Implementation and Operational Experience of a Wide Area Special Protection Scheme on the Salt River Project System

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1. Abstract

As existing transmission system infrastructure is challenged to support loads beyond original design limits, the implementation of "wide area" Power System Protection Systems (PSPS) is often required to maintain transmission system integrity. Such a system, with stringent performance and availability requirements, has recently been designed and installed on the Salt River Project (SRP) system. In particular, measurements of generation levels on one side of the system must affect load balance on the other side of the system over 150 miles in less than 1 second.

This paper starts by presenting the need for the PSPS and the resulting design requirements. It then discusses the architecture that resulted from the requirements and the subsequent implementation and testing issues. Actual operation and performance results, including end-to-end timing tests, will be presented. The paper concludes with a discussion of desired improvements in the architecture and new solutions that are available through Generic Object Oriented Substation Events (GOOSE), Virtual LAN (VLAN), and priority messaging technologies that are now available through the IEC61850 communication protocol.

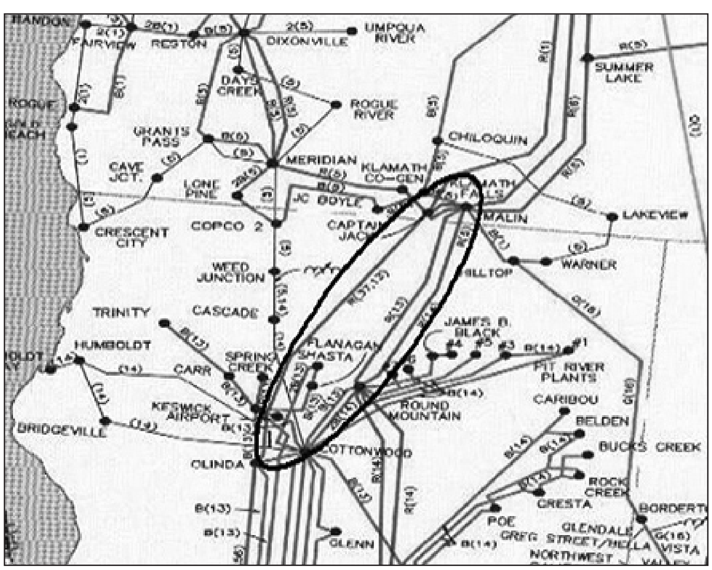

Fig 1.
California-Oregon Intertie Area of Concern

2. Introduction

Palo Verde is the largest nuclear power plant in the western hemisphere and is located approximately 50 miles west of Phoenix Arizona, in the United States. The power plant has three reactors that originally produced 1287 MW each, yielding a total output of approximately 3860 MW. The plant is situated in a transmission corridor that supplies power to the Los Angeles basin and Southern California. Consequently, loss of multiple units at Palo Verde can cause voltage dips, frequency excursions, and cascading problems throughout the Western Electricity Coordinating Council (WECC) region. WECC modeled the loss of two of these units to determine stability guidelines for loss of single blocks of generation in the region. With the originally planned generation output levels, the WECC region remained stable with the loss of 2 units and, as such, no remedial action was needed.

The design of the original units allowed room for augmenting the output of the generators. The owners of Palo Verde decided this additional generating capability and re-rated the output of the generators. This re-rating initiated a new study to review the stability in the WECC region. In the re-study, it was found that the loss of two units plus this upgraded margin caused problems on flows of the California Oregon Intertie (COI – Path 66 – see Figure 1). Specifically, the studies indicated that the loss of these units could cause COI lines to overload and also indicated that the frequency in the region would decay to slightly less than 59.75 Hz. Given this finding, mitigation was required to resolve this problem. Studies showed that shedding the up-rated portion of the generation would mitigate the problem. This required the implementation of a load-shedding scheme to shed only a value of load equal to the upgraded amount. Since the first unit was being upgraded by 120 MW, the system had to shed 120 MW on the loss of two units operating at the up-rated level.

The scheme to implement this load shedding qualified as a Remedial Action Scheme (RAS) by the Western Electric Coordinating Council (WECC). The WECC Region provides a review process of Special Protection Schemes (SPS) or RAS in the region by a Subcommittee. The SC reviews any remedial action scheme that is required to prevent cascading problems from affecting other control areas. The SC also provides a stringent examination for credible failures of the scheme. The scheme must not have common mode failures that would prevent the successful operation and subsequent mitigation.

The owners needed the solution implemented quickly so that the retail sales of the upgrade could be realized. The quick mitigation scheme that was chosen was to arm a pro-rata share of the ownership (plus some margin for error) to trip at an underfrequency value of 59.75 Hz. This solution was approved by WECC which allowed the owners to proceed and utilize the up-rate of Unit 2. However, each owner assumed a certain risk with this solution as other electrical disturbances in the region could also cause frequency excursions below 59.75 Hz and result in an undesirable load shed. It should be noted that this under-frequency load shed scheme was always "armed" – even when it didn't have to be. The owners wanted to remove this exposure as soon as possible to provide a more dependable and secure solution.

The solution decided on by the owners was to provide an intelligent tripping system that would arm when needed and provide load shedding in various locations throughout the owners control area. It was determined very early that the cost of secure, redundant digital communications across all the owners' territories and across three states was cost prohibitive.

The targeted implementation time was five months and the only practical solution was to implement the load shed in the Phoenix area, as Palo Verde is located only 50 miles to the West of the Phoenix metro area. This decision reduced the scope of the project to a magnitude that could be achieved in the short time frame targeted as SRP's digital communication system was well distributed in this region to allow the load shedding to be dispersed through the metro area and thus reduce the need to drop one large block of contiguous load.

As mentioned earlier, the interim under-frequency load shed solution with relays set at 59.75 Hz was armed at all times and had the potential of operating for non-generation issues. To prevent inadvertent load shed based on frequency alone, logic would be needed that could dynamically measure the unit loading, arm the required amount of load to shed, and only operate the scheme when the proper generation loss criteria were met. This scheme required the relays to measure the generation level of each unit and sum the totals of each pair of units. This sum could be compared to a set point equal to the original output of two units and provide arming if the paired unit loading was exceeded.

As it was neither practical nor desirable to shed one large block of contiguous load, a scheme was designed, using SRP's digital communication system, to allow load to be shed in smaller blocks at many locations throughout the Phoenix metro area. In creating this load-shed scheme, various loading and timing parameters had to be considered. The load profile of each site had to be measured and total load available to shed had to be calculated to insure enough load was available at all times. The common mode failure of the communication system needed to be considered and no single failure could prevent the system from operating. Critical customers would have to be avoided.

The load in the Phoenix area typically reaches a peak in the late afternoon and settles at its minimum values in the early morning hours with a minor peak in mid-morning. The monitored sites were required to provide at least 120 MW of sheddable load at the system minimum and were found to provide up to 650 MW of load at system peak. The system needed to be smart enough to arm and unarm sites as needed and still guarantee that enough sites were available to provide 120 MW of sheddable load when needed. The available load at each site was added together to determine the load profile of the monitored system. As a site was chosen, the monitored load profile would be re-examined to make sure that the required mitigation amount (120 MW) was always available. The overall system arming and load selection logic is shown in Figures 2a and 2b respectively.

Besides the availability of sheddable load in a station, the choice of which substations to select in the shed scheme included the availability of redundant communications. Although most SRP distribution substations contained SONET multiplexers, not all of the nodes were part of a ring that provided redundancy. Ultimately, a site was chosen if it had sufficient load, was not

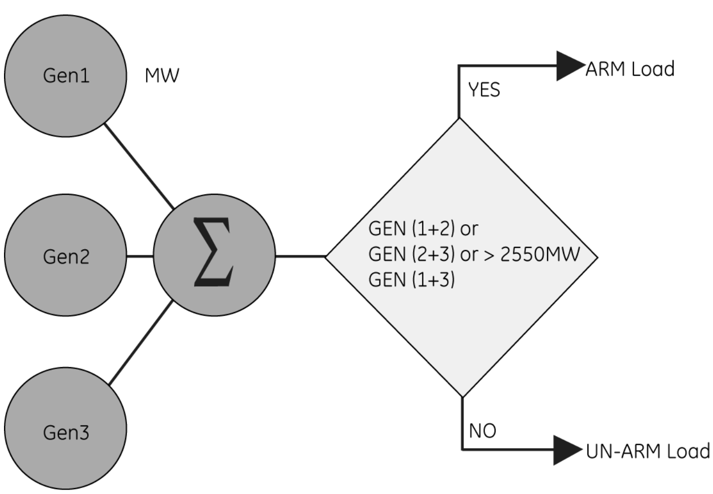

Fig 2a.
Load Shed Arming Logic

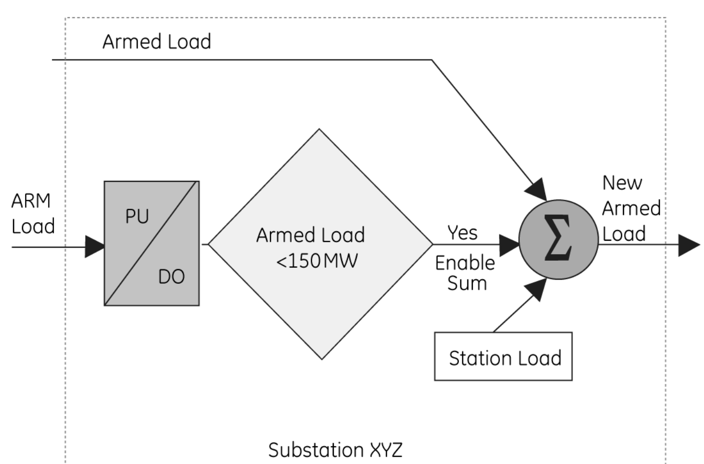

Fig 2b.
Load Calculation Logic

located on another site's communication ring, and did not have any critical customers such as hospitals. The iterative process of choosing sites and examining load and communication ring availability produced a total of 14 sites. These sites provide a total of at least 150 MW of sheddable load at all times. The 150 MW provided a 30 MW margin in case of failure of multiple components, numerical roundoff, or unavailability of sheddable load in a station.

3. System Design

Given the requirements of optimized load shed, high availability, and performance, the system design was centered around the interface of modern measurement relays as connected into SRP's SONET communication system. SONET or Synchronous Optical Network is a fiber-based communication system that is typically built in a ring configuration (see Figure 3). Data from any node in the ring is sent two directions around the ring to the intended receiver(s). If any part of the ring structure fails, the receivers can dynamically switch to the alternate data source in as little as 3 ms. To implement high system availability, redundant measuring relays were implemented – each with redundant communication channels, namely, an Ethernet channel and 64,000 bps synchronous serial communication channels via a G.703 physical interface.

The solution required watt flows to be measured at all 15 sites and then communicated to each site. The power flows at the generator and load centers were input into the measuring relays from 0 to 1ma watt transducers at each location. As the available communication data formats only supported single bit status information, in order to transmit power in this format, it was necessary to scale the computed power into 8-bit integers which could then be mapped into 8 status points in the respective messages.

In the case of the Ethernet channel, the UCA Generic Object Oriented Substation Event or GOOSE (IEC61850 Generic Substation Status Event – GSSE) was used as the message carrier. The GOOSE is a multi-cast message originally designed to carry binary state information among multiple relays connected to the same Ethernet network inside a substation. As a multicast message, the GOOSE can be sent to many other devices through an Ethernet switch (Level 2) but cannot be routed, as the GOOSE message does not contain any routing (Internet Protocol – IP) information. One of the interface options into the SRP SONET multiplexer was an Ethernet card, which acted as a level 2 switch. As such, when connected to the measuring relay, the SONET Ethernet card would accept and carry the multi-cast GOOSE message over the SRP SONET network to any node equipped with an Ethernet card. This application was able to create a "free range", wide area GOOSE.

With the G.703 communication system, each measuring relay had two G.703 – 64000 bps ports which were configured to transmit information out of both ports on a change of state. This capability enabled the G.703 communication path to be configured in a ring. At each of the 14 nodes in the ring, the received data was captured for local use and then repeated for the other devices in the ring to be able to access the transmitted information. The G.703 ring topology enabled the implementation of several communication diagnostics such as ring timing, high packet error rate, and broken G.703 ring detection. Data integrity on both media was ensured by data integrity checking through a 32-bit Cyclical Redundancy Code (CRC).

Both the Ethernet and the G.703 interfaces were connected into the SONET multiplexer system. As some of the rings were only connected with single tie connectors, the communication paths of both communication interfaces were designed to be different to avoid the possibility of a single point failure taking the system down.

To start the scheme process, a decision had to be made as to when to "arm" the system. The criteria, as stated above, was that the total power output of any two units was greater that 2550 MW (see Figure 2a). To implement this function, the power

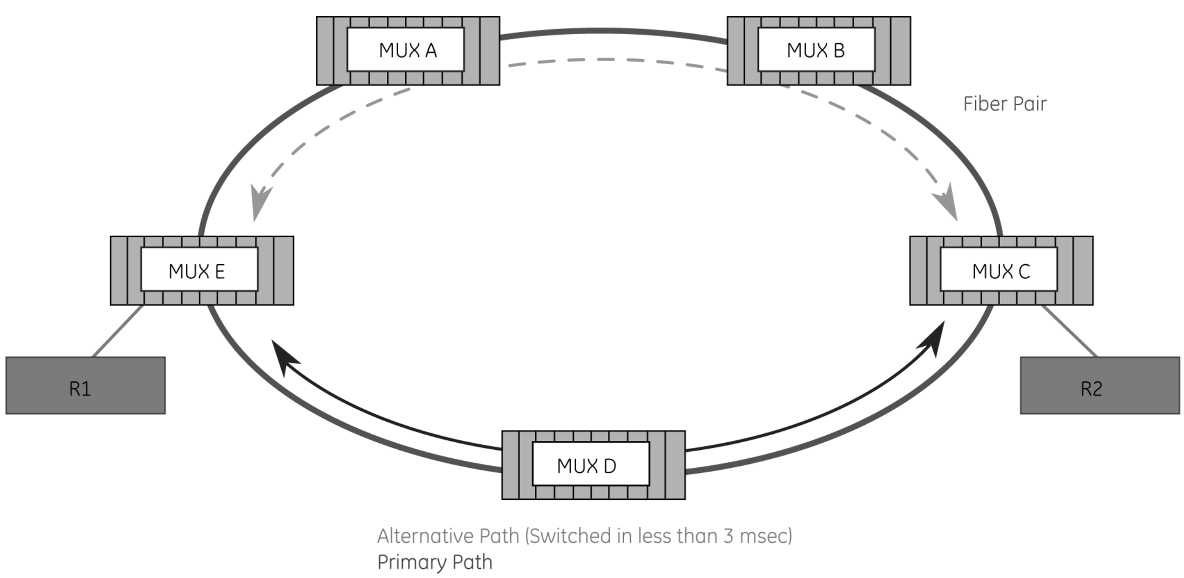

Fig. 3
SONET Concept

output of units 1 and 2, units 2 and 3, and units 1 and 3 was measured and summed. Each power sum was then compared against the arming threshold of 2550 MW. If any of the three combinations of unit power outputs was greater the threshold, an "arming" signal was sent to all the connected substations (14 of them) in the RAS.

Given that an arming signal had been issued and after a programmed delay time, the first unit in the string would "arm" itself to shed load and would then transmit the amount of load it could shed (read from a 0 to 1ma transducer) to the next substation in the string. The "summed" watt value was also transmitted back to Palo Verde where it was compared against the set point of 150 MW (see Figure 2b). If the arming signal was still high after a pre-programmed amount of time, the next substation in the string would then add its MW contribution to the "total" and send the total to Palo Verde. If the total amount of "armed" Watts was greater than 150 MW, the arming signal was turned off.

A "digital summer/comparator" was used to add the various MW values together and to check the limits of the armed load. The sign of the "B" input could be dynamically changed to perform subtraction if desired (see Figure 4). The comparator had a pickup level setting, direction of comparison (over limit/under limit), compare mode (absolute vs. signed), and a hysteresis range. If the summed value of available load reached the required shed value (150 MW), then no more load was sought to arm. As the transmitted data was only 8-bit, only 1% of full-scale could be achieved in a measurement. As such, the quantization limits of the digitizers had to be factored into the set points and summing logic. These numerical limitations resulted in additional load needing to be armed and arming of the system at generation values less that needed.

Given an armed system, "shedding" logic was needed to detect loss of generation at Palo Verde. The shedding logic looked for the tripping of two Palo Verde units within 5 minutes of one another and would then issue a "shed" command. Once initiated, the "armed" devices, based on a pre-calculated schedule, would sequentially open the substation breakers over the course of 1 second. It should be noted that there is no automatic restoration with this system as load restoration must be coordinated with the system security coordinator and the loads are manually restored once permission is given.

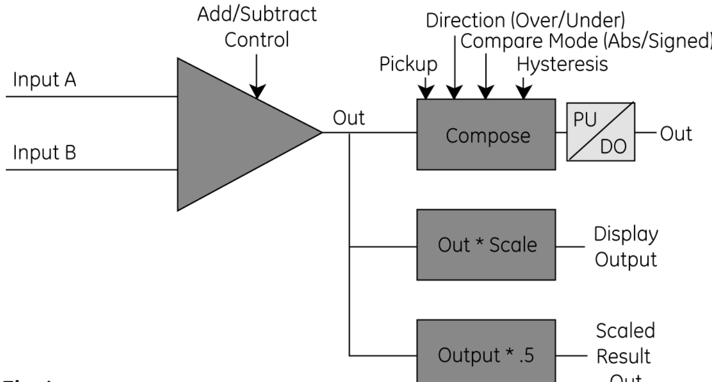

Fig 4.
Summer - Comparator Function

Over the course of the day, the load at the various substations would normally increase and where at the start of the day, 150 MW would have been armed, the armed load would typically increase significantly above this value. To minimize the amount of load armed, when the revamped total exceeded 250 MW, a "disarm" command was issued. Given this command, the selected substations, in reverse sequence, would remove themselves from the shed group thereby minimizing the amount of load shed and maintain an armed load band width of 150 to 250 MW.

The two systems operated independently and the variance of the digitizing and summing features would sometime lead to each system arming and unarming sites at slightly different times. Occasionally each system would get "out-of-sync" and have different sites armed. This was undesirable and would result in the shedding of more load than was needed if a trip occurred. Because each system would maintain the 150 MW of armed load but with different sites. If the two systems became unsynchronized, the operators would have to cycle each system OFF and then ON (one at a time). As the systems powered up they would re-synchronize and once again, arm just the load needed.

4. Implementation Issues/New Solutions

In the initial testing of GOOSE communication, several routers were encountered in the desired paths that prevented passage of the GOOSE message. In contacting Cisco (the router manufacturer) it was discovered that an add-on software package was available known as Cisco's Internetworking Operating System software or IOS. The IOS software package was configurable such that it could be programmed to "bridge" any multi-cast data packets – such as GOOSE. With the IOS properly configured in the routers, GOOSE packets were demonstrated to be switchable throughout the SRP network. In the actual implementation, a "flat" Ethernet ring was constructed such that there were no routers to pass through and, as such, configuration of the IOS software was not needed in this implementation.

Since this system has been installed, a new solution space has been made available through the communication capabilities of IEC61850 GOOSE. IEC GOOSE brings with it several desirable new features for future implementations, namely:

- The ability to directly send analog data values
- The ability to map data onto a VLAN
- The ability to set the priority of the message through a switch

IEC GOOSE [1], in contrast to UCA GOOSE, carries a "user defined" dataset. The dataset can be configured with any "visible" data object in the relay such as volts, watts, vars, breaker status, etc. The data items in the dataset carry the same "type" (such as Float32, Integer 16, Boolean, etc) as the original data item. In the application of transmitting power flows, data, in engineering units, can be easily transferred among all locations as needed.

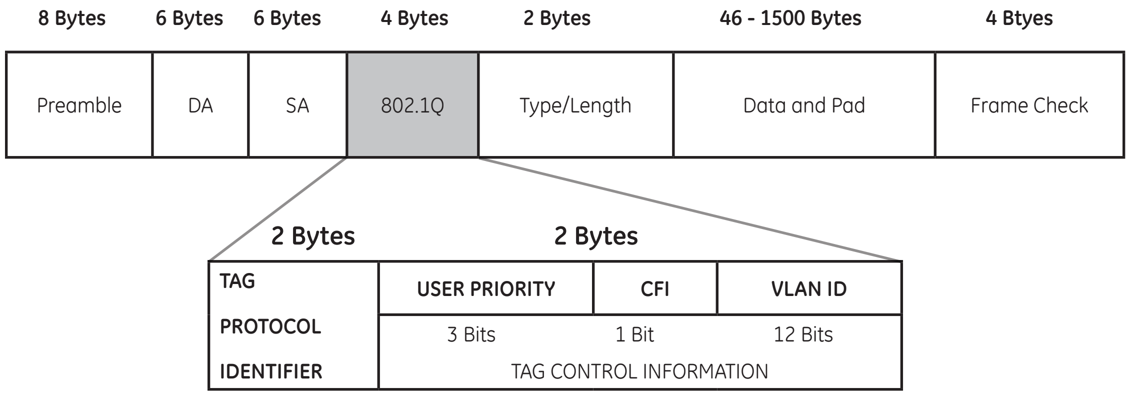

Fig 5.
Extended Ethernet Frame

With UCA GOOSE, when the multi-cast packet left the station, the packet would travel anywhere there was an Ethernet switch. This resulted in GOOSE packets being delivered to more locations than they had to be. A new feature supported in IEC GOOSE is the ability to logically restrict the flow of data to a particular broadcast domain through the creation of a Virtual Local Area Network or VLAN [2]. This dataflow restriction is achieved by adding four bytes to the Ethernet data frame per the IEEE 802.1Q [3] standard (see Figure 5). The extended dataframe is identified by a two-byte Tag Protocol Identifier value of 8100 hex. The other two bytes include 12 bits for a VLAN ID, 3 bits for priority encoding of the Ethernet message, and one bit for backward compatibility with Token Ring. Once identified as an extended Ethernet frame, a device (switch/bridge-router) in the network can decode the VLAN ID or VID. This ID is read by the device and "switched" to those ports programmed with the same VLAN ID. Figure 6 shows the delivery of a message to multiple devices connected to VLAN ID 5.

The third area addressed by IEC GOOSE is that of Ethernet priority in communication. Ethernet has traditionally been known as "non deterministic" in that collisions on a shared wire made the delivery time of a message a random variable. With the introduction of Layer 2 full-duplex switch technology, Ethernet collisions no longer exist. Switches receive all messages and store and forward them to the destination locations as programmed. It is possible for a single port to have several messages queued for delivery which would add a certain amount of delay in the processing of a message. Ethernet priority, however, even removes this delay. Upon receipt of an Ethernet message with "high priority", the received message is moved to the front of the queue and becomes the next message to be input to the receiving device thereby eliminating all processing delay in Ethernet communication.

5. System Performance

As part of system commissioning, round trip time for a message from Palo Verde to several of the remote substations was measured. The timing test involved logging when a message was sent from Palo Verde, receiving the message a remote substation, replying back to Palo Verde, and logging the return receipt in the original sending relay's event log. This test was performed on both the Ethernet and the G.703 communication systems. Results from these tests can be found in Table 1.

Referring to Table 1, the Ethernet System (System B) did not appear to be dependant on distance from the sender to the receiver and typical propagation times recorded were typically 14 ms or less implying a one-way communication time of less than 7 ms (as there is some internal relay processing included in the 14 ms). It should be noted that there was not much traffic on the Ethernet system other than the 15 relays installed for this scheme. Since the original implementation, several devices have been added to the Ethernet system and re-testing of this system will occur this May to see if the propagation delays have changed. The G.703 - System A - was more dependant on channels bank processing and took more time as the sender and receiver were separated by distance and number of channels banks. Each channel bank and relay combination introduced some communication delay time. Overall, both systems performed well within the required tripping time of 1 second.

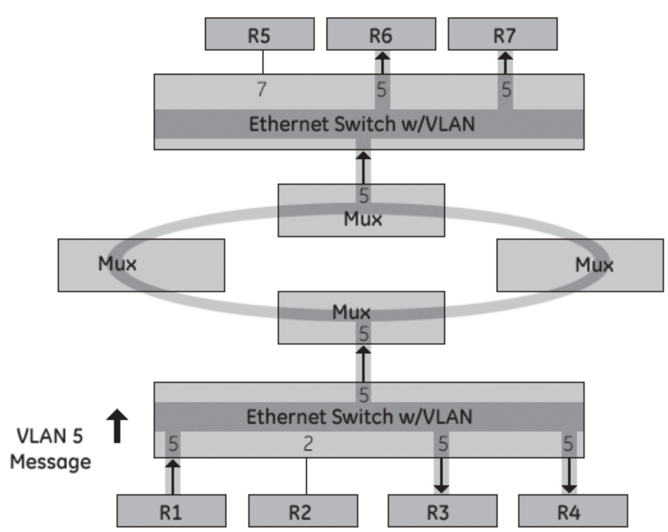

Fig 6.
Track of VLAN Message

6. Testing

The RAS Systems are tested annually from Palo Verde. Normal SRP practice is to schedule maintenance and outages of the RAS through the scheduling coordinator of the Operations Department. This will include notification to the Owners of Palo Verde Nuclear Generating Station (PVNGS), California ISO, and PVNGS itself.

There are three tests that are performed, namely:

- Scheme Checks
- Logic Tests
- End-to-End Tests.

The Scheme Checks verify the wiring, contact continuity, input function, etc., and are used to verify the physical connections to the relay and schematics. The Logic Tests are used to test the settings and logic of each relay. The End-to-End Test verifies that the arming and tripping from Palo Verde to each distribution site is functioning properly.

Each distribution site and Palo Verde are equipped with test switches. These test switches disable tripping and dispatching is automatically notified when the distribution site is placed in the test position. When the test switch is placed in the "test" position at Palo Verde, a signal is sent to the distribution stations that will block the trip contacts from operation. Dispatching is also notified when Palo Verde is placed in the test position.

The End-to-End Test can only be performed when Palo Verde and the site being tested are in the "test" position. There are push buttons for each site located at Palo Verde that can be used to test the transmission of the trip signal (see Installation picture of Palo Verde – Figure 7). The pushbuttons, however, cannot initiate a trip unless the test switches in Palo Verde and the site under test are in the "test" position. Performance of a System Test requires maintenance personnel to be at both Palo Verde and the distribution site being tested.

7. Operational experience

The system has been in service for a year now and has had no false operations, has not been called upon to operate, and properly did not operate during a recent trip-out of the plant.

Station	Ethernet Timing	G.703 Timing
Gaucho	14 ms	11 ms
Alameda	14 ms	20 ms
Indian Bend	14 ms	33 ms
Buckhorn	14 ms	46 ms

Table 1.
Palo Verde to Station Round Trip Communication Timing

8. Conclusions

Utilities are finding themselves drawn to Remedial Action Schemes on their systems. Drivers include the increasing complexity of the power system and the social and economic pressures that inhibit the construction of new power lines. As such, real time control schemes will increasing play a role in maintaining the security, stability, and integrity of the electric power network. Today's digital relays – in close integration with advanced communication networks – promise to provide solutions for remediation of identified power system problems. A tightly linked network of relays was demonstrated to provide an intelligent wide area protection system at a significantly lower cost than building a new transmission line.

Although the system worked well, room for improvement in several areas were identified – many of which are addressed by new technology such as analog data transmission, VLAN, and priority – all of which are enabled by the new IEC61850 communication standard. The tools and infrastructure for implementing Wide Area Protection and Control are here today and promise great things in the future.

9. References

[1.] IEC61850 Communication networks and systems in substations – Part 7-2: Basic communication structure for substation and feeder equipment – Abstract communication service interface (ACSI); www.iec.ch

[2] IEC61850 Communication networks and systems in substations – Part 8-1: Specific Communication Service Mapping (SCSM) –Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3; www.iec.ch

[3] 802.1Q - Virtual LANs; http://www.ieee802.org/1/pages/802.1Q.html

Palo Verde Installation *Typical Substation Installation*

Fig 7.
Installation Pictures