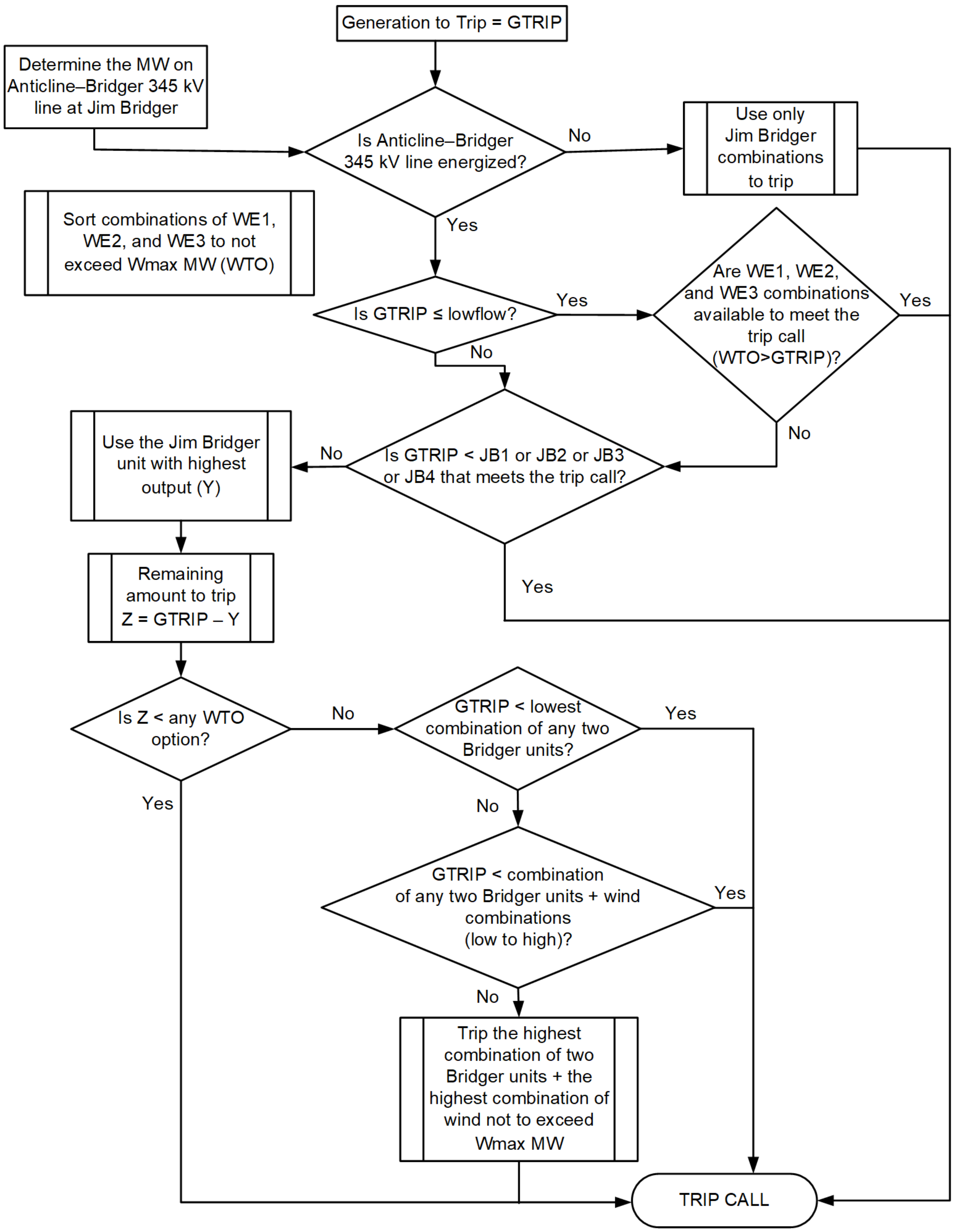

Fig. 9. Optimal unit selection flow chart.

B. *Split Configurations*

If the RAS calls for tripping one or more units via the unit selection process, it ensures that tripping them does not result in splitting the Jim Bridger 345 kV bus. If the RAS requires two Jim Bridger units to trip, but all the combination of units results in splitting the Jim Bridger 345 kV bus, then it trips only one unit with the highest power, irrespective of the generation that is required to be tripped.

As shown in Fig. 10, there will be an additional bay on the Bridger 345 kV bus connecting to Anticline, to bring the wind generation into Jim Bridger. Under a bus split condition, in addition to the highest Jim Bridger unit being tripped, wind generation is tripped. Hence, there is a possibility of tripping more generation under the configuration where tripping more than one Jim Bridger unit splits the bus. The bus split logic has been updated accordingly to account for the new bay on the Jim Bridger 345 kV bus.

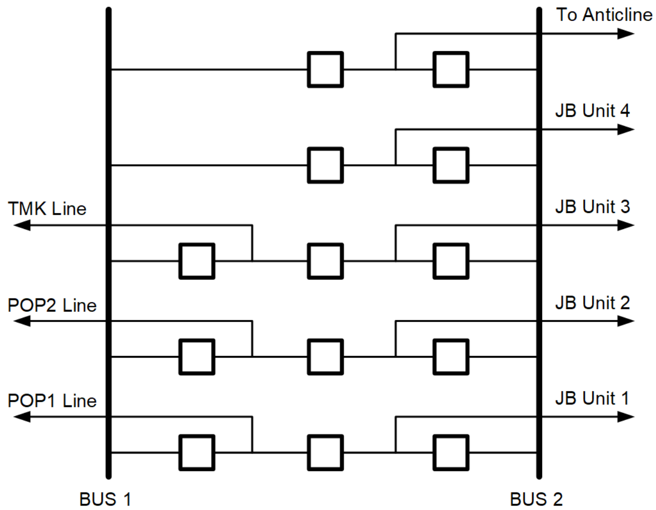

Fig. 10. Jim Bridger bus configuration.

C. *Coordinating With Neighboring RAS*

The RAS also receives trip calls from the adjacent Idaho Power (IPCO) RAS [8]. When the existing RAS receives either the IPCO Level 1 or Level 2 trip signal from Idaho Power, it issues a trip of either 350 MW or 700 MW, respectively. The existing RAS trips up to two Jim Bridger units for this call. With the availability of wind generation, the trip call of 350 MW is treated like a shedding requirement and units are selected accordingly.

Under operating conditions where the Jim Bridger units are at lower output and tripping two units does not satisfy the IPCO Level 2 requirement, then additional wind generation is tripped to achieve the remaining amount. In tripping the wind generation for the IPCO Level 2, the effectiveness factor is applied to achieve the required impact of an IPCO Level 2 trip.

VIII. RAS Scheme Validation With Test Simulator

In addition to the test simulator at the site, there is a replica test system simulator at PacifiCorp which was designed with future upgrade projects and updates in mind. This replica test system simulator includes the simulator system and one RAS system (RAS C). The test system simulator was updated for the wind generation integration and all the items associated with it. After updating the RAS controllers, FEPs, simulator system, and HMI and SCADA interfaces, the RAS scheme was validated with the test system simulator.

A series of test cases were developed to test the RAS logic with the all the power system information including the existing Jim Bridger configuration and the newly added wind generation, new 500 kV line, and all related data. System planning identified the required actions for each test case; using the playback simulator mode, the test cases were played one after the other to verify and validate RAS actions. RAS logic and its actions were verified by looking at the Sequential Event Recorder (SER) and event report files generated after each contingency event, capturing all the relevant system data during a contingency. Including the old test cases and new test cases, a total of 130 test cases were simulated and the response for each test recorded, verified, and validated. This rigorous testing effort helped the team identify certain scenarios for which the RAS actions have to be modified for an appropriate response.

After the internal testing, a factory acceptance test (FAT) was performed with the customer in a remote fashion given the pandemic situation at the time. The remote FAT took longer than normal but at the end gave the team the confidence in the ability of the updated RAS scheme to be commissioned in the field.

IX. Commissioning and Challenges Faced While Upgrading an In-service RAS System

The process of commissioning an upgrade on an existing functional RAS system with dual TMR architecture as shown in Fig. 11 is highly complex and critical and required people from many different groups within the two authoring companies, such as protection engineering, operations, and dispatch as well as field service and communication technicians, etc. It was critical to have the team working together to achieve the commissioning in a smooth manner.

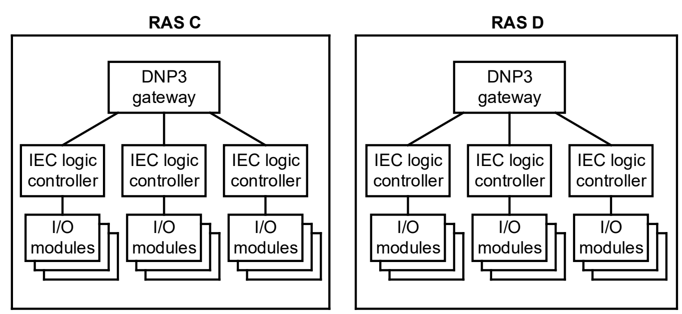

Fig. 11. Dual TMR architecture.

Dual TMR architecture has two RAS systems, RAS C and RAS D, with triple modules in each. There are three RAS controllers and three I/O modules for each RAS. A detailed commissioning procedure and checklist was developed for RAS C and RAS D. According to the plan, one RAS was kept active all the time except for a short amount of time during switchover while one RAS was upgraded. Commissioning was carefully planned to upgrade the system one RAS at a time. All three controllers in RAS C were upgraded first, along with the FEP C and new I/O points for RAS C. RAS D was still operating with existing I/Os without the changes. A site acceptance test with some of the predetermined cases was performed using the test simulator system.

After RAS C was completely upgraded, it was in monitoring mode for a short duration while its performance, calculations, and decisions were monitored and verified before putting it in service. Both RAS systems were out of service during a short time during which the Microsoft Windows HMI system was upgraded. The updated RAS C was put back in service, then RAS D went offline. RAS C was monitoring and protecting the system; it was configured to work both with the wind generation and without it, depending upon the status of the new 500 kV line and the wind generation units. This helped in seamless transition of the system in monitoring and including the new assets once they came online.

RAS D was upgraded while RAS C was in service. After the upgrade and completion of the functional tests, it was put in monitoring mode for a short duration and then the system was turned on and made operational. With careful planning between all the parties involved the system was updated in 4 weeks.

X. Conclusion

The Jim Bridger RAS was upgraded after 10 years. The additional wind generation from eastern Wyoming was incorporated in the arming level and generation-to-shed calculations. Wind generation units were included in the generator-dropping algorithm in the RAS. Data from the wind farms is integrated to the RAS scheme and RAS sends trips to the wind farms through the FEP located in Jim Bridger and I/O modules located in the wind generation substations. As part of the upgrade, RAS HMI screens were updated with information related to the new 500 kV line and the wind generation substations. The RAS simulator system and the replica simulator was updated to include the new details.

The system study results showed that a combination of Jim Bridger and wind generation tripping was beneficial in maintaining the system stability and reliability. The effectiveness factor (Ef) determined the equivalent wind generation tripping for comparable Jim Bridger generation to achieve similar results. Testing of the RAS scheme with the simulator system using a multitude of test cases validated the RAS logic and proved the design. The RAS system has been commissioned and working.

The RAS is designed to allow future expansion with little interruption to performance. The hardware design allows for RAS C or D to be disconnected from the live power system and connected to a test simulator. This not only allows for quick changes to occur within the RAS, but also for expansion and other maintenance actions without taking the entire system out of service.

XI. Acknowledgments

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XIII. Biographies

Rikin Shah is currently working as a principal engineer in the Area/Transmission planning department at PacifiCorp. He has a master’s degree in general engineering-electrical option from Montana Tech. He received his bachelor’s degree in electrical engineering from India. In his 17 years of transmission planning experience, he has worked on several transmission related studies such as reliability planning analysis, generation interconnection, and compliance-related studies. He is currently performing studies for the development of the Gateway South project, which is a 400 mi, 500 kV line connecting eastern Wyoming to central Utah. He has participated in the regional standard drafting committee for the Western Electricity Coordinating Council (WECC).

Robert Hines received a Bachelor of Science in electrical engineering from Washington State University in 1993. In 1999, Robert joined the protection and control engineering department at PacifiCorp where he has worked on protection systems for equipment ranging from distribution to extra-high voltage (EHV). His experience includes over 12 years of specialized control system design and relay settings development with multiple large scale remedial action schemes (RASs). Robert is currently a senior engineer in the protection and control engineering department where he continues to focus on the development, testing, commissioning, and field support of complex control systems for high-voltage and EHV equipment. In a recent project, Robert worked with Pamela Palen (PacifiCorp) to design, test and, commission protection and automated controls for the paralleling of 3 345 kV phase-shifting transformers at Pinto Substation. This is the only arrangement of its kind in the Northwest power system.

Pamela Palen received her bachelor’s degree in electrical engineering from Portland State University in 1996. In 2004, she joined PacifiCorp where she has worked on substation design, protection, control, and automation. Pamela is currently a senior engineer II in the protection and control engineering department where she specializes in substation control and automation. She has experience in the design, development, testing, commissioning, and field support of complicated control systems for high-voltage and extra-high voltage (EHV) equipment. In her 17 years at PacifiCorp, Pamela has been responsible for the creation of multiple company design standards for capacitor control automation, phase shifting transformer control, substation HMI, and automation for distribution and transmission. In a recent project, Pamela worked with Robert Hines (PacifiCorp) to design, test, and commission protection and automated controls for the paralleling of 3 345 kV phase-shifting transformers at Pinto substation. This is the only arrangement of its kind in the Northwest power system.

Hariharan Subramanian received his BE from College of Engineering Guindy in 2005 and an ME from Texas A & M University in 2009. In 2005, he joined Neureol Technologies Pvt Ltd as an electrical design engineer working on battery monitoring systems for two years. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2018, he worked at Bechtel Corporation for six years in different roles in electrical engineering and also previously worked in SEL as automation engineer for three years. He is presently a senior engineer at SEL. He has experience in power system design, power system automation, power system protection and studies, and power management systems. He is experienced in the design, development, testing, and commissioning of projects. He has worked on multiple projects with various customers in the oil and gas and utility industries. He is a senior member of the IEEE and a registered professional engineer in Texas.

Rameez Syed received a Bachelor of Applied Science in electrical engineering from the University of Windsor, Ontario, Canada. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008 and is currently an SEL Engineering Services, Inc. (SEL ES) manager. He has 12+ years of experience in the field of power system automation, including power management schemes for large-scale industrial power plants, remedial action schemes (RASs), and microgrid solutions.

Alejandro Carbajal received his electronic engineering degree in 2008 from the Universidad Autónoma de San Luis Potosí (UASLP) in San Luis Potosí, Mexico. In August 2009, Alejandro joined Schweitzer Engineering Laboratories, Inc. (SEL) as a development engineer. After working in different areas of SEL, he specialized in automation and gained international experience working with various project architectures. In 2014, he joined the special protection schemes team in Mexico, working with remedial action scheme (RAS) projects. His specialty is programming different controller platforms for RAS automation. In 2019 he moved to SEL Engineering Services, Inc. (SEL ES) in Boise, Idaho as an automation engineer. He is presently working in the same office gaining experience in different roles in design of automation systems.

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