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***Abstract*—A remedial action scheme (RAS) implemented in the south of Peru reacts to excessive angle differences between the synchronized voltage measurements of two nodes that are 400 km apart in order to disconnect loads and maintain the stability of the country's power system. The RAS was required for the safe operation of the power system because of the recent expansion of large loads in the southern region of the country.**

The RAS concept was developed by the system operator (COES) after a detailed analysis of the power system response for certain system contingencies. The study was performed with power system stability software, and it identified six contingencies that could jeopardize the operation of the southern part of the Peruvian power system. It was determined that the best indicator of a problem was the angle difference between substations and that the remedial action would be to disconnect some of the large mining loads.

The RAS architecture uses phasor measurement and control units (PMCUs) installed in the substations of the country's southern 500 kV corridor. These PMCUs supply synchronized measurements to redundant synchrophasor processors, where the measurements are time-aligned and the phase angles compared. Decision-making logic is applied by the synchrophasor processors, and trip commands are sent to the large mining loads. The RAS operation takes place within milliseconds after the angle threshold is satisfied. The implemented system has allowed the large mining installation to connect to the Peruvian grid while complying with power system stability regulations and reliability requirements.

This paper describes the power system stability problem, the RAS logic design, the communications infrastructure used, and the real-time testing that was performed before commissioning, as well as the staged testing of the system.

I. Introduction

The Cerro Verde mine is located 30 km south of Arequipa, Peru's second-largest city after the capital city of Lima. Lima is approximately 1,100 kilometers north of Arequipa. Currently, the radial 500 kV Chilca-Poroma-Ocoña-San José-Montalvo transmission corridor (shown in Fig. 1) is the main transmission path for Peru, feeding all loads in the south, together with the 220 kV Mantaro-Cotaruse-Socabaya-Moquegua-Montalvo system. Most of Peru's power is generated north of Chilca (near Lima) and power is supplied to the south through this 500 kV corridor.

The partial or total loss of the 220 kV transmission path can be tolerated because the 500 kV system can support the load; the reverse is not true. This 500 kV north-central-to-south corridor and its Synchronous Digital Hierarchy (SDH) fiber-optic communications link run along the Pacific Ocean coast of Peru.

Fig. 1 shows a geographical view of the 500 kV and 220 kV southern transmission systems, and Fig. 2 shows the system as a one-line diagram. Bus reactors are present in the 500 kV substations to provide voltage compensation.

The Cerro Verde Production Unit Expansion (CVPUE) mining project requires approximately 300 MW of power, which is supplied by Peru's 500 kV national transmission system, Sistema Interconectado Nacional (SINAC). CVPUE receives power from the 500 kV transmission system at the San José substation through two 500/220 kV autotransformers. Two lines branch to the San Luis and San Carlos substations at 220 kV. These two CVPUE 220 kV substations provide power to loads such as the ball mills, fresh water pump motors, crushers, high pressure grinding rolls, conveyors, and so on inside the mine. The project loads are connected to 220/34.5 kV transformers.

The Economic Operations Committee of the Interconnected National System (Comité de Operación Económica del Sistema Interconectado Nacional [COES]) is responsible for the power flow and operation of Peru's grid. Phase 1 of the RAS, drafted by COES, called for the implementation of automatic load shedding by angle difference (desconexión automática de carga por diferencia angular [DACA]) based on synchronized phasor (synchrophasor) measurements of the loads of the Cerro Verde mine. It also called for local disconnection of reactive power compensation (desconexión automática de reactores locales [DARL]) to control the busbar reactors of the 500 kV substations. The operational study deemed it necessary to trip the busbar and line reactors after a load shedding action because an undervoltage condition might occur on the 500 kV substation bus. The DARL acts in 500 ms, but there is a supervisory control and data acquisition-operated (SCADA-operated) control for the same reactors.

Fig. 1. Geographical view of the 500 kV (orange) and 220 kV (blue) lines

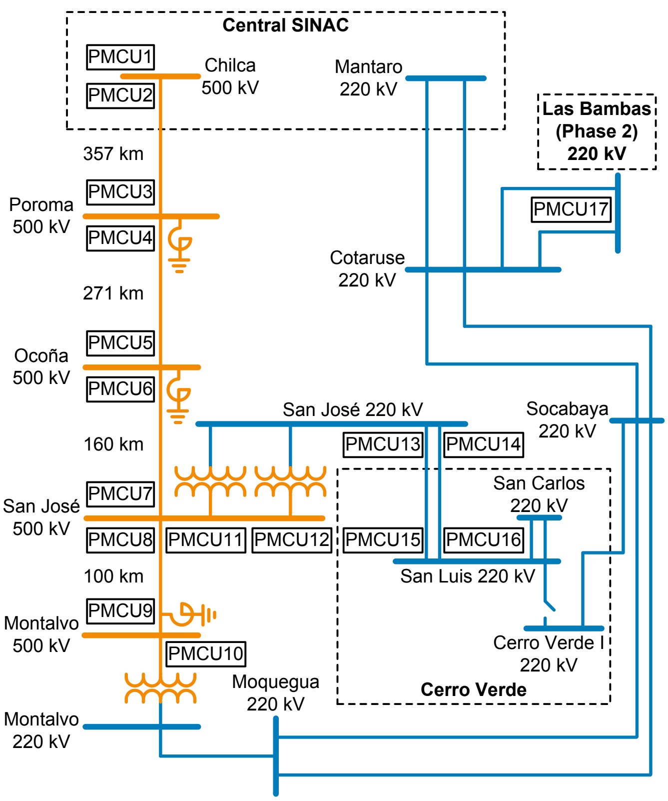

Fig. 2. Simplified representation of the components of the remedial action scheme (RAS)

The southern Peru mining industry is expanding. These expansions represent high loads that could threaten the stability of the Peruvian power system if the 500 kV corridor is lost. The implementation of a RAS was deemed necessary due to the lack of a redundant 500 kV path in the transmission system.

The operating speed of the RAS to trip mining loads is less than 100 ms, starting from the time that a contingency (angular difference) is detected by the phasor measurement and control unit (PMCU) to the contact output time of the load-shedding controller (LSC). The function of the PMCU and LSC are described later in the paper. The RAS takes up to 100 ms to respond, and an additional 100 ms for the circuit breakers to open provides a total time of 200 ms.

Phase 1 has already been commissioned. Phase 2, an expansion of the initial system, will be implemented during the coming years to increase the load sharing table and accommodate more loads from the southern mines of Peru.

II. The Solution

The Peruvian power system transmission network operates at 500 kV and 220 kV. The bulk of the power transmission to the southern part of the country uses the 500 kV corridor shown in Fig. 2. The 220 kV system is a secondary path for power transmission.

Fig. 3 shows a very simplistic representation of the Peruvian power system. Notice that the equivalent 500 kV and 220 kV systems are represented by equivalent reactances (X500 and X220, respectively).

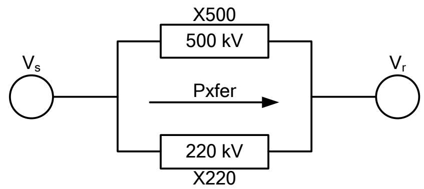

Fig. 3. Simplified representation of the Peruvian power system

Based on the formula for power transfer capability in [1] (where V_s is the sending source and V_r is receiving), when the two systems are in service, the equivalent reactance (Xeq) is the parallel combination of X500 and X220 [2]. When the 500 kV transmission network is lost, Xeq is X220 or larger. To keep the power transfer intact, the angle difference between the sources needs to increase.

The maximum power that is transmitted from the source to the receiving end is at 90 degrees. The equal area criterion, based on (2), illustrates that a power system becomes unstable if there is not enough power transfer capability [2]. In the previous example, the X220 equivalent reactance may not provide the capability required to transmit the electrical power and the system could become unstable.

$$\text{Pxfer} = \frac{|V_s||V_r|}{\text{Xeq}} \sin\left(\gamma_{V_s} - \gamma_{V_r}\right) \quad (1)$$

An angle difference increase is a good indicator that the power system is becoming unstable. The solution algorithm proposed for the Peruvian system incorporates angle difference monitoring between the sending and receiving measuring points. Simulations of this transmission network in power stability software have provided angle difference thresholds for logic schemes that were implemented as a RAS. Synchrophasors allow for this comparison of power system angle differences.

Fig. 4 shows two PMCUs time-synchronized by high-accuracy GPS receivers. These PMCUs are the measuring devices. The GPS time signal provides a common reference for both PMCU 1 and PMCU 2. The phasor measurements, with magnitude and angle, are transmitted by the PMCU communications ports to a centralized measuring device for the purpose of analyzing angle differences between different locations on the transmission line.

The project described in this paper illustrates the use of PMCUs to monitor angle differences between sending and receiving measuring devices. The synchronized measurements travel through communications channels to reach two phasor data concentrators (PDCs), which ensures that the data being received are archived and time-aligned. The PDCs are the centralized measuring devices that receive messages from the PMCUs. These PDCs with control capabilities are able to process the information and make control decisions. The decisions become control actions that are sent via a communications network to the appropriate devices to perform them.

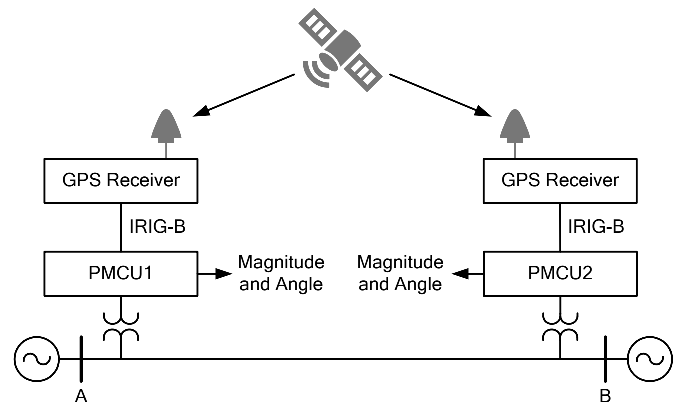

Fig. 4. Synchrophasor technology components

The two PDCs with control capabilities, shown in Fig. 5, receive the synchronized measurements from two (or more) substation PMCUs and process the measurements with built-in logic. Typically, the programming language is a real-time control language like IEC-61131-3.

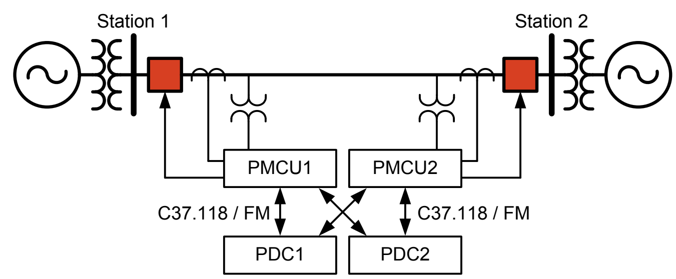

Fig. 5. PDCs with control capabilities monitoring the angle difference

PMCUs are distributed along the 500 kV corridor, as shown in Fig. 2. These PMCUs monitor and send the voltage and current magnitude and angle values (and other values) of the lines they are connected to via IEEE C37.118 protocol. The measurements are sent to two redundant PDCs with control in the San Luis and San José substations, as shown in Fig. 5.

III. Logic and Architecture

In the Cerro Verde project, the logic schemes designed were programmed with IEC 61131-3 languages in two redundant PDCs with control capabilities called synchrophasor vector processors (SVPs). These SVPs act as PDCs and time-align incoming IEEE C37.118 messages from the sixteen PMCUs. The SVPs process these messages with an internal logic engine that calculates and validates conditions to implement the RAS logic. They send IEEE C37.118 messages or derived data to devices such as other PDCs, and monitoring systems (e.g., transmission system operators).

Moreover, the SVPs implement Network Global Variable Lists (NGVLs). NGVL is a variable sharing network technology that allows the sending of commands and analog values to other NGVL-capable devices [3]. They also send proprietary control messages, such as Fast Messages (FM), for control of other devices.

The SVPs in this project implement the logic schemes and send control messages to other devices. The control messages from each SVP are as follows:

- FMs to the PMCUs for reactor control.
- NGVL commands and data exchange to the LSC to trip loads and to update the human-machine interface (HMI) with real-time data.

Fig. 6 is a data flow diagram showing the protocols used between each measuring and control device for load shedding and for the RAS in general.

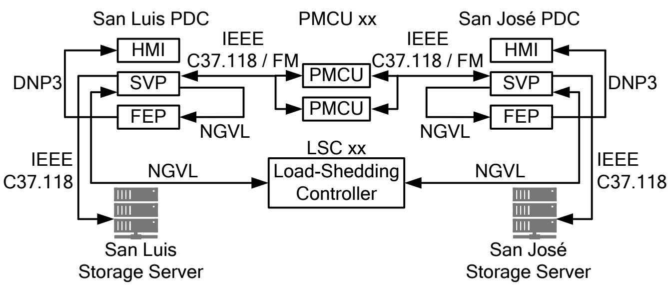

Fig. 6. Data flow diagram

The system is redundant, with two SVP controllers functioning in parallel, along with two front-end processors (FEP). All sixteen PMCUs send data simultaneously to both SVP controllers in real time. Both SVP controllers receive IEEE C37.118 messages with the same exact data frame and perform the same deterministic logic functions. When a contingency is validated by both SVP controllers, each of them sends a fast control message simultaneously to the LSCs to trip only the loads that are selected for that contingency. The LSC is an I/O device with several binary outputs to control circuit breakers. The LSCs are located in three separate stations inside of the Cerro Verde mine, and these trip the assigned load(s) after receiving the fast control message from only one SVP.

The HMI of the RAS has a static list of loads that correspond to the amount of power to shed. The HMI operator selects loads from this list and assigns them to a contingency.

IV. Communications

The sixteen PMCUs communicate via fiber-optic links in a closed network implemented on SDH station multiplexers. The geographical distances between the nodes are shown in Fig. 7. The longest distance that a message has to travel (from the Chilca substation to the San Luis substation) is approximately 800 km.

When designing the network, the most important consideration was speed. Various tests were conducted before commissioning to define the channel requirements. Based on the number of exchanged messages, a calculation was performed to derive the necessary bandwidth.

After all of the RAS components were installed and the communications channel was commissioned, latency tests were conducted to measure the real-time delay between each of the geographical locations (i.e., from each of the sixteen PMCUs to both the San Luis and the San José SVPs). Fig. 8 shows these results in milliseconds.

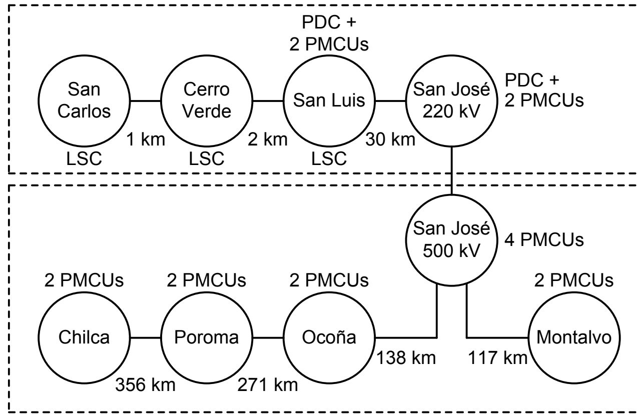

Fig. 7. Geographical distances between SDH nodes

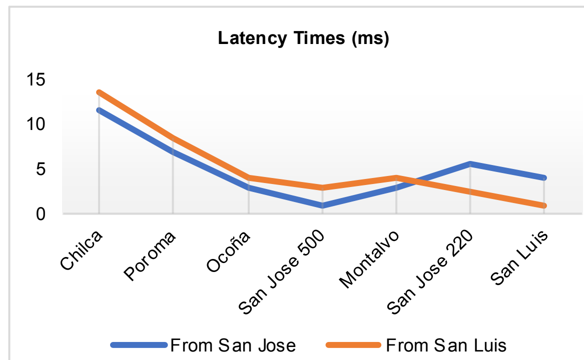

Fig. 8. Latency times from each PMCU to the SVPs in milliseconds

V. Time Synchronization

High-accuracy time stamps are required for the correct performance of the PMCUs. GPS clocks were used to synchronize the PMCUs and controllers in this project.

Solar flares, jamming, and antenna failures can cause a clock to lose its GPS signal. When a GPS clock determines that it has lost the GPS signal, it switches to its internal holdover oscillator until a GPS signal is acquired. A system-logged event is recorded as a holdover alert with a time stamp, and the clock does not use the GPS signal until the primary source is properly verified.

GPS clocks retain appropriate time-stamp precision for a period of time and maintain the PMCU functionality. Certain designs use very accurate oscillators to keep the accuracy. The GPS clocks in this project use internal oven-controlled crystal oscillators (OCXOs) that maintain the relative time error to within ±5 µs for 24 hours, which generally provides ample time to rectify the loss of the GPS signal.

VI. Logic

The purpose of the fast and automatic load shedding is to mitigate abnormal power system conditions when a contingency occurs. These abnormal power system conditions are summarized broadly as follows:

- Overloaded lines and transformers, which may also cause severe low-voltage conditions.
- Loss of the 500 kV line leading to angular instability.

The positive-sequence voltage angles of two PMCUs are compared by the DACA logic. Two consecutive comparisons are required to signal the detection of a contingency, and these decisions are processed by the DACA logic in real time. The remedial action command is received by the LSCs inside the mine to shed the loads that correspond to the contingency, which are selected by the Cerro Verde operators. Table I lists the six contingencies to be detected, which were identified by COES and Cerro Verde's system study.

TABLE I
CONTINGENCIES

Contingency Number	Description	Voltage Level (kV)
C1	Chilca-Poroma Line opened	500
C2	Poroma-Ocoña Line opened	500
C3	Ocoña-an José Line opened	500
C4	Mantaro-Cotaruse Line opened	220
C5	Cotaruse-Socabaya Line opened	220
C6	Mantaro-Cotaruse Line opened and the 500 kV corridor is open	220

The RAS system monitors the angle difference of two pairs of PMCUs according to Table II. Two angular differences are monitored, and the decisions are based on both. This is done for security purposes and to ensure that two independent measurements confirm the angular separation in the power system. Fig. 2 shows the geographical location of each PMCU listed in Table II. For example, in Contingency C1, the first pair of PMCUs compared are PMCU1 (Chilca) and PMCU4 (Poroma), and the second pair are PMCU1 (Chilca) and PMCU10 (Montalvo). The electrical degree or angle thresholds were obtained from COES and Cerro Verde's system study.

TABLE II
ANGLE DIFFERENCE THRESHOLDS

Contingency Number	First Pair of PMCUs Compared in SVP		Phase Angle 1 Threshold	Second Pair of PMCUs Compared in SVP		Phase Angle 2 Threshold
C1	1	4	40º	1	10	45º
C2	3	6	50º	2	9	50º
C3	5	8	50º	2	9	50º
C4	2	9	25º	1	7	65º
C5	2	9	n/a	1	7	n/a
C6	2	17	50º	2	9	30º

Table III specifies the amount of load to be shed for each contingency. This table includes the amount of power that was assigned to be shed by the Cerro Verde and Las Bambas mines. At the time of this writing, only Cerro Verde had LSCs to shed the power assigned.

TABLE III
LOAD-SHEDDING PERCENTAGE

Contingency Number	Cerro Verde Percentage	Las Bambas Percentage
C1	25% (91 MW)	NA
C2	60% (224 MW)	60% (90 MW)
C3	60% (224 MW)	60% (90 MW)
C4	NA	49% (74 MW)
C5	NA	NA
C6	NA	100% (150 MW)

The RAS system implements arming logic to add an extra level of security to the system. The PMCU programmable logic is used to check a list of conditions that are validated both in the PMCUs and the SVPs. Each PMCU sends an IEEE C37.118 message with the synchronized measurements of currents, voltages, real power of the transmission line, and binaries such as breaker status. The following conditions were used for the arming logic:

- No drastic changes of angle difference in consecutive measurements.
- No drastic changes of power flow in consecutive measurements.
- Current flow in each end of the line to confirm that breakers are closed in at 500 kV.
- Minimum power flow threshold met in the 500 kV corridor.
- No DACA logic previously operated.

Fig. 9 is a logic diagram for the arming of DACA1. The pickup and dropout times of the logic were carefully selected, taking into consideration the protection relay's reclosing times to avoid pole-open conditions or pole discrepancies.

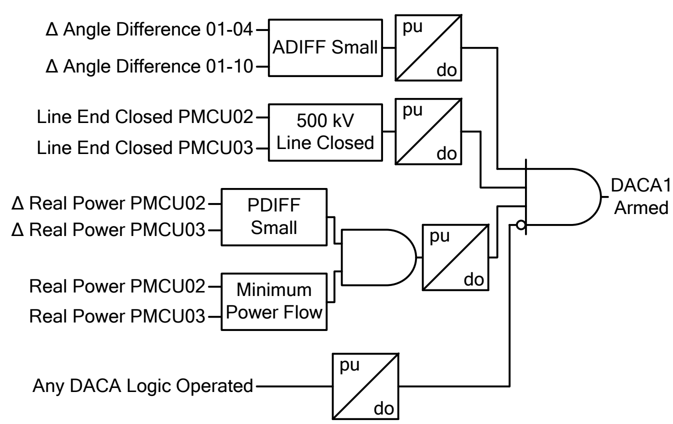

Fig. 9. DACA1 armed logic diagram

The following conditions are monitored to enable the DACA logic:

- Communications link quality bit in good status for data exchange between PMCUs and SVPs.
- High-accuracy time synchronization quality bit in good status for the PMCUs.
- No loss-of-potential logic operated in the PMCUs that participate in the DACA logic.

- No low-voltage threshold operated.
- No operator manual block of the RAS system from the HMI, which might be used in maintenance mode.

Fig. 10 shows the logic for DACA1.

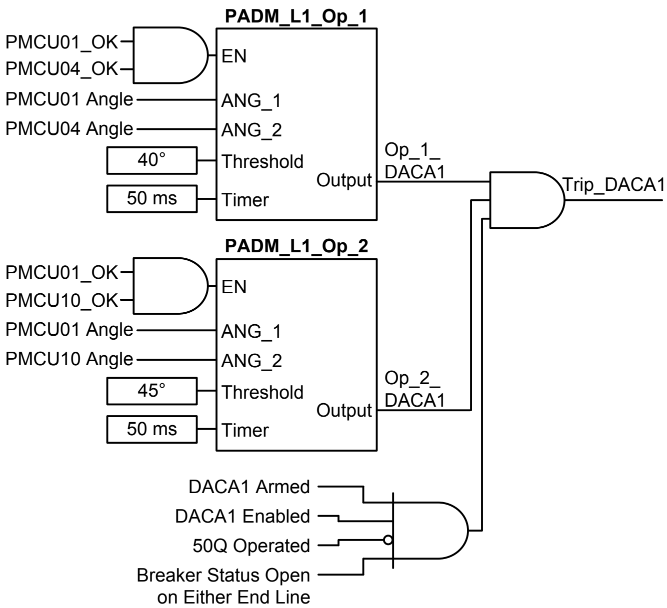

Fig. 10. PADM logic diagram to send trip command

The PADM (phase-angle difference monitoring) logic is used to detect whether the phase angle difference is over a threshold when a 500 kV line is opened. The DACA1 logic should be armed and enabled. No fault or single-pole-open condition should exist, which is verified by the absence of negative-sequence current (50Q). When all of this logic is met, then DACA1 operates and sends a control message to the LSC. Only one DACA logic operation at a time is permitted to trip the loads of the Cerro Verde mine, which means that the LSC only accepts the first control message received from either of the two SVPs that are working in a hot-hot configuration. The LSC is hard-wired to the breakers inside the mine to trip their loads.

It is possible that after any of the DACA schemes operates that the voltage might drop in the 500 kV transmission system. When an angle difference contingency is detected and the DACA logic operates, a DACA_Operated status bit is sent to all PMCUs. There are three PMCUs that have internal logic to trip either the line or bus reactor. The logic implemented is called DARL, and it operates if the low-voltage threshold is met and the DACA_Operated bit is received by the PMCU. The DARL logic was also identified by COES and Cerro Verde's system study.

VII. RTDS Model Validation

A real-time digital simulator (RTDS) was used to validate the RAS. It performs electromagnetic power system transient simulations, with a typical simulation time step in the order of 50 µs.

The overall network solution technique employed in the simulator is based on nodal analysis. The Dommel algorithm [4] allows the following two levels of parallel processing:

- Level 1 entails parallel processing of components connected to a common admittance matrix (i.e., within one subsystem).
- Level 2 entails parallel processing of subsystems (i.e., decoupled admittance matrices).

The simulator mimics Level 1 by using tightly coupled processors to solve components connected to a common admittance matrix. Level 2 is implemented by using separate processors to solve different simulation subsystems. In addition to being designed to execute the Dommel algorithm in real time, the simulator is designed to test physical protection and control equipment, such as RAS systems.

The RTDS uses a model that is based on the electrical configuration of the Peruvian power system. The model was specifically developed to validate the RAS. The RTDS with the Peruvian power system model had the RAS control system connected to it so that a closed-loop validation of the RAS could be accomplished during factory acceptance testing prior to field installation.

The RTDS model represents the Peruvian power system based on one-line drawings. All data required for modeling the different power system components (generators, transformers, transmission lines, distribution lines, cables, and loads) were provided by COES. Each power system component is validated prior to RAS testing. The Peruvian electrical system is modeled graphically and data are assigned to each component. The completed model, with graphics and data, is designated as a "case."

Once a power system case is built, it is compiled on the RTDS hardware and then executed in the RTDS run-time module. All the controls for interfacing with the model in real-time are placed there. This includes, but is not limited to, sliders to change set points, raise and lower controls, breaker controls, fault controls, and plots for capturing data.

A. Generator Modeling

The mechanical and electrical parameters of physical generators, along with governor and exciter systems, were developed for the simulation model. Step tests were performed to study the response of the exciter and governor models on a per-generator basis. For the validation, a test system was developed consisting of a generator connected to an infinite bus and two loads through a step-up transformer. Each of the components could be isolated by operating the breaker connected to the generator bus. This validation demonstrated the effects of the prescribed gains and time constants of the excitation and turbine governor system with the given generator. These tests included load acceptance, load rejection, and governor step response. For the exciter, these tests included exciter step response and a full-speed, no-load test.

B. Load Modeling

Constant impedance and constant power load models were developed for the power system model. The loads were further divided into sheddable and non-sheddable loads. Sheddable loads were hard-wired to the RAS system with the ability to be individually shed during a contingency. The active power, reactive power, voltage, and frequency could be monitored in real time during testing.

C. Network Aggregation

Parallel transformers and transmission lines that did not directly impact the RAS system were aggregated into a single transformer. Network equivalents were also created at the boundaries for simplicity. System inertia, impedance, and capacity were considered during the network and system aggregation.

D. Protection and Line Reactor Modeling

The RTDS model of the Peruvian system included the modeling of protective tripping to understand the interaction of the RAS with the existing protection system. Protective tripping included generation protection, transmission line protection, and voltage-based load-shedding schemes. The system model also included automatic reactor control at all 500 kV transmission lines.

Generator protection included trips for abnormal frequency and voltage excursion on the system. This included two levels of overvoltage, undervoltage, overfrequency, and underfrequency protection. Line protection trips for overvoltage on the system were implemented, which included two levels of overvoltage protection. Excursions beyond predetermined pickup thresholds result in protection-based tripping in the given transmission line or generator.

An undervoltage-based, load-shedding scheme at the feeder level was implemented for the RTDS model for extreme voltage excursions to verify the RAS interaction and stable operation.

VIII. RAS Dynamic Testing and Analysis

Once the model components were individually verified, the combined system model was validated using the dynamic response of the power system during different contingencies. The validation of the model involved the comparison of the RTDS results to those from stability simulations performed by COES.

Prior to installation of the RAS system, complete I/O testing was performed in a laboratory. The RTDS model described in the previous section was used to validate the functionality of the RAS system. Several studies were performed using the model, providing insight into plant operation, vulnerabilities, and system response for many contingency events. Studies were also completed to determine the optimal set points for RAS system.

The real-time model also permitted the RAS system to be tested as a live simulation in the factory acceptance test. This was accomplished by connecting the RAS system to the simulation hardware, as shown in Fig. 11.

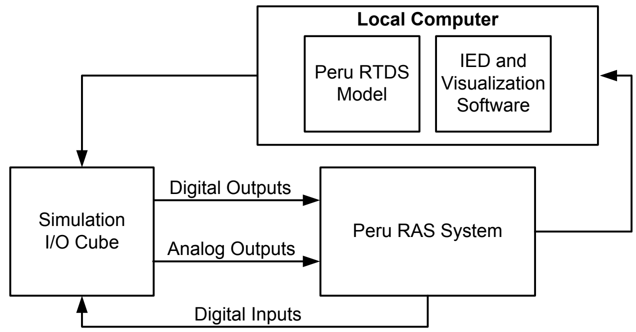

Fig. 11. RTDS interface with RAS System

A variety of tests were performed to determine the speed and reliability of the RAS system. These tests ranged from typical scenarios to corner cases. Several predefined tests were used in the testing of the centralized RAS system. These included line faults, sudden breaker open, successful and unsuccessful single-pole reclosing, load rejection, and loss of generation. The following subsections illustrate some of these tests.

A. Case 1: Three-Phase Fault and Opening of Chilca-Poroma 500 kV Transmission Line

A three-phase fault was applied on the Chilca-Poroma 500 kV transmission line and the line was opened. The Cerro Verde-San Luis transmission line was closed. The opening of the line (simulating protection system operation) yielded the gradual increase of the angular difference between the Chilca-Poroma and Chilca-Montalvo substations. The DACA1 logic operated, and the RAS shed load.

Fig. 12 shows the synchrophasor plot for Case 1. The DACA1 logic monitors the angle difference between PMCU1 and PMCU4 and the DACA2 logic monitors the angle difference between PMCU1 and PMCU10. When the fault is applied, the angle difference jump is monitored and once the breaker opens, the angle difference increases across the threshold. Once the pickup timer is satisfied, the RAS system operates to perform load shedding and preserve system stability.

Fig. 12. Software plot for angle difference TDS interface.

A three-phase fault was applied at 0.75 seconds. Fault detection took approximately 30 ms before a trip signal was sent to the breaker, and the three-phase breaker (CB) opened after another 50 ms. At 1.084 seconds, the angle difference threshold was reached, and another 50 ms internal pickup was required before the load trip was issued at 1.21 seconds. Fifty milliseconds after the load trips were received, the loads were shed. The total round-trip time, from the threshold crossing to the initiation of the load trips minus the 50 ms internal pickup, was calculated to be 76 ms. The timeline for this case is shown in Fig. 13.

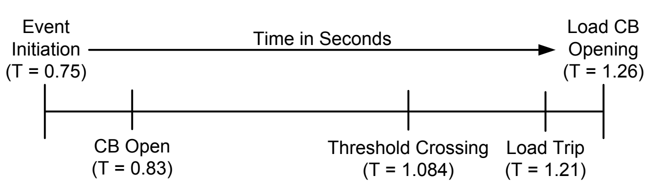

Fig. 13. Case 1 timing chart

B. Case 2: Single-Phase Fault and Three-Phase Open of Chilca-Poroma 500 kV Transmission Line

A single-line-to-ground fault was applied to the Chilca-Poroma 500 kV line with an approximate power flow of 940 MW to the south. The test simulated a failed single-pole-trip reclosing sequence. The single-pole-open interval of 900 ms was followed by a reclose attempt onto a permanent fault. A three-pole trip followed. The loss of the line increased the angle difference between the Chilca 500 kV and Poroma 500 kV substations. The angle difference between the Chilca 500 kV and Montalvo 500 kV substations also increased (the second requirement). The DACA logic detected the power system angular differences above the thresholds and the RAS system operated.

The single-line-to-ground fault was applied at 0.75 seconds. Fault detection took approximately 30 ms before a trip signal was sent to the fault phase breaker, and the breaker opened after 50 ms. The faulted phase opened for 900 ms, which is the reclose interval. After reclosing, due to the presence of the permanent fault, all three phases opened at 1.78 seconds. At 1.967 seconds, the angle difference threshold was reached, and another 50 ms internal pickup was required before the load trip was issued at 2.09 seconds. Fifty milliseconds after the load trips were received, the loads were shed. The total round-trip time, from the threshold crossing to the initiation of the load trips minus the 50 ms internal pickup, was calculated to be 73 ms. The timeline for this case is shown in Fig. 14.

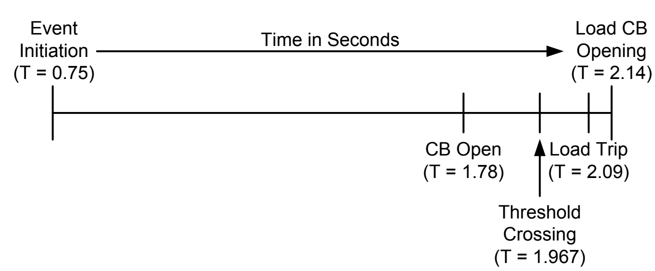

Fig. 14. Case 2 timing chart

The DACA1 logic operated, and the RAS action shed load according to user selections on the load status screen in the RAS HMI (see Fig. 15).

Fig. 15. Software plot for angle difference

IX. Field Test and Field Event Analysis

A. Field Test

A field test operation was carried out after validation of the system status. This served as the final test to demonstrate the system functionality, with the aim of measuring operating time.

The operation of the system for the real test was performed by means of manual opening the Ocoña-San José line on the San José substation side. The operation of the DACA3 logic was expected to operate the scheme with the RAS armed. In order to achieve RAS operation, lower thresholds than normal were used, which were provided by COES. These thresholds are as follows:

- Power arming (pickup) = 180 MW
- Power disarming (dropout) = 120 MW
- First pair angle difference = 30°
- Second pair angle difference = 30°

The load-shedding test was conducted controllably. Two loads were selected from the system HMI, and critical loads were manually blocked from the operation of the dual-redundant RAS systems.

The operation of the DACA3 is shown in the Fig. 16. The first section shows the angular difference between PMCU5 (Ocoña) and PMCU8 (San José). The second section shows the angular difference between PMCU2 (Chilca) and PMCU9 (Montalvo). The third section shows the digital inputs that were enabled in PMCU16 to receive signals from the LSCs. Input IN206 is a replica of the trip signal to the load selected, while IN207 is the breaker status of the same load.

In Fig. 16, the vertical yellow line corresponds to the time the threshold of 30° is exceeded between Chilca and Montalvo, which begins the RAS operating time. The vertical magenta line corresponds to the moment where the trip signal to the breaker is recorded. The gray box displays the operation time of the RAS, which is 102 ms. Considering that an intentional delay of 50 ms was used in the system to provide security, the operating time of the RAS was 52 ms.

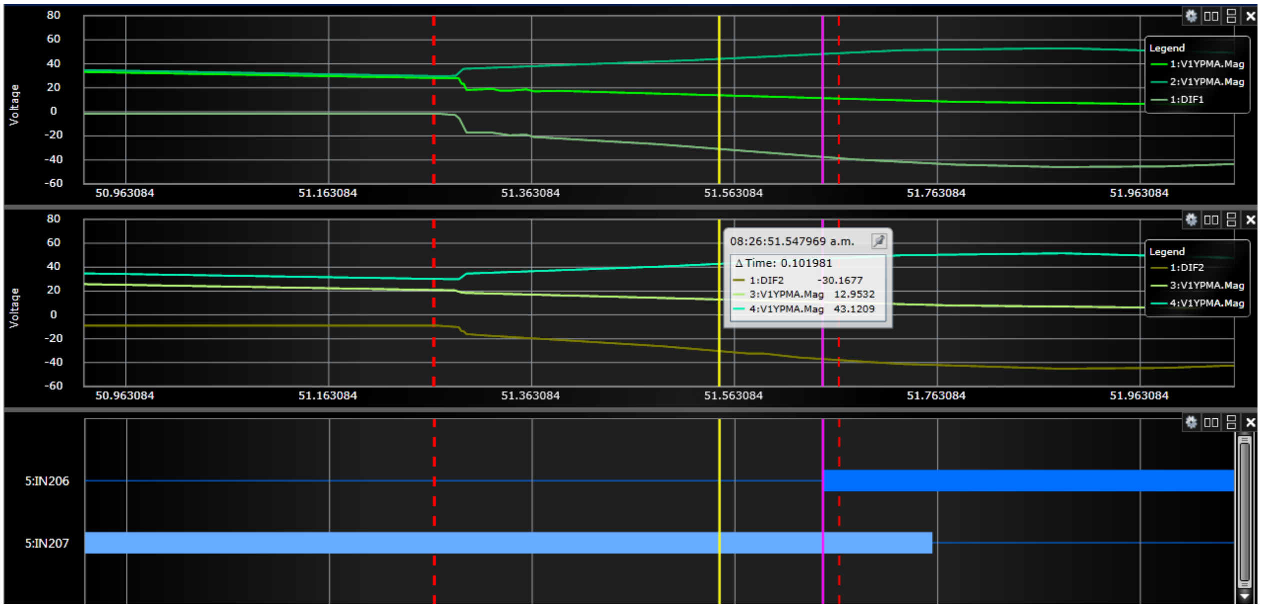

Fig. 16. Real test (operation time) showing operation of DACA3

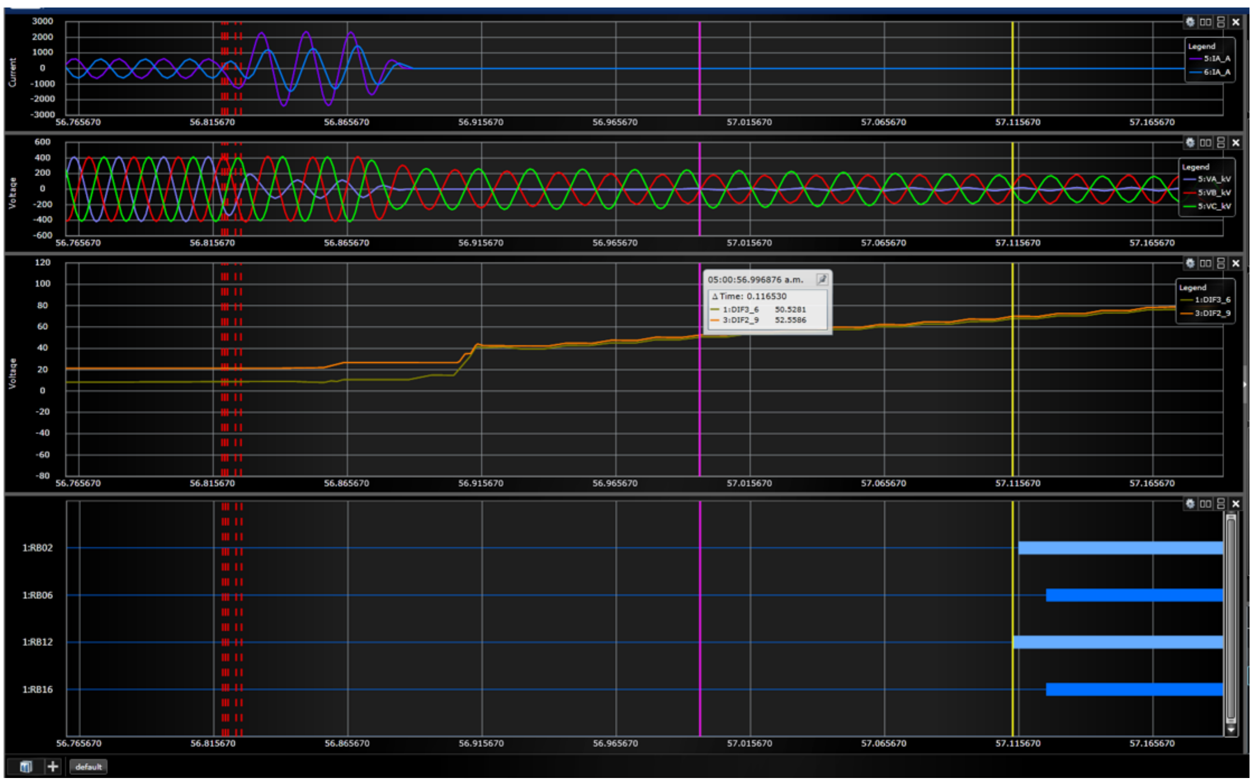

Fig. 17. Real event (operation time) showing operation of DACA2

B. Field Event Analysis

A three-pole opening event of the Poroma-Ocoña line occurred on February 22, 2016, at 5:00:56 a.m. Records of PMCU equipment at both ends of the line provided by Cerro Verde were used to analyze the event.

Fig. 17 shows the operation of the DACA2 logic. The first section shows current into Poroma-Ocoña at both ends of the line (i.e., measurements from PMCU4 [5:IA_A] and PMCU5 [6:IA_A]). The second section shows three-phase voltage at Poroma substation (i.e., measurements from PMCU5 [5:VA_kV, 5:VBA_kV, and 5:VC_kV]). The third section shows the angular difference between PMCU3 and PMCU6 (1:DIF3_6) and the angular difference between PMCU2 and PMCU9 (3:DIF2_9). The fourth section shows the trip binary elements related to the DACA2 logic into PMCU4. These elements are trips from the dual-redundant RAS systems (RB02 and RB12).

The time for the real event is measured from when the threshold of 50° for both pairs of angle differences is exceeded (magenta vertical line) and when the first trip signal indication is received from the PMCU in Poroma substation (yellow vertical line). The gray box shows that the operation time of the RAS was 117 ms. Considering the intentional delay of 50 ms, the actual RAS operating time was 67 ms.

X. Conclusion

The Peruvian power system required a solution to maintain stability when transmission capacity was lost in the southern region. A RAS was implemented that uses synchrophasor measurements to monitor angle differences and make operation decisions to trip large loads.

The RAS was implemented with PMCUs located in several locations on the 500 kV and 220 kV corridors. The PMCUs send IEEE C37.118 synchrophasor streams to SVPs in two locations to implement predetermined decision logic. The contingency detection logic is based on angular differences and arming conditions to increase the security of the decision. The operation of the RAS logic requires the sending of trip signals to LSCs that open predetermined loads, mitigating the loss of transmission capacity.

The RAS was tested and validated using a real-time power system model. A staged field test was used to validate the installation of the system. A real field event is documented in this paper, illustrating the successful operation of the scheme.

The RAS scheme has operated successfully since the end of 2015.

XI. References

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XII. Biographies

Yofre Jacome graduated as an electrical engineer from the Universidad Nacional de Ingeniería-Lima in Peru. Yofre has taken courses on power system protection in the United States, Germany, and Mexico. His main interests are power system protection and fault analysis. He works as a protective relaying engineer for the Comité de Operación Económica del Sistema Interconectado Nacional (COES), and he is responsible for relay settings in the Peruvian power system. He has experience with transmission, distribution, and generation relays.

Luis Figueroa graduated as a mechanical electrical engineer from the Universidad Nacional de San Agustin in Arequipa, Peru. He also obtained an M.B.A. at Centrum Graduate Business School in Lima, Peru. He is a power systems supervisor and the head of the load transmission control center for Freeport-McMoRan Inc.'s Cerro Verde operations in Arequipa, Peru. His responsibilities include coordination, analysis, and leadership of the high-voltage and extra-high-voltage transmission systems and distribution systems that supply electrical energy to the mining complex. He began his professional career with ETESUR as field engineer, where participated in the implementation of the first regional control center to manage and control the energy and power of southern Peru. He then worked for Red de Energía del Peru, an ISA Group company, performing operational analysis and coordinating substations.

Eduardo Palma received his Bachelors of Science in electrical engineering from the University of South Florida in Tampa, Florida in May 2003, and his Master of Business Administration with a concentration in globalization and international business in May 2012. Eduardo joined Schweitzer Engineering Laboratories, Inc. (SEL) in January 2003 and is the regional technical manager for the Latin America region. He has experience in international sales, applications, automation, integration, and the testing of digital protective relays and industrial-grade communications equipment. Eduardo conducts and provides international technical seminars, technical sales presentations, and training to introduce and implement SEL solutions and services worldwide.

Fernando Calero is a principal engineer in the Schweitzer Engineering Laboratories, Inc. (SEL) international organization. His responsibilities include application support for SEL products, training and technical support for SEL customers, and internal training and mentoring of SEL engineers. He started his professional career with the ABB relay division in Coral Springs, Florida, where he participated in product development and technical support for protective relays. He also worked for Florida Power & Light in the energy management system group and for the Siemens energy automation group. Since 2000, he has worked for SEL as an application engineer. He holds five patents and has written technical papers on protective relaying, remedial action schemes, and other protection and control applications.

Pedro Loza received his B.S.E.E. degree in 1998 from the National Autonomous University of Mexico (UNAM). He also obtained a M.Sc. degree in electrical power systems at UNAM. From 1998 to 1999, Pedro worked in the Electric Research Institute in Mexico. In September 2000, he joined Schweitzer Engineering Laboratories, Inc., where he worked as a protection design engineer and as a field application engineer in the Mexico City office. He is currently a protection engineer, working on protection electrical studies and special protection systems.

Alejandro Carbajal received his electronic engineer 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.

Ashish Upreti is a protection engineer in the engineering services division at Schweitzer Engineering Laboratories, Inc. in Pullman, Washington. He received his Bachelors and Masters degree in electrical engineering from the University of Idaho. He is a registered professional engineer in the state of Washington and a member of the IEEE. He has experience in the field of power system protection and automation, including power management schemes for large-scale industrial power plants.

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