Generator Black Start Validation Using Synchronized Phasor Measurement

Kris Koellner
Salt River Project

Chris Anderson and Roy Moxley
Schweitzer Engineering Laboratories, Inc.

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Generator Black Start Validation Using Synchronized Phasor Measurement

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***Abstract*—History has repeatedly demonstrated the need to start generating units without access to the external power grid. This "black start" ability speeds power system recovery from both system instabilities and natural disasters. Readiness for an actual black start condition can be demonstrated by bringing a generator up to speed and synchronizing it to the electric system without using any grid power for auxiliary functions.**

Salt River Project, based in Phoenix, Arizona, conducted an exercise using a number of hydroelectric generating stations and a thermal-generating station. This was a legitimate "black start" exercise because every part of the system connecting the hydro and thermal generation was fully isolated (islanded) from the Western Electric Coordinating Council (WECC) power grid.

Synchronized phasor measurements, or synchrophasors, provided a real-time measurement of conditions during this black start exercise. Frequency and phase angles were monitored both within the island and on the WECC power grid. By using synchrophasor technology, frequency and phase angle in the two systems could be compared in real time without the use of a physical connection.

This paper illustrates the use of synchrophasor data to view frequency stability, verify system independence, and observe the synchronization point. Phasor measurement units, together with synchrophasor Collector and Display software, provided valuable data to operators during the course of the exercise. This paper provides discussion of problems encountered, trade-offs made, and lessons learned during the exercise.

I. BACKGROUND

On April 6, 2005, Salt River Project (SRP) conducted a black start exercise.

A. Scope of Exercise

The scope of the exercise was to:

1. Isolate a portion of the SRP electric system.
2. Bring a number of hydroelectric generating units (referred to subsequently in this paper as the SRP Hydro System) online.
3. Perform switching to energize a path from the 115 kV SRP Hydro System to bus V3 (see Fig. 1).
4. Start a thermal-generating unit on bus V3 and synchronize this unit with the SRP Hydro System.
5. Remove the V3 thermal unit from the SRP Hydro System.
6. Adjust voltage at 230 kV buses V2 left of the synchronizing breaker (see Fig. 1) and V3 via the 115 kV hydroelectric generating units.
7. Synchronize the islanded system with the rest of the Western Electric Coordinating Council (WECC) at bus V2 via 230 kV breaker 678 (see Fig. 1).

B. Discussion of the SRP Hydro System

The SRP Hydro System consists of a series of hydroelectric generating stations located at a string of dams on the Salt River, which runs through central Arizona. The combined net capacity of the Salt River hydroelectric generating stations is 266 MW. The exercise this paper discusses uses seven generating units at three facilities. While these units are some of the oldest facilities in the SRP system, SRP considers these units highly valuable for their black start capability and rugged response to operation at off-nominal frequencies [1]. These hydroelectric units can also run in condensed mode to provide a load versus generation balance, as necessary.

C. Overview of Black Start Path

Fig. 1 shows the black start path. We chose this path based on a combination of factors, including the hydroelectric generating source(s), availability of load, number of voltage transformations required, proximity of thermal generation, and synchronizing capability.

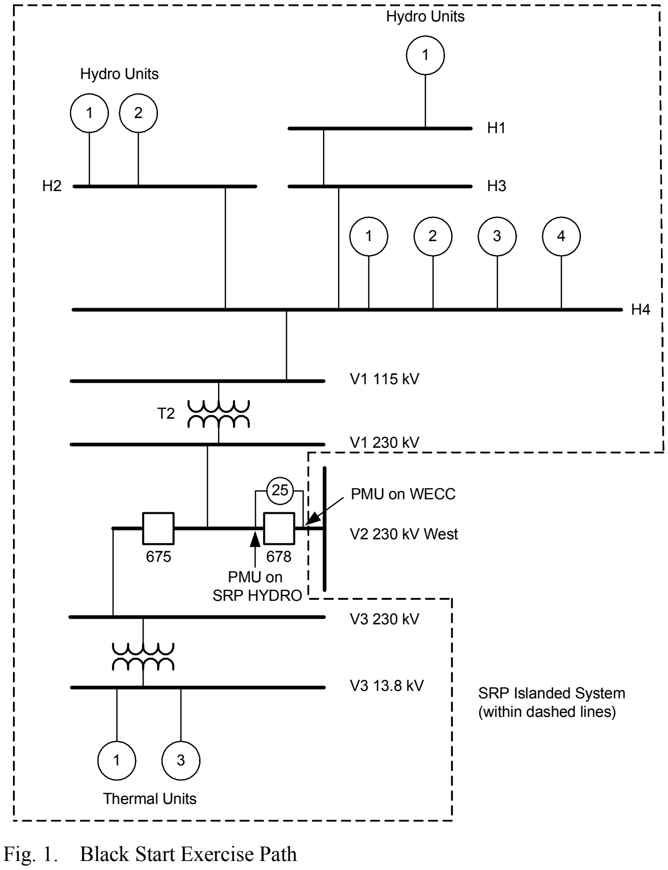


Fig. 1. Black Start Exercise Path

D. Goals of Exercise

The goals of the exercise were varied and included personnel training as much as verification of black start capabilities. Two key goals were the starting and synchronizing of a nearby thermal unit as well as the synchronizing of the islanded system with the WECC. A further goal was to test new black start logic, hydroelectric unit automation systems, and digital governor controls for the first time in a black start situation. Satisfying North American Reliability Corporation (NERC) guidelines in this area [2] [3] was a consideration as well.

E. History of Past Black Start Exercises at SRP

SRP had conducted black start exercises previously, but none had ever successfully started and synchronized a thermal unit. An isolated system also had never been synchronized with the WECC at any point. The most recent exercises prior to 2005 occurred in October 2004, October 1993, and May 1989. SRP aborted the 2004 exercise while attempting to pick up load to balance generation and halted the 1993 test after observing excessive harmonic levels.

II. SRP SYSTEM PROTECTION PRELIMINARY TASKS

The SRP System Protection department was involved in planning and developing the scope of the exercise in this paper. Tasks undertaken before the exercise described two main areas: verification of the relaying system and testing of the synchronism-check relay and phase angle transducer.

A. Relaying System Verification

We examined all protective relaying along the black start path to verify that relaying would operate as intended for a genuine fault during the exercise and would not operate inadvertently during the exercise. The transmission line relaying along the path included a mixture of vendors and techniques, including current differential, ground and phase distance, and ground overcurrent relaying.

Of particular concern was the fact that much less generation would be online during the exercise, meaning that less fault current would be available for protective relaying operation. We used ASPEN OneLiner™ to model the reduced system and confirm that distance relay fault detection supervision and differential relay current magnitudes would be sufficient, even at minimum fault levels. Table I compares the relative fault magnitudes and system impedance levels for different system configurations.

TABLE I
FAULT MAGNITUDES AND SYSTEM IMPEDANCE LEVELS

System Configuration	SLGF Magnitude at V3 230 kV bus	Positive-Sequence Thevenin Impedance
SRP Hydro System only	760 A	16.112 + j194.396
SRP Hydro System plus thermal unit online	1,850 A	3.609 + j83.007
Normal system	33,100 A	0.302 + j3.938

B. Synchronism Relay and Phase Angle Transducer Testing

A major goal of the exercise was to ultimately synchronize an isolated system with the WECC system, so the SRP System Protection group tested the relays and transducers that we would use for synchronization at the V2 230 kV station.

The synchronizing functionality at this station comes from a manual permissive synchronism-check relay (25F device) with voltage magnitude and angle limits in parallel with an anticipatory automatic synchronizer relay (25P device) that takes slip frequency into account. During testing, we found that the automatic synchronizer was not functioning and that only the manual permissive synchronism-check relay was available. The synchronism-check relay settings allowed for a phase angle difference of ±15 degrees. With no slip frequency supervision, the 30-degree window would only be suitable for safe closing if the slip frequency were less than 0.5 Hz. Table II shows the maximum breaker closing time for a range of slip frequencies given a 30-degree window at 60 Hz.

TABLE II
MAXIMUM BREAKER CLOSING TIME

Slip Frequency	Max. Breaker Closing Time	Margin
0.1 Hz	50 cycles	Conservatively Safe
0.5 Hz	10 cycles	Safe
1.0 Hz	5 cycles	Potentially Unsafe

The phase angle transducer functioned properly, but it only provided a single numeric indication of the phase angle across the two systems and it only updated as often as Energy Management System (EMS) polled the device (i.e., every few seconds). This made it difficult for dispatchers at the SRP Power Dispatch Office (PDO) to use the transducer as a reference when attempting to synchronize.

Fig. 2 shows a portion of the synchronism-check relaying and phase angle transducer scheme.

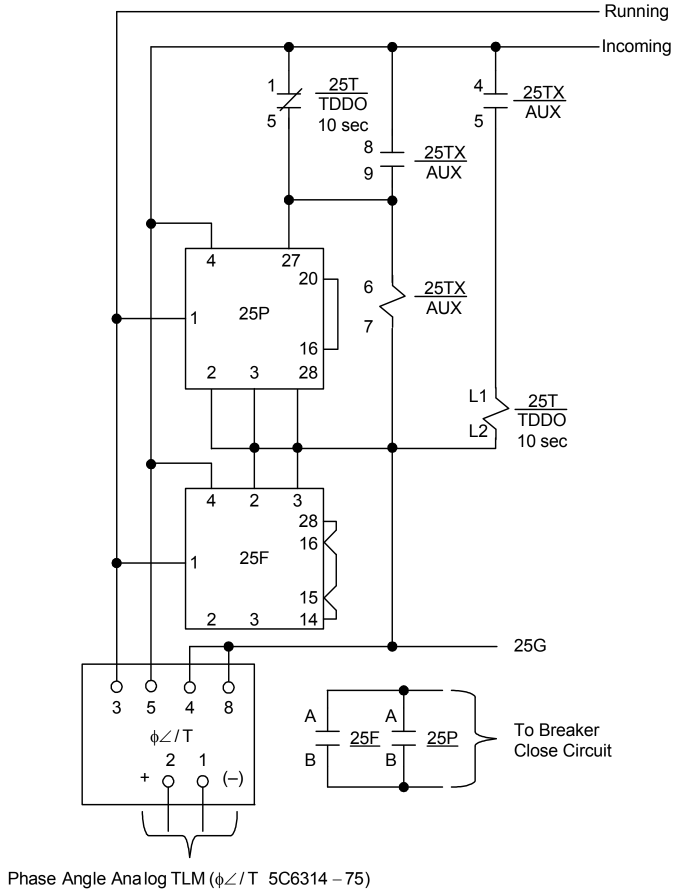


Fig. 2. Synchronism Relay Scheme

III. SYNCHROPHASOR SETUP

To provide better visibility of the exercise to the SRP PDO, we decided to use the capability of synchronized phasor measurements, or synchrophasors. We temporarily installed a pair of relays with integrated synchrophasor technology on the V2 bus before the exercise. Our goal was to provide near real-time visualization of several power system attributes during the exercise so we could better understand the effects of the exercise on both the islanded generation and its synchronization to the main WECC grid.

A. Hardware

1) Installation

We located two protective relays with integrated phasor measurement capabilities on either side of breaker 678, the synchronizing breaker for this exercise, as shown in Fig. 1. Three-phase voltage sources were available from coupling capacitor voltage transformers (CCVTs) on each side of the synchronizing breaker. We connected no current sources during the exercise, to avoid breaking into existing current circuits and because this was a temporary installation. Also, our primary focus in the exercise was on the voltage angle relationship and frequency rather than power flow.

2) IRIG-B Signal

Synchronized phasor measurement requires a high-accuracy time signal to provide an absolute reference for comparing power system quantities. Initially, we used an IRIG-B signal propagated over the serial communications cable from a communications processor. However, because of various signal latencies resulting from isolation circuits in the communications processor and relay, we found this connection to be unsuitable for the application. Thus, we connected each device directly to a high-accuracy timing source, in this case a Global Positioning System (GPS) satellite-controlled clock. We programmed the clock to provide IRIG-B time code, including the IEEE PC37.118 time code extension. The GPS clock provided an accuracy of approximately ±200 ns of Universal Time Coordination (UTC). This time signal accuracy combined with the measurement accuracies of the relay allowed for a phasor measurement accuracy of better than 1.0 percent total vector error (TVE) [4].

3) Settings

We programmed each relay to stream synchrophasor data per the IEEE PC37.118 draft standard via an EIA-232 serial port. We connected Port 2 of each relay to a local laptop, and programmed each relay to communicate in the appropriate protocol using typical serial communications settings: 57600 baud, 8 data bits, 1 stop bit, and no parity bits. Then, we set the relay to transmit data at a rate of 60 messages per second. We chose a narrow bandwidth filter and a 32-bit floating-point number format for phasor and frequency quantities. This provided better resolution than fixed-point integer quantities at the cost of a slight increase in packet size. The relays transmitted only voltage phasors, because we did not make current connections. As a result, the packet size totaled 58 bytes for each data sample.

4) Communication

We connected additional independent Ethernet and serial communications paths to each relay to provide access for making settings and retrieving event data.

SRP has deployed a 10 Mb/s Ethernet WAN at a majority of substations via high-speed OC1 fiber rings and JungleMUX SONET multiplexers. We connected the local laptop PC to this network to stream the data the relays collected back to the PDO. As shown in Fig. 3, average round-trip times for packets as large as 256 bytes were less than 16 milliseconds (ms). All round-trip times shown here are based on an average of 50 geographically widespread sites on the SRP network.

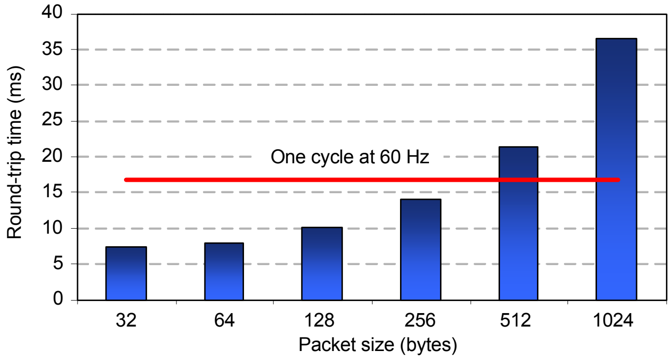


Fig. 3. Round-Trip Delay Times

Considering the 58-byte packet size and that the data packets only transmit in one direction, we can see in Fig. 3 a communications latency of less than 5 ms average throughout the SRP system. Note that this does not include signal processing or filtering of the phasor measurement data, packet buffering to time-align multiple data sets, or the processing latency of computers used to process and visualize the data.

B. Software

1) Collector Software

We connected a 9-pin serial cable from Port 2 of each relay to a local laptop PC (designated the "collector") located in the field at V2. Because the laptop had only a single serial port, we had to add another serial port via an USB-to-serial-port adapter. Fortunately, this additional piece of equipment posed no problems for the relay, laptop, or Collector software.

The Collector software requested a configuration packet to determine what data the relay would send and how often the relay would send these data. The software then initiated streaming of phasor data from both relays.

Once data streamed from both relays, the Collector software time aligned the data according to Second of Century (SOC) and Fractional Second (FOS) timestamps. After this time alignment, the Collector software concentrated the data, creating a new super packet ready for transmission upon request by the display computer (via the corporate WAN) located at the PDO.

2) Display Software

The Display software operates on another computer (in this case, a laptop) as a client to the Collector software. The main function of the Display software is to provide visualization for the data stream. These visualizations can vary from trending graphs that can display frequency, magnitude, or angle over time to instantaneous phase angle displays that show an instant view of the phase relationship between phasors. The resolution of the data refresh is adjustable. For this exercise, we set the resolution to 100 ms, or every sixth data point.

IV. SYNCHROPHASOR RESULTS DURING EXERCISE

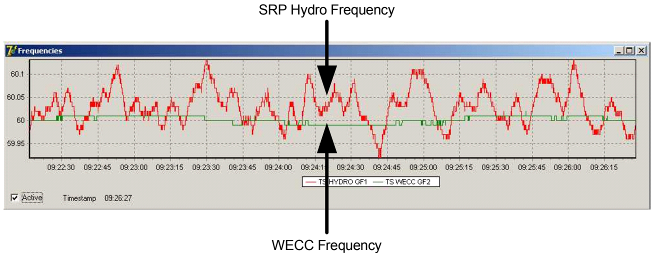
The following section highlights several key points during the black start exercise. We captured the images from the Display software running on a laptop at the PDO.

A. Frequency Deviations

During this exercise, the synchrophasor display provided system operators real-time, high-speed visibility of WECC and SRP Hydro System frequencies.

1) Hydroelectric Unit Frequency Control

In Fig. 4, we can see the SRP Hydro System frequency varying from approximately 60.15 Hz to 59.9 Hz over the course of several minutes. The figure shows both sets of three-phase vectors, with the A-phase voltage of the WECC system fixed as the reference angle. At this particular moment, the two systems were approximately 180 degrees out of phase with each other. However, because of the changing slip frequency between the two systems, the SRP Hydro System was in constant rotation relative to the WECC system. At various times during the exercise, the SRP Hydro System ran faster and slower than the WECC system.



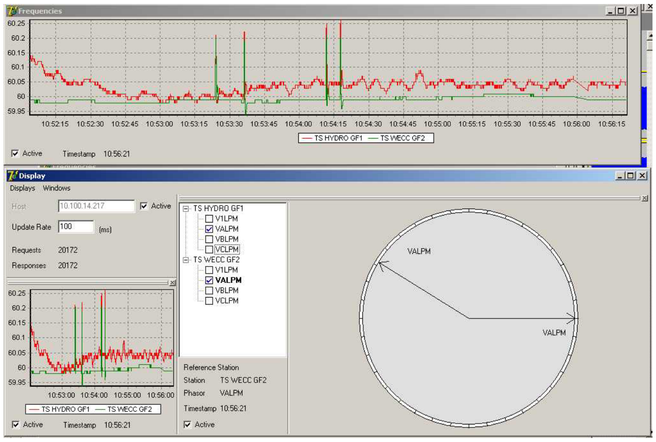
Timestamp 09:26:27

Fig. 4. SRP Hydro System Frequency Versus WECC System Frequency

2) Thermal Unit Frequency Control

Later during the black start exercise, we brought a 90 MW thermal generating unit online at V3 and synchronized with the SRP Hydro System. The addition of this unit to the hydroelectric units already online provided improved frequency control, as we can see in Fig. 5. The frequency variations were reduced from the 150 mHz range (as seen on the left side of Fig. 5) down to a 50 mHz range (as seen on the right side of Fig. 5).

Also in Fig. 5, note a few extreme frequency excursions. These are not "real" frequency excursions but are the result of an intermittent problem with the satellite clock. Also note that now only a single pair of voltage phasors appears in the simplified display.



☑ Active Timestamp 10:56:21

Host 10.100.14.217 ☑ Active

Update Rate 100 (ms)

Requests 20172

Responses 20172

☑ Active Timestamp 10:56:21

Reference Station

Station TS WECC GF2

Phasor VALPM

Timestamp 10:56:21

☑ Active

Fig. 5. Improved Frequency Stability With Thermal Generator

We ran the thermal unit at an output near 5 MW and kept the unit online for approximately 10 minutes. We used unit auxiliary loads in the range of 1 to 2 MW to balance load and generation. Once we took the thermal unit and its auxiliary loads offline, the SRP Hydro System frequency spiked to 60.4 Hz briefly, as Fig. 6 shows, and then returned to levels we saw prior to the addition of the thermal unit.

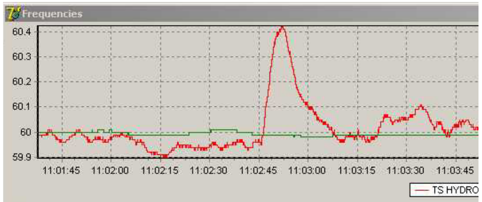


Fig. 6. Removal of Thermal Generator

B. *Voltage Control by Hydroelectric Units*

In this exercise, we also wanted to examine how much the hydroelectric-generating units could impact the bus voltage at the end of the isolated system at V3 and V2. We attempted to control (lower) the SRP Hydro System voltage by varying the operation of the hydroelectric units. A few successive snapshots from one of the relays confirm the lowering of the system voltage at V2. Note in Table III the successive drops in voltage magnitude over the course of several minutes.

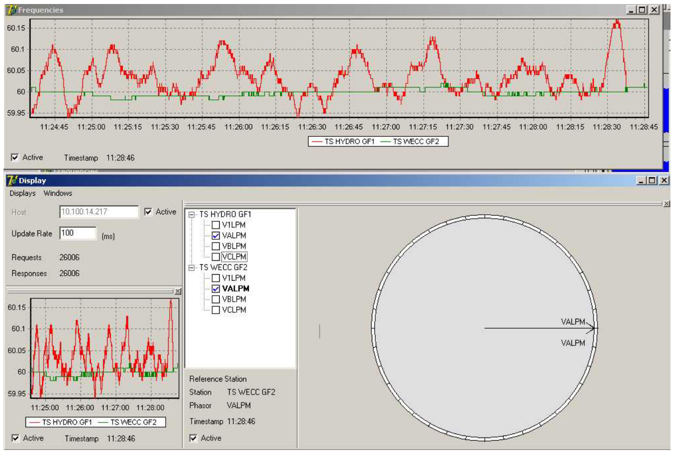
TABLE III
VOLTAGE REDUCTION USING SRP HYDRO SYSTEM VOLTAGE CONTROL

HYDRO SIDE V2	Date: 04/06/2005 Time: **11:17:28.931**					
	Phase Voltages			Phase-Phase Voltages		
	VA	VB	VC	VAB	VBC	VCA
V MAG (kV)	140.209	140.833	143.555	243.566	246.429	245.435
V ANG (DEG)	0.13	-120.02	119.87	30.13	-89.76	149.61
HYDRO SIDE V2	Date: 04/06/2005 Time: **11:18:39.071**					
	Phase Voltages			Phase-Phase Voltages		
	VA	VB	VC	VAB	VBC	VCA
V MAG (kV)	139.038	139.642	142.363	241.519	244.358	243.400
V ANG (DEG)	0.13	-120.02	119.88	30.13	-89.75	149.61
HYDRO SIDE V2	Date: 04/06/2005 Time: **11:19:41.397**					
	Phase Voltages			Phase-Phase Voltages		
	VA	VB	VC	VAB	VBC	VCA
V MAG (kV)	138.540	139.138	141.856	240.647	243.481	242.532
V ANG (DEG)	0.13	-120.02	119.88	30.13	-89.75	149.61

C. *Synchronizing With WECC System*

After we confirmed voltage control capability, our next task was to synchronize the SRP Hydro System to the WECC system. Because the automatic synchronizer was not functioning and only the manual permissive synchronism-check relay was available, we relied on the synchrophasor display to provide valuable, real-time feedback of system conditions before closing the 230 kV breaker to synchronize. The display allowed operators to confirm that the slip frequency was of a small enough magnitude that we could close the breaker safely without fear of over running the 30-degree window the synchronism-check relay allowed. The display also provided operators the ability to "time" their close command as close as possible to a point at which the phase angle difference between the two systems approached a minimum. Fig. 7 shows this moment of synchronization. At the far right of the frequency trend, the traces have come together and are now synchronized, as are the voltage synchrophasors. Shortly before synchronism there was 150 mHz of frequency difference between the two systems. With traditional transducers sending data through a supervisory control and data acquisition (SCADA) system every five seconds, this could lead to serious closing angle problems. Continuously streaming synchrophasor data avoids these problems.

A traditional SCADA solution, providing 5-second-old data, is equivalent to adding 5 seconds to the breaker closing time. As shown in Table II, this would require a much lower slip frequency between the two systems for safe breaker closing.



☑ Active Timestamp 11:28:46

Host 10.100.14.217 ☑ Active
Update Rate 100 (ms)
Requests 26006
Responses 26006

TS HYDRO GF1
☐ V1LPM
☑ VALPM
☐ VBLPM
☐ VCLPM
TS WECC GF2
☐ V1LPM
☑ VALPM
☐ VBLPM
☐ VCLPM

Reference Station
Station TS WECC GF2
Phasor VALPM
Timestamp 11:28:46
☑ Active

☑ Active Timestamp 11:28:46

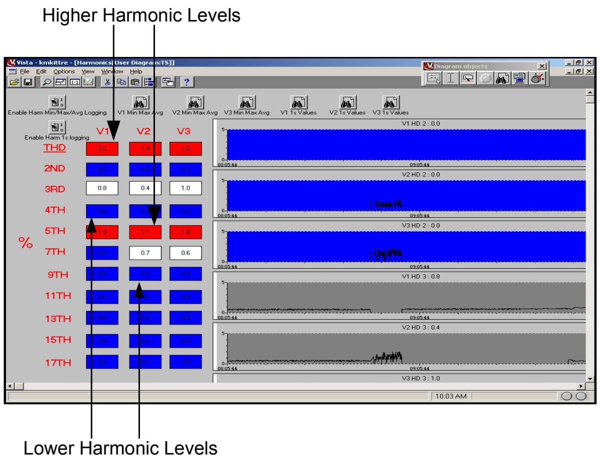
Fig. 7. Synchronization Point

D. *Data Retrieval From Other Devices*

In addition to the synchrophasor data made available during the course of the exercise, information from several other devices helped us monitor electric system parameters. Having multiple devices available for this purpose decreased the likelihood that we would miss key pieces of data.

We installed temporary, offline power quality (PQ) monitors at six of the sites involved to provide data captures of voltage, frequency, harmonics, and power-flow parameters for later analysis.

We installed one online PQ monitor with Ethernet communications at V2 on the SRP Hydro System CCVT in parallel with the synchrophasor-embedded relays to provide real-time voltage harmonic information. These data were also of particular interest to system operators at the PDO because of concerns about harmonic voltage magnitudes during past black start exercises. Fig. 8 shows a harmonic voltage summary screen available to system operators. To provide a quick visual indication, the darkest boxes indicate the lowest harmonic levels, the lighter boxes indicate higher harmonic levels, and the white boxes indicate harmonic levels in between. The screen also provides a scrolling trend of individual harmonic voltage magnitudes.



Higher Harmonic Levels

	V1	V2	V3
THD	2.0	1.4	2.0
2ND	0.0	0.0	0.0
3RD	0.8	0.4	1.0
4TH	0.0	0.0	0.0
5TH	1.9	1.1	1.6
7TH	0.0	0.7	0.6
9TH	0.0	0.0	0.0
11TH	0.0	0.0	0.0
13TH	0.0	0.0	0.0
15TH	0.0	0.0	0.0
17TH	0.0	0.0	0.0

Lower Harmonic Levels

Fig. 8. Harmonic Levels

Harmonic voltage levels (shown in Table IV) were acceptable throughout the course of the exercise, but these levels improved considerably with the thermal unit online in addition to just the SRP Hydro System.

TABLE IV
HARMONIC CONTENT FOR VARIOUS SYSTEM CONFIGURATIONS

System Configuration	Total Harmonic Distortion at V2 230 kV bus
WECC system just before exercise	0.64%
V1 230/115 kV transformer energized	1.26%
V3 13.8/230 kV transformer energized	2.16%
V3 thermal unit online	1.04%
WECC system just after exercise	0.75%

V. CONCLUSIONS AND RECOMMENDATIONS

A. System Performance

This paper proves for the first time that the SRP Hydro System truly provides a viable black start resource for SRP. All relaying systems performed per design during the exercise. No inadvertent trips occurred, and there were no faults during the exercise. Synchronizing the SRP Hydro System with the thermal unit and with the WECC system worked well. Voltage harmonics were not a problem in contrast to past black start exercises.

B. Synchronizer Relay and Telemetry Upgrades

Following the discovery of the failed automatic synchronizer relaying, SRP decided to upgrade the automatic synchronizer and the manual permissive synchronism-check relay to a newer microprocessor-based relay in the future. As part of this upgrade, it may also be advantageous to upgrade the phase angle transducer—perhaps replacing it entirely with a permanent synchrophasor display for operations personnel.

C. Future Black Start Plans

Per the applicable NERC standards [3] shown in Table V, we will perform future black start exercises of a similar scope as often as once per year to fully exercise the systems involved and to train personnel. We strongly recommend that future exercises use synchrophasor technology for enhanced visibility.

TABLE V
NERC STANDARDS

NERC Std.	Title
EOP-001-0	Emergency Operations Planning
EOP-005-0	System Restoration Plans
EOP-007-0	Establish, Maintain, and Document a Regional Blackstart Capability Plan
EOP-009-0	Documentation of Blackstart Generating Unit Test Results

VI. FUTURE SYNCHROPHASOR WORK AT SRP

Following the successful role of synchrophasors during the black start exercise, it became apparent that SRP would benefit greatly from a permanent synchrophasor system. Benefits from such a system include better visibility during black start exercises and other synchronizing activity, line impedance verification, improved State Estimator (SE) operation, and enhanced electric system parameter displays for operators.

A. Synchrophasor-Embedded Relay Installations

SRP determined that the fastest path toward implementing a permanent, system-wide synchrophasor system would be taking advantage of existing synchrophasor-embedded relay installations. SRP has identified more than 20 relays at 11 transmission-level substations that can presently support synchrophasor technology. If all of these existing relay installations are commissioned, we would have the capacity for a “depth of two unobservability” [5] on the SRP 230 kV and 500 kV electric systems.

This project will require minimal investment because it leverages devices already installed. Expenses will still be incurred in the areas of communications architecture, relay firmware upgrades, and centralized data collection and storage.

B. Phasor Data Concentrator Testing

In late 2005, SRP will begin testing a pair of phasor data concentrator (PDC) devices. Each device is designed to collect, store, and translate synchrophasor data from as many as seven remote phasor measurement units (PMUs). SRP will install one PDC device at the SRP Power Operations Building (POB) and another in the field at a 500 kV substation. SRP chose these two locations to gain experience with both types of installation and to optimize communications architecture costs. Fig. 9 shows the two different topologies for connecting the PDCs to EMS and SE systems. On the left side of Fig. 9 is the separate location connection option, and on the right side are both PDCs in the same location.

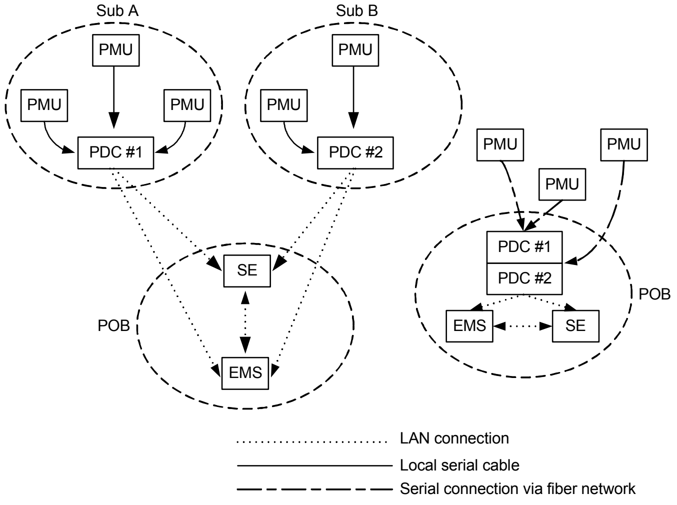


Fig. 9. SRP Synchrophasor System

If the first pair of PDC installations fares well, SRP has tentative plans to add three more PDC installations at other key transmission sites. SRP is also sponsoring university-level research in the area of optimal PMU placement for maximum electric system observability.

VII. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Arizona Sun Sales employee Bob Paris and SRP employees Giang Vuong, Dan Goodrich, Hassan Dehghanpisheh, Bill Russell, and John Hunter.

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IX. BIOGRAPHIES

Kris Koellner is a Senior Engineer with SRP. Kris has worked at SRP since 1994 in the areas of Distribution Planning, Power Quality, and most recently, System Protection. Kris graduated with a B.S.E. degree in Electrical Engineering from Arizona State University and is registered as a Professional Engineer (PE) in the state of Arizona.

Chris Anderson has an A.A.S. in Electronics Engineering Technology from ITT Technical Institute and is currently working on his B.S. in Electrical Engineering through Kennedy Western University. He joined Schweitzer Engineering Laboratories in July 1999. In the first three years at SEL, he worked in product development for transmission protection products. Since 2002, he has been an associate product engineer supporting transmission protection in Research and Development.

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as market manager for transmission system products. He is now a senior product manager. Prior to joining SEL he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the state of Pennsylvania.

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Conference and Exposition and the 2007 Texas A&M
Conference for Protective Relay Engineers.

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