Case Study: Integrate Substation IEDs to Provide Reliable, Independent Dual-Primary Remedial Action Schemes

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Case Study: Integrate Substation IEDs to Provide Reliable, Independent Dual-Primary Remedial Action Schemes

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Abstract—**This paper is a case study in using protective relays, intelligent I/O processors, digital I/O modules, and communications processors to provide dual-primary monitoring and control capabilities for a Remedial Action Scheme (RAS) while also supporting SCADA monitoring requirements for regional transmission. The multifunction protective relays and other intelligent electronic devices (IEDs) create two unique and independent RAS systems with redundant functionality, thus referred to as dual-primary, whereas backup systems refer to reduced-functionality secondary systems. These dual-primary RAS systems work simultaneously or individually as operational and testing situations require. Discussion includes design and implementation of integrated digital communications of data to add RAS and SCADA functionality to mission-critical IEDs. Innovative, real-time communication quality measurements demonstrate that the performance and reliability meet or exceed the requirements of this transmission system.**

One of the independent RAS systems is built with protective relays, and the second is built with I/O processors and I/O modules. They both also connect to independent communications processors to provide engineering access, integrated communications, and monitoring and control, via DNP3 protocol, to an existing SCADA RTU. This design supports two new, redundant, and reliable RAS systems while maintaining and enhancing the existing legacy SCADA connection to the regional transmission SCADA system. We discuss the innovative and proven relay and I/O processor logic configurations, which are used for RAS alarming and tripping decisions, along with the integrated communications design. The design uses products and communications methods that support real-time communications quality monitoring. These measures quantify and verify the reliability of the communications design and real-time performance.

Western Area Power Administration (Western) had used this type of communications previously and considered the demonstrated reliability of the communications method and IEDs as selection criteria during the design stage to assure the success of these mission-critical RAS systems.

I. Introduction

The recently constructed Blythe Energy Power Plant (BEPP), located in Blythe, California, as shown in Fig. 1, is designed to incorporate a gas-fired combined-cycle configuration consisting of two 175 MW combustion turbine generators and one 170 MW steam turbine generator. The 520 MW electrical output is connected to the region's transmission grid via Western's transmission system.

Impacts to existing power systems, typically caused by adding new generation to the established transmission grid, often include overloaded transmission lines, transformers, circuit breakers and other system components that may cause violations of accepted reliability criteria. The North American Reliability Council (NERC), Western Electric Coordinating Council (WECC), and local reliability requirements determine the criteria for California installations, including the new Blythe substation. When Blythe Energy proposed constructing BEPP, Western performed a system study that revealed a maximum of 260 MW could be added without the potential to violate system reliability. To satisfy this constraint, Blythe Energy agreed to construct a 560 MW plant that would accept commanded control from Western to decrease plant output to 260 MW when overload conditions were detected.

Fig. 1. Blythe Power Plant

To mitigate potential reliability problems, Western deployed a RAS prior to connecting BEPP to the transmission grid. This RAS system provided generation reduction capabilities during transmission line overload conditions. Recognizing the increasing importance of reliable operation of RAS and other special protection schemes (SPS), Western chose to implement this system in a dual-primary design so that no single device or connection would be a single point of failure. This paper discusses the design and implementation of these RAS systems using protective relays, communications processors, I/O processor, and digital I/O modules.

II. Design Criteria

Western recognized the need to implement a RAS system to prevent or mitigate potential violations. The RAS would reduce or terminate generation output during an emergency condition, should the new generators, while connected to the transmission grid, create system conditions that violate accepted reliability criteria. With the interconnection of this new power plant, Western designed a RAS system to meet its internal reliability requirements in addition to satisfying both NERC and WECC reliability criteria. The design includes full redundancy via completely unique and separate hardware systems and unique and separate communications paths to monitor and control the RAS scheme. For the BEPP RAS installation, this included two online systems operating in parallel (dual primary), performing independent monitoring, automation, and controls based on transmission line conditions.

III. RAS

Maintaining system reliability without RAS would have limited BEPP's generation to a maximum of 260 MW, half the plant's output. To add full plant capacity to the transmission grid and meet WECC reliability criteria, required a fully redundant RAS system with a scheme that would prevent grid overloading, even in the unlikely event of a total RAS failure. These were the guidelines used to develop the RAS action logic. Another requirement was that, in the unlikely event that dual-primary redundant RAS systems fail simultaneously, the output of BEPP be limited to 260 MW.

The BEPP RAS system is composed of four subsystems working together to provide monitoring for transmission line current overloads. When the RAS system detects overloads, it triggers transmission of a 30-minute alarm or a transmission trip command to BEPP for generation reduction based on present load conditions. The four subsystems include the following:

- Blythe Substation (BLY)
- Buck Boulevard Substation (BKB)
- Blythe Energy Power Plant (BEPP)
- Phoenix Operations Control Center (POCC)

These systems work together to monitor five 161 kV transmission lines from BLY for the following current overload conditions:

Condition One. One or more transmission lines are loaded by greater than 100 percent but less than 120 percent capacity.

Condition Two. One or more transmission lines are overloaded by greater than 120 percent capacity.

When Condition One, referred to as 100 percent ALARM, is detected, the RAS transmits an alarm signal from BLY to BEPP, via BKB, where the power plant operator ramps down generation to 260 MW within 30 minutes. If generation reduction is not performed within the 30-minute window, the RAS automatically transmits a trip signal to trip one of the combustion turbine units and reduce the output on a second unit. The trip command results in the shutdown of one combustion turbine, a 175 MW unit, and the reduction of the steam turbine generation to 85 MW. This results in a combined reduction of 260 MW of generation, which leaves the required 260 MW output.

When Condition Two, referred to as EMERG OVLD TRIP, is observed for 20 consecutive seconds, the RAS transmits the trip signal to BEPP, which clamps down power generation to 260 MW as described in Condition One.

If integrated RAS system diagnostics detects a communications or equipment failure within both primary A *AND* primary B RAS systems, the trip signal is transmitted to automatically trip one of the combustion turbine units and reduce output to the steam turbine generator. These actions limit the output of BEPP generation to the aforementioned 260 MW, which prevents overload conditions from being possible even if they do not presently exist. It is interesting to note that the communications protocol used in this design automatically detects error conditions in message transmission. Other Ethernet-based methods are not designed to automatically detect these errors, and no channel performance and availability calculations are possible. This is because messages are transmitted by exception or at an infrequent rate to support "heartbeat" or "watchdog" alarm detection. Logic can be added to detect if a heartbeat message is not received but not if a change-of-state message is not received using these Ethernet methods. Ethernet methods, therefore, are presently considered less reliable for RAS systems.

The RAS substation implementation uses BLY and BKB IEDs and digital I/O modules to implement this RAS system with redundant functionality. The primary A RAS system uses a bus differential protective relay functioning as the RAS controller (PRC—**P**rimary A **R**AS **C**ontroller), overcurrent protection relays, a communications processor (CP), and a digital I/O module to monitor and issue controls from BLY to BKB and on to the power plant, BEPP.

The real-time redundant primary B RAS uses an I/O processor as the RAS controller (BRC—Primary **B** **R**AS **C**ontroller), digital I/O modules, and CP to provide the redundant RAS functions. Utilizing an RTU, the POCC remotely monitors and controls RAS operations for both primary A and primary B systems. All RAS alarms and statuses received by POCC SCADA will eventually be provided to BEPP SCADA via an Inter-Control Center Protocol (ICCP) link that is under construction.

A. Blythe Substation RAS

BLY is a transmission hub interconnecting a number of Western's 161 kV transmission lines, a Southern California Edison (SCE) line, and an Imperial Irrigation District (IID) line.

The BLY dual-primary RAS system monitors for current overload conditions, makes decisions based on those conditions, and implements the appropriate RAS action. Parker Dam (PAD), Headgate Rock (HDR), Knob (KNB), Eagle Mountain (EGL MTN), and the BLY transfer bus (TBUS) currents are monitored for the two conditions previously mentioned. Additional inputs, monitored by the BLY RAS, include Southern California Edison's Eagle Mountain Substation breaker maintenance status, integrated IED self-diagnostics statuses, and RAS on/off controls issued by POCC via the substation RTU.

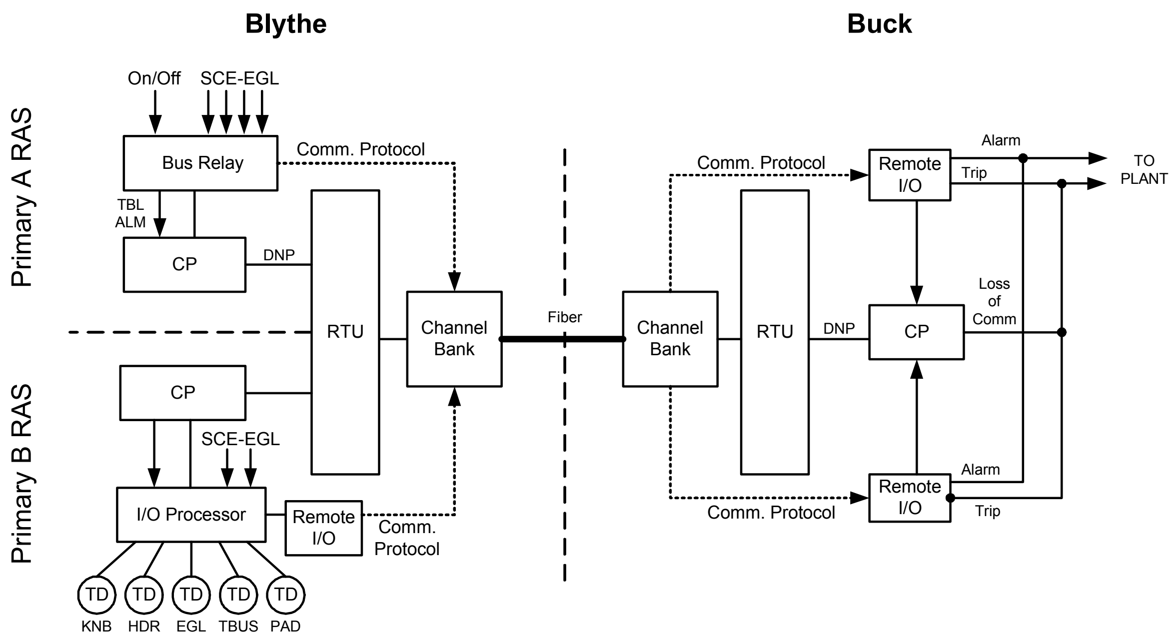

Fig. 2. RAS System Drawing

B. Primary A RAS (see Fig. 2)

1) Primary A RAS Controller (PRC)

The BLY PRC is created from a single protection IED (see Fig. 3) that was selected for the following features:

- Individual CT winding inputs for each transmission line
- Integrated protection logic
- Integrated free-form control logic
- Dedicated communications port and secure protocol to transmit RAS alarms to BKB
- Dedicated separate communications port to support monitoring via CP
- Discrete inputs to monitor Southern California Edison's Eagle Mountain Substation breaker status and RTU RAS on/off control
- Integrated RAS communications diagnostics
- Integrated self-diagnostics alarm

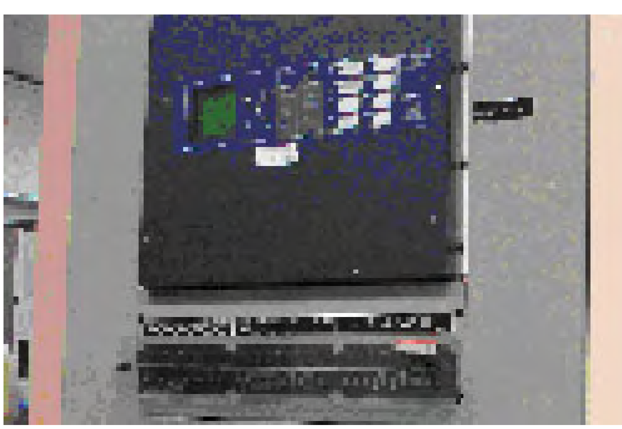

Fig. 3. Primary A RAS Controller

The PRC uses 12 of the 18 available CT winding inputs to monitor all three phases of PAD, HDR, KND, and TBUS lines. Protection logic settings are used to monitor the overcurrent element of each phase with a two-second pickup. If any overcurrent element picks up, the 100 percent ALARM is generated. Protection free-form logic also starts a timer when the 100 percent ALARM is detected using phase overcurrent elements with 30-minute pickups. If this violation is not corrected and the timer times out, the PRC protection logic generates a trip signal. The 120 percent emergency overload condition, referred to as EMERG OVLD TRIP, is also detected using phase overcurrent elements with a 20-second pickup. When any line phase meets the pickup condition, the PRC generates a trip signal and transmits it to BKB.

When any one of the two conditions is detected, the trip is immediately transmitted to BKB using high-speed communications over a dedicated serial communications channel to a remote digital I/O module, which in turn, rapidly converts it into an output contact. The protocol used to communicate these alarms incorporates multiple security features to guarantee successful transmission between the RAS controller and the remote digital I/O module. These synchronization checks include receive and transmit IDs to prevent accidental loop back, byte checks for parity, framing and overrun errors, and multiple message redundancy checks. A serial-to-fiber converter transmits the alarm and trip signals over fiber-optic cable to BKB where they are received by the digital I/O module, functioning as the PRC's extended I/O. Each signal received by the digital I/O module closes an associated contact output, which the POCC monitors. The PRC continually monitors the RAS alarm communications channel between BLY and BKB remote digital I/O module to make sure none of the security features incorporated in the protocol are violated. The PRC instantly detects any of the above mentioned potential transmission errors or any time that an expected message is not received from the I/O module in an appropriate amount of time. Though rare, if a transmission error disruption is detected, the PRC creates a communications alarm (PRIMARY

RAS COMM FAIL) and forwards it to the polling CP. The CP then transmits it to the POCC via the RTU.

The start time and end time of each disruption are recorded and the difference is calculated as the disruption duration. If the disruption lasts longer than the customizable time duration threshold, the channel monitoring function within the PRC also detects that the disruption duration has exceeded this threshold. This causes the PRC to create a communications alarm, customizable for each channel, when it detects that this threshold has been exceeded. The duration is set based on the existing communications system performance to avoid nuisance alarms.

RAS communications channel unavailability is the ratio of the amount of time that the channel is unavailable to pass messages (determined as the sum of all disruption durations) to the total recording interval time. This is calculated by dividing the aggregate of all outage durations by the total time span for a recording period presented as ppm unavailability.

All PRC alarm statuses and load current values are viewed locally using the RAS controller's integrated HMI LCD and LED displays.

2) Eagle Mountain Line Monitoring

The EGL MTN line has individual primary and backup overcurrent relays monitoring each RAS alarm condition as shown in Fig. 4. These relays use CT winding inputs to monitor A-phase currents and protection logic to identify the three RAS alarm types as described previously. When an alarm condition is detected, an associated relay output contact closes. This sends the alarm status to a discrete input on the PRC and indicates the alarm type. The PRC uses internal mapping logic to direct the alarm status to the PRC's RAS communications channel for transmission to BKB's digital I/O module and on to the BEPP DCS. This status is also sent to the CP via client-server polling data acquisition and up to the POCC via the RTU.

Fig. 4. Eagle Mountain Line RAS Monitoring Relays

This SCE-maintained substation includes an additional status alarm, EGL SOLID (within the protective relays associated with the breakers), which alerts Western when the breakers are out for maintenance. When this condition occurs, an input contact on the PRC is closed. This detected change of state is used within the internal logic and causes the PRC to ignore all alarms received from EGL MTN.

3) Self-Diagnostic Alarms

The PRC continuously runs many self-tests to detect out-of-tolerance conditions. These tests run simultaneously with the protection and free-form logic, without degrading system performance. The controller reports out-of-tolerance conditions as a status warning or status failure. For conditions that do not compromise the controller, yet are beyond expected limits, a warning alarm is asserted. A severe out-of-tolerance condition causes the controller to declare a status failure and enter a protection-disabled state. During this disabled state, protection element and trip-logic processing is suspended, all control outputs are de-energized and the controller disable alarm is asserted. The primary CP continually monitors for each of these alarms and when detected, reports them to the RTU and on to the POCC where a technician is dispatched to the substation. The system continues to operate by relying on the online primary B RAS system. Though statistically it is nearly impossible, in the extremely rare instance that both the PRC and BPC status alarms are asserted simultaneously, the CP at BKB interprets the condition as loss of RAS A and B communications and sends a trip signal to BEPP that automatically trips generation.

C. Primary B RAS (see Fig. 2)

1) Primary B RAS Controller (BRC)

The BLY BRC is created from a single I/O processor IED (see Fig. 5) that was selected for the following features:

- Individual analog inputs for each transmission line
- Integrated protection and control logic
- Integrated free-form control logic
- Discrete outputs connected to an I/O module with a dedicated communications port and secure protocol to transmit RAS alarms to BKB
- Dedicated separate communications port to support monitoring via CP
- Discrete inputs to monitor Southern California Edison's Eagle Mountain Substation breaker status and RTU RAS on/off control
- Integrated RAS communications diagnostics
- Integrated self-diagnostics alarm

Fig. 5. Primary B RAS Controller

The primary B RAS system uses a different combination of IEDs than does the primary A RAS, so as to eliminate common mode failure. This system monitors transmission line conditions, performs automation logic, and generates and transmits alarm and trip signals identical to those provided by the primary A RAS system. This parallel system uses an I/O processor to monitor RAS input analog quantities (line currents from transducers) and generate alarms. It also includes a digital I/O module to transmit alarms to BKB and on to the BEPP DCS system and a CP to collect RAS data from the I/O processor and digital I/O module. The CP then passes it on to the POCC via the substation RTU.

2) I/O Processor

The I/O processor, acting as the primary B RAS controller (BRC), uses configurable analog input, discrete input, and contact output cards to provide the same functionality as the PRC. The analog card, with configurable input levels, monitors the A-phase currents on each of the four transmission lines entering the BLY and the transfer bus. The discrete input card monitors the EGL MTN line maintenance alarm, digital I/O communications diagnostics, and RAS on/off control signal from the RTU. The output card is used to transmit RAS alarms to a local digital I/O module, which communicates these alarm and trip signals to the remote digital I/O module, located at BKB, and then on to the BEPP DCS.

Simple I/O processor settings are applied to create analog deadband alarms, pickup timers, and Boolean logic—used to process each line's current value and RAS status inputs. If the programmed conditions are met, the appropriate current overload alarms are generated using a contact output connected to a local digital I/O module input. The I/O module distributes the alarm to BKB and on to the BEPP DCS. The I/O module also distributes the alarm to the discrete input contacts on the CP that are associated with the primary B RAS. At B RAS, the RTU passes the input contacts to the POCC.

The I/O processor includes a front-panel display and annunciator LEDs, which provide local operators with individual current values and overload alarm conditions for each of the four lines and the transfer bus.

3) Digital I/O Module

Local and remote digital I/O modules, as shown in Fig. 6, are installed at BLY and BKB and are used by the online primary B RAS to communicate the 100 percent ALARM and EMERG OVLD 20 SEC TRIP alarm to BEPP DCS and the POCC. Integrated fiber-optic transceivers and fiber-optic cable are used to mirror the input contacts on the local module to the output contacts on the remote module. The two I/O modules communicate to the remote digital I/O module in the primary RAS system using the same secure protocol incorporated by the PRC.

When the BRC detects a RAS alarm, it closes an output contact that the local digital I/O module monitors. The status is transmitted to the BKB remote I/O module where the associated output contact is closed, sending the BEPP DCS the detected alarm condition or trip control output. The local digital I/O module is also wired to the integrated input of the CP associated with the primary B RAS for monitoring by the POCC.

Each I/O module includes annunciator LEDs and a communications alarm contact to indicate intermittent or total communications failures. This alarm contact is wired to the CP, which is associated with the primary B RAS, for monitoring by the POCC.

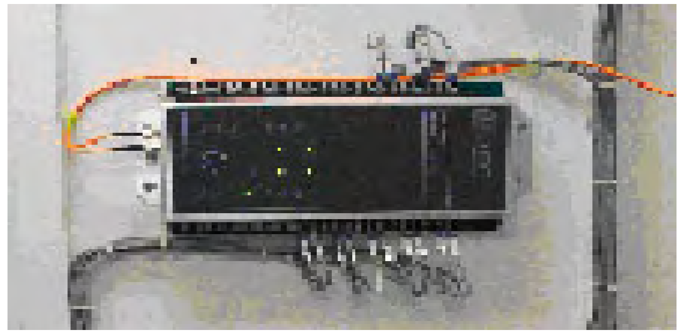

Fig. 6. Digital I/O Module

D. Communications Processor

Each RAS controller's CP plays an important role in managing the RAS system. They continuously update POCC operators with real-time data from all the system's electrical components while also adding real-time system health monitoring. The CPs associated with both the primary A and primary B RAS systems are responsible for tracking and reporting the following data to the POCC system operators:

- Instantaneous load currents and alarm statuses
- Primary A and primary B RAS communications channel status
- Southern California Edison's Eagle Mountain Substation breaker maintenance status
- CP communications status between PRC and BRC
- PRC and BRC internal diagnostic status
- CP internal diagnostics status

These data are collected by communicating directly to the RAS controllers and by using integrated I/O with the CPs to monitor contact input alarms. The CPs are configured to process and organize the data prior to sending the data to the RTU over a separate serial communications channel.

In addition to managing the RAS data for the POCC SCADA system, the CPs provide engineering access to the PRC, BRC, and EGL MTN protective relays and other IEDs over a separate communications channel. Using this capability, Western engineers can remotely access IED settings, detailed diagnostics, event reports, and SER logs without interrupting alarm logic or SCADA reporting.

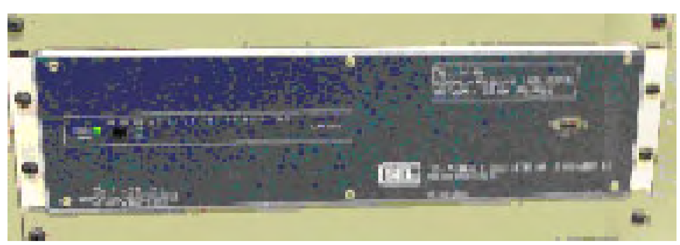

Fig. 7. Communications Processor

E. Buck Boulevard Substation

BKB is located within 100 yards of the plant and provides the BEPP connection point to the grid. Its RAS subsystem includes the following:

- Primary A RAS digital I/O module
- Primary B RAS digital I/O module
- Communications processor (CP)

The digital I/O modules receive RAS alarms and controls from the BLY primary A and primary B RAS systems via fiber-optic cables and integrated fiber-optic transceivers. When an alarm is detected, the digital I/O modules close two contact outputs. The BEPP DCS monitors one contact, the local CP input monitors the other for transmission to the POCC via the BKB RTU. The BKB CP also monitors the communications status of each I/O module. If a failure is detected on one RAS system, the POCC is notified and a technician is dispatched. In the extremely unlikely event that both systems experience problems, the CP uses an integrated output contact to notify the BEPP DCS to automatically trip one of the 175 MW combustion turbine units.

F. Communications Architecture

The RAS system communications architecture uses Western's communications network and individual microwave links to satisfy the redundant communications requirement. PRC and BRC use separate fiber-optic communications channels to provide the primary communications link between BLY and BKB, and microwave communications provide redundant paths. The POCC uses a T1 channel to communicate RAS conditions to BEPP via ICCP protocol.

The RAS system is currently operating under WECC conditional approval of the communications system. To complete the WECC communications requirements, Western is in the process of adding a new fiber-optic cable to separate PRC and BRC communications to BKB, which are presently in one conduit. They are also adding microwave links to complete the redundant paths.

IV. Conclusion

Adding new generation to the transmission grid can impact the existing power system by potentially violating reliability criteria. To prevent these violations with the addition of BEPP, Western designed and installed a redundant RAS system to meet specific functionality required by the WECC along with its own internal standards. This dual primary system used the flexibility of substation IEDs and digital I/O modules to meet these requirements.

A bus differential relay was chosen as the primary A controller because of its capability to monitor CTs for each phase of the five transmission lines and its capability to provide protection and free-form logic to verify and communicate each RAS alarm condition. The I/O processor was selected as the primary B controller because it provided the required functionality while reducing costs and preventing equipment common mode failure. Both systems provide real-time internal equipment and communications diagnostics allowing the POCC to closely monitor both RAS systems and both communications paths to immediately dispatch a technician if equipment or communications problems are detected.

Secure communications of each alarm condition between BLY and BEPP are met using separate fiber-optic channels, multiple security features inherent in the communications protocol, and digital I/O modules. These IEDs provide fast response times to the alarm and unit trip signals.

Western deployed CPs as part of each system to manage transmission line monitoring, equipment and communications diagnostics, status and alarm data, and remote RAS controls. They also used the capability of the CP to provide engineering access to each RAS controller without interrupting SCADA monitoring and control.

The final requirement to provide isolated redundant communications paths between BLY and BKB is nearing completion.

V. Acknowledgements

The authors gratefully acknowledge the invaluable project contributions of Maher Nasir, Nick Saber, Dan Hamai, and Lewis Trujillo of Western; Frank Ashrafi and Ed Romero of SCE; and Jack Hochheimer, Bob Bruno, and Chuck Cadiente of FPL-Blythe Energy.

VI. Biographies

Michael E. Agudo is lead electrical engineer for Desert Southwest Region, Western Area Power Administration in Phoenix, Arizona. His group is responsible for system protection engineering and commissioning. He received his BSEE, MEE and D.Sc. (EE) degrees from U.S. Naval Academy, Catholic University of America, and George Washington University respectively. He was previously employed by Rural Utilities Services as chairman of the Technical Standards Committee, Naval Surface Warfare Center as a systems analyst, and Potomac Electric Power Company as a substation test engineer. He was a registered professional engineer in Washington, D.C. and Virginia.

David M. Fox received his BS in engineering (electrical option) from the Colorado School of Mines, Golden, Colorado, in 1991 and is a registered professional engineer in Colorado. He is currently employed in the System Control Branch of Western Area Power Administration where he provides technical direction for Western's substation automation and integration projects.

David J. Dolezilek received his BSEE from Montana State University in 1987 and is now the technology director of Schweitzer Engineering Laboratories, Inc. He is an electrical engineer with management and development experience in electric power protection, integration and automation, communications, control systems, SCADA and EMS design, and implementation. He is the author of numerous technical papers and continues to research and write about innovative design and implementation affecting our industry. Dolezilek is a patented inventor and participates in numerous working groups and technical committees. He is a member of the IEEE, the IEEE Reliability Society, CIGRE working groups, and two International Electrotechnical Commission (IEC) Technical Committees tasked with global standardization and security of communications networks and systems in substations.

Robin R. Jenkins received his BSET degree from California State University, Chico. From 1984 to 1988, he was employed as a systems integration engineer for Atkinson System Technologies. From 1988 to 1999, he was with the California Department of Water Resources, where he worked as an associate and then senior control system engineer. In 1999, he joined Schweitzer Engineering Laboratories, Inc., where he currently holds the position of integration application engineer, responsible for technical support, application assistance and training for SEL customers in the southwestern United States.

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