REDUCING BLACKOUT RISK BY A WIDE-AREA CONTROL SYSTEM (WACS): ADDING A NEW LAYER OF DEFENSE

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Abstract – Large-scale blackout risk is greatly reduced by multiple layers of defense. With best practices for tree trimming, power system planning and design, control center operation, prioritized control and protection upgrades, automatic load shedding, special protection systems, etc., blackout risk becomes very low. Wide-area feedback control for discontinuous actions such as generator or load tripping and capacitor/reactor bank switching, is an advanced "special protection system."

After reviewing blackouts and close calls in 1996, 1999, 2003, and 2004, we describe Bonneville Power Administration (BPA) development and on-line demonstration of Wide-Area stability and voltage Control System (WACS). WACS uses phasor measurements from many stations as inputs, with existing special protection system transfer trip circuits available for outputs. We describe in detail WACS response and validation for the June 14, 2004 outage of 4600 MW of generation near Phoenix, Arizona.

Keywords: blackouts, special protection systems, wide-area controls, WACS, phasor measurements

1 INTRODUCTION

Costly large-scale blackouts have occurred in recent years. Blackouts in western North American in summer 1996, Brazil in 1999, northeastern North America and Europe in August/September 2003, and Greece on July 12, 2004 are notable. While many factors contributed to the blackouts, we highlight power system dynamic performance aspects and automatic stability controls.

Blackout risk is greatly reduced by multiple layers of defense or "defense in depth" [1,3]. This guards against extreme events, undesired protective relaying, the uncertainties of operator actions and of simulations used to set transfer limits, and numerous other factors.

First we review relevant aspects of recent blackouts. A key point is that control actions such as load shedding should be *automatic*. We next describe on-line demonstration of a Wide-Area stability and voltage Control System (WACS) envisioned as another layer of defense. We then describe tuning and validation of WACS based on an actual event.

2 CONTRIBUTING FACTORS TO SELECTED RECENT BLACKOUTS

Although each blackout is different, there are often common causes. Causes include inadequate tree trimming, inadequate operator awareness, inadequate operator actions, undesirable protective relay operations, and deficiencies in power plant and substation equipment. Feasible and cost-effective best practices to prevent blackouts include removal or modification of zone 3 and other backup relays, automatic load shedding, prioritized equipment upgrades such as excitation equipment replacement, capacitor bank additions, and control and protection modernization.

2.1 July and August 1996 in Western North America

Uncontrolled islanding with blackouts in the states of California, Nevada, Arizona, and New Mexico occurred on July 2 [1,2] and August 10 [1,3]. The July 2 cascading outage evolved over 20–30 seconds, while the August 10 outage evolved over five minutes. Aspects included inadequate time for system operator assessment and actions, undesired protective relay actions including generator exciter protection, inadequate models for dynamic simulation of operating conditions, unknown sensitivities to actual operating conditions, and inadequate reactive power support.

Because of uncertainties in dynamic simulation including the differences between actual and predicted operating conditions, planning/operating criteria margins applied to simulation results are usually too small. For example, we use a few hundred megawatt margin for a 4800 MW intertie.

These blackouts and uncertainties led to development and on-line demonstration of the Wide-Area stability and voltage Control System (WACS) described herein.

2.2 March 11, 1999 Blackout in Brazil [4]

A short circuit on a 440-kV bus without bus protection led to remote protection tripping resulting in a blackout with load loss of 25,000 MW. Subsequent improvements included prioritized upgrades of station bus arrangements and control and protection, elimination of remote backup protection by addition of redundant local protection, and increased use of special protection systems (SPS) to cope with multiple contingency disturbances. It was noted that blackouts occur because of multiple contingencies (including undesirable control and protection response to the first event), and that SPS needs to be constantly reevaluated.

2.3 August 14, 2003 Blackout in Northeastern North America

This blackout with load loss of 61,800 MW has been widely investigated and discussed [5]. Degradation of the northeastern Ohio grid evolved over several hours without meaningful actions by system operators. Somewhat surprisingly, voltage decay during the evolution was moderate (Figure 1). Generators, however, were near or at reactive power limits (Figure 2). In fact, high reactive power output resulted in the generator trip that was the first significant outage.

Although there was sufficient time for operator-initiated load tripping, operators were understandably reluctant to trip load in a new situation that was not fully understood. In many cases, however, there is simply insufficient time for operator-initiated actions. *Automatic* load shedding should be the primary control.

Figure 2 clearly shows that generator reactive power output is a sensitive indicator of system security.

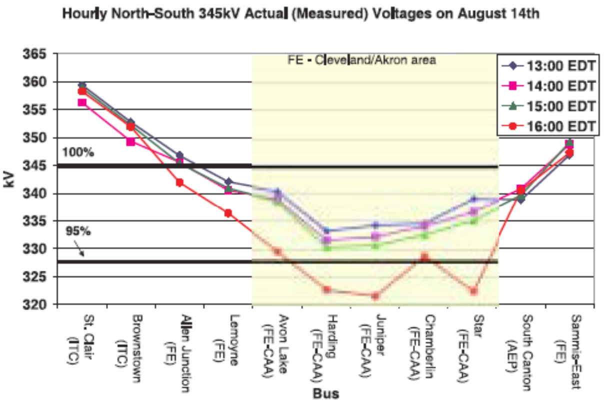

Figure 1: Decay of voltages on August 14, 2003 [5]. The first event, outage of Eastlake 5 generator, was at 13:31.

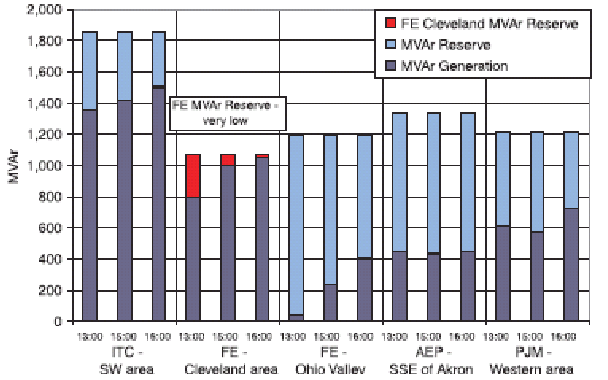

Figure 2: Reactive power reserves were very low in northeastern Ohio (FE – Cleveland area) [5].

2.4 July 12, 2004 Blackout in Greece [6,13]

Network upgrades to be in service prior to the Olympic games were not complete, and there were several other elements out of service. July 12 was a peak load day. Following a unit outage, generating stations could not supply needed reactive power, and voltages declined. Operator-directed manual load shedding was insufficient and too slow to prevent voltage collapse and blackout of the Athens/Peloponnesian areas.

3 BPA'S WIDE-AREA STABILITY AND VOLTAGE CONTROL SYSTEM (WACS)

3.1 WACS Overview

WACS has two main functions. The first is to add another layer of defense for the angle or voltage stability problems described above that resulted in very costly blackouts. In Western Electricity Coordinating Council (WECC) terminology, this is a *safety net*. With acceptance of the WACS on-line demonstration, the installed equipment can provide the safety net function with good reliability.

The second function is to increase transfer capability. This future goal requires a very high reliability control system with redundancy such as duplicated controllers at both BPA control centers. Similar to special protection systems, WECC peer-review certification is necessary.

For the on-line demonstration, the WACS application is oriented towards stabilization of the Pacific 500-kV ac intertie between the Pacific Northwest and Southern California. The non-simultaneous intertie rating is 4800 MW. Pacific Northwest power exports are the main interest, with high speed PNW hydro generator tripping and 500-kV capacitor/reactor bank switching being important control actions. While installed event-driven SPS provides stabilization for disturbances within the PNW network, WACS responds to stability-threatening disturbances originating anywhere in the western North American interconnection.

Reference 7 describes initial investigation, and references 8 and 9 provide simulation results and full details of the WACS design that we summarize below. Figures 3 and 4 are block diagrams of the power system stability control environment, showing WACS as a wide-area response-based (feedback) discontinuous control.

BPA and others have developed Wide-Area Measurement Systems (WAMS) [10], employing GPS-synchronized positive sequence phasor measurements. A goal, now being realized, is to use these phasor measurements for control. WACS uses phasor measurements from eight BPA stations. The phasors are transmitted at a 30-packets/second rate over BPA's SONET self-healing fiber optic rings. Existing SPS transfer trip circuits to multiple stations are available for generator tripping and 500-kV capacitor/reactor bank switching. Capacitor/reactor bank switching is supervised by local voltage measurement.

The controller is at a BPA control center. Time-tagged phasor measurements from the many stations are first organized by a Phasor Data Concentrator (PDC) [11], and then sent to the WACS controller. We selected National Instrument's LabVIEW software and real-time hardware [12]. The graphical software is a true dataflow language that prevents race conditions and allows for parallel tasking (multitasking and multi-threading are supported). It has needed programming features and library components such as data acquisition and processing, TCP/UDP, signal processing, filtering, math, state machine and other execution logic, display graphics, fuzzy logic, and execution tracing and timing. Software developed on a PC is downloaded to embedded PXI real-time operating system hardware.

Two algorithms are used: a voltage magnitude based algorithm (*V*mag), and a voltage magnitude and generator reactive power based algorithm (*V*mag*Q*). The algorithms provide first swing transient stability stabilization and relieve stress to improve transient damping. For growing oscillations it will operate at some point for stabilization. The algorithms also provide short- and long-term voltage stabilization and support.

WACS first processes the phasors to obtain the needed voltage magnitudes, and real and reactive powers. Data sanity checks are made. Simulations confirm that partial failures of measurements or communications will usually only slightly degrade control.

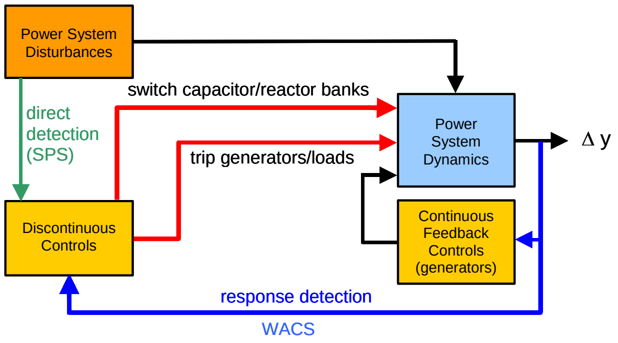

Figure 3: Power system environment for WACS.

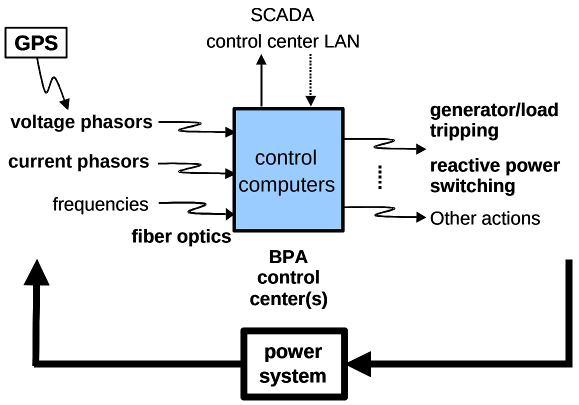

Figure 4: WACS high-level block diagram.

3.2 *WACS Voltage Magnitude Based Algorithm*

The *V*mag algorithm is fairly simple, based on 12 voltage magnitude measurements at seven 500-kV stations. We compute a weighted average voltage from the measurements, with highest weight for measurements near the Oregon–California border where the voltage swings are greatest (Malin, Captain Jack, Summer Lake).

Non-linear accumulators (integrators) compute volt-seconds below voltage threshold settings. Separate accumulators are programmed for each actuator, but currently a common setting is used for all generator tripping locations and a different common setting is used for all capacitor/reactor bank locations. Accumulation is blocked for voltage recovery. Control actions are commanded when volt-second accumulation reaches a setpoint. For generator tripping the weighted average voltage must also be below a setpoint.

The algorithm thus has semblance to PI (proportional-integral) control. Beneficially, faster operation results for more severe disturbances similar to an inverse time protective relay.

3.3 *Voltage and Generator Reactive Power Algorithm*

The *V*mag*Q* algorithm combines voltage magnitude measurements and generator reactive power measurements using fuzzy logic. Similar to the voltage magnitude based algorithm, we compute a weighted average 500-kV voltage magnitude from twelve phasor measurements at seven locations. More complicated is computation of weighted average reactive power from fifteen transmission lines emanating from six large power plants (phasor measurements are at the transmission-side switchyard).

First, we estimate the number of connected generators from the active power—up to four generators per line may be connected on lines from three hydro plants.

Next, we normalize reactive power based on generator active/reactive power capability curves.which are mapped from the generator terminals to the transmission side. We account for bus-fed auxiliary load, and generator step-up transformer impedance and tap ratio.

Normalization results in reactive power output on a scale of approximately ±1 (generator controls allow large temporary and small continuous operation outside limits). We next compute a weighted average of the normalized reactive powers. The individual weights are the product of the generator or generator group MVA rating, and a factor based on location and voltage support sensitivity. We give generators with automatic voltage regulator line drop compensation or with automatic high side voltage control a higher value.

We combine the weighted average voltage magnitude and the weighted average generator reactive power using fuzzy logic [7,8]. So far, linguistic variable tuning is based on rules of thumb such as overlap cross points at 0.5. The crisp (defuzzified) output range is approximately ±1 but a default value of 0 is used for rule combinations not needed (i.e., high voltage with bucking reactive power).

For fuzzy logic crisp output above a threshold, accumulation begins similar to the *V*mag algorithm. With accumulator setpoint reached, capacitor/reactor bank switching or generator tripping is commanded. Capacitor/reactor bank switching occurs first, with generator tripping only in severe situations where capacitor/reactor bank switching is not available or is not sufficient.

The input measurement weights and accumulator thresholds and settings, rather than the fuzzy sets, are the main tuning parameters. References 8 and 9 provide large-scale simulation results.

This algorithm provides sensitive control for conditions where voltage depression is mild, but voltage security is low because of low reactive power reserves. For voltage stability problems, load shedding would replace the generator tripping used in the BPA application. *Think August 14*—see Figures 1 and 2. On August 14th voltages remained above settings normally used for local undervoltage load shedding until the final seconds.

3.4 WACS Testing and Tuning

WACS code is tested and tuned three ways.

Firstly, the on-line performance is monitored; e.g., contact outputs are monitored by a sequence of events recorder.

Secondly, archived phasor measurements of events are played into the WACS real-time code on a PC.

Thirdly, outputs from large-scale simulations [8,9] are played into the WACS code. This is important because severe disturbances are rare. Large-scale simulations include re-creation of events, such as described below, with "what-if" variations.

4 WACS RESPONSE FOR THE JUNE 14, 2004 PALO VERDE AREA OUTAGE

At 07:40:56 on Monday June 14, a fault occurred near the Palo Verde Nuclear Plant west of Phoenix, Arizona. The fault was not completely cleared for almost 39 seconds! Approximately 4589 MW of generation tripped, at and near Palo Verde in the southern part of the western North American interconnection.

Pacific intertie stability was threatened, but maintained. With the Malin–Round Mountain #2 line between Oregon and California out of service, the intertie limit prior to the event was 3200 MW. North to south intertie flow swung from the initial 2650 MW to 5500 MW and settled at 4500 MW several minutes later. Malin and Captain Jack voltages near the Oregon–California border swung from the initial 548 kV to 443 kV at approximately 07:41:21.6. BPA series and shunt capacitor/reactor banks switched during the swings and the subsequent intertie power increase. The power increase is from governor action at PNW hydro plants, which carry large amounts of spinning reserve.

On June 14, WACS was in a monitor mode at a laboratory installation five km from the control center and Phasor Data Concentrator. The phasor measurement unit (PMU) at one substation was not yet in service, and conversion of some communications from higher latency analog microwave radio to SONET was not complete. More significantly, the PDC allowed up to one-second delay in message broadcast to wait for late arriving packets. Since a link to another utility was down, there was a full one second delay. The recorded operating time to command control action was thus over one second slower than is expected in the final implementation that uses a special message with minimal wait for late packets. Subtracting this delay, the discontinuous control actions would occur on the forward angle swing before the voltage minimums in order to improve first swing transient stability.

To validate the WACS algorithms, we played archived data from the June 14 event into the WACS code on an offline PC. Some retuning was done.

4.1 Voltage Magnitude Based Algorithm Validation

Figures 5 and 6 show Northwest voltages from phasor measurements for the event.

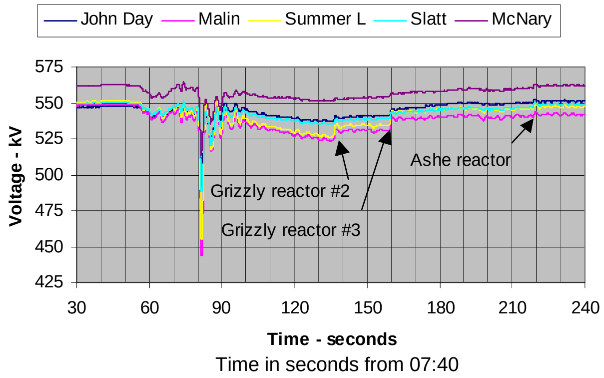

Figure 5: Northwest voltages in minutes following Palo Verde area generation loss. Shown are 500-kV reactor switching by BPA SCADA operator action. After initial swings, voltage decays because of PNW hydro governor action.

Figure 6 includes the weighted average voltage computed by WACS (same weights used for both algorithms). The accumulator thresholds for capactor/reactor bank switching are 525 kV and the thresholds for generator tripping are 520 kV. Accumulator setting for capacitor/reactor bank switching is 2 kV-seconds and accumulator setting for generator tripping is 4 kV-seconds. For generator tripping the weighted average voltage must also be below 490 kV.

For first swing stabilization, discontinuous control action should occur before the voltage minimum at around 81.6 seconds after 07:40. This time is estimated for the real signal without measurement delay (PMU timetags are at the last sample of the phasor computation window; the PMUs uses a four-cycle moving average filter with phasors calculated over one cycle).

Using the archived data, WACS output for capacitor/reactor bank switching occurs 81.033 seconds after 07:40. Adding 170 ms for communications, PDC, and circuit breaker delay, switching would be at 81.203 second or around 0.4 seconds before the real signal voltage minimum.

WACS output for generator tripping occurs at 81.233 seconds after 07:40. Adding 170 ms for the delays, tripping would be at 81.403 seconds or around 0.2 seconds before the real signal voltage minimum.

4.2 *Voltage Magnitude and Generator Reactive Power Based Algorithm Validation*

The *VmagQ* algorithm may operate in a slower time frame as generator reactive power increases because of slow stress increase from governor action, tap changing, overexcitation limiting, or load increase.

For June 14, however, operation of this algorithm occurs on the first swing. Figure 7 shows reactive power on the four lines from the John Day hydro plant (four generators per line, 16 units total). John Day power plant lines 1 and 2 measurements are given high weight, and they dominate the weighted average reactive power.

Figure 8 shows the weighted average voltage and weighted average reactive power that are combined using fuzzy logic. The crisp (center of gravity) fuzzy logic output is also shown. Fuzzy logic output above a threshold is accumulated. For capacitor/reactor bank switching the thresholds are 0.40 per unit. For generator tripping, the thresholds are 0.45 per unit. Accumulator settings are 0.05 per unit-seconds for capacitor/reactor bank switching, and 0.2 per unit-seconds for generator tripping.

Figure 9 shows more detail for both algorithms.

Using the archived data, WACS output for capacitor/reactor bank switching occurs 81.033 seconds after 07:40 (same time as the voltage magnitude based algorithm). Adding 170 ms for communications, PDC, and circuit breaker delay, switching would be at 81.203 second or around 0.4 seconds before the real signal voltage minimum.

WACS output for generator tripping occurs at 81.533 seconds after 07:40 (300 ms later than the voltage magnitude based algorithm). Adding 170 ms for the delays, tripping would be at 81.703 seconds or around 0.1 seconds after the real signal voltage minimum. While this will cause a larger backswing, the generator tripping reduces intertie loading and system stress. The settings allow time for the effect (feedback) of capacitor/reactor switching to influence the need for generator tripping.

Referring to reference 7, we originally found that the fuzzy logic algorithm would be substantially slower than the voltage magnitude based algorithm, as well as more complex. As described above, however, the operating times are similar. This is at least partly because slow exciters were recently replaced with static exciter at two plants. Figures 6– 8 shows the reactive power swings are in close anti-phase to the voltage swings.

4.3 *A Close Call*

The June 14 massive loss of generation was well beyond planning and operating reliability criteria. While unusual (incredible!), power systems are continuously exposed to such events. For example, on November 30, 2004 all five units at the Four Corners plant in New Mexico were lost (2060 MW); WACS did not operate, which was correct for the operating conditions that day.

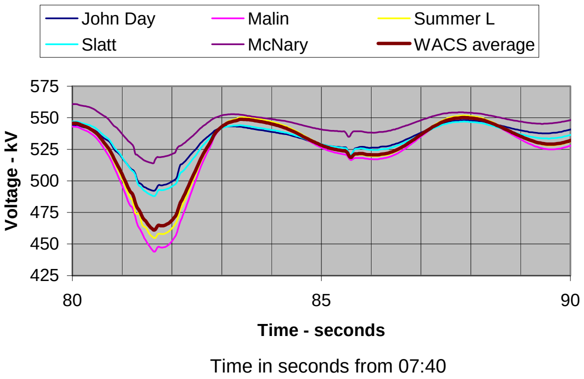

Figure 6: Northwest voltages for first three swings. BPA series and shunt 500-kV series and shunt capacitor banks were inserted during first swing by local response based control.

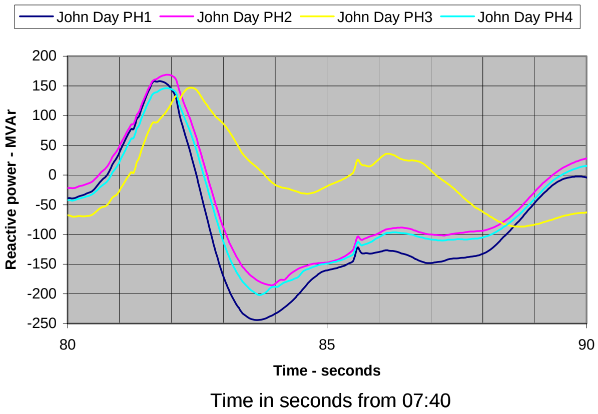

Figure 7: Reactive power response of 2608 MVA John Day hydro power plant. Generators on lines 1, 2, and 4 have had replacement of old rotating exciters with static exciters and digital voltage regulators with line drop compensation; exciter replacements on line 3 generators are in process.

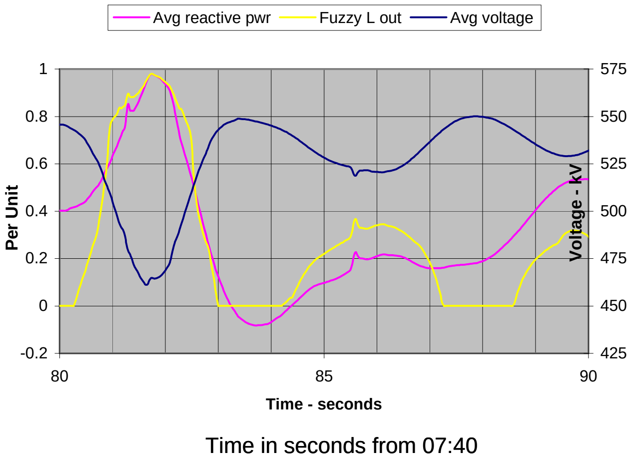

Figure 8: Voltage magnitude and generator reactive power algorithm: inputs and output

If Pacific intertie loading was somewhat higher on June 14, instability would have occurred and caused controlled islanding with massive generation/load imbalance in the importing southern island that suffered the initial 4600 MW loss. Either massive underfrequency load shedding or a widespread blackout in California, Nevada, Arizona, and New Mexico would have resulted. Loading would have been higher later in the day as temperatures and load increased.

Pacific Northwest generator dropping (~900 MW) in northern Washington State or British Columbia is the most powerful WACS action. While this would increase the system frequency excursion (59.5 Hz on June 14), it would not activate the main WECC underfrequency load shedding that starts at 59.1 Hz. Generator tripping to prevent instability is clearly preferable to islanding and massive load shedding or blackout.

June 14 type events are exactly what WACS can protect against. To quantify benefits we plan simulations of the June 14 event with variation of intertie loading.

5 BENEFITS OF WACS

Besides improving reliability and/or transfer capability, WACS has other advantages:

- WACS is a flexible platform for rapid control implementations. This will be increasingly true with ongoing phasor measurement additions. The chosen software platform allows “open system” development and modifications.
- WACS provides greater observability and controllability compared to local control. WACS is tolerant to partial failure of inputs and outputs.
- WACS powerful discontinuous control is safer than local and especially wide-area continuous control such as wide-area PSS (small exposure to adverse interactions).
- WACS is simpler than event-driven SPS where dozens of lines must be must be monitored for outages. For example, BPA’s SPS requires a 24/7 dispatcher. With a large number of key measurements, WACS can easily be self-arming.
- Compared to pre-planned event-driven SPS, WACS will respond to any disturbance (Figures 3 and 4).
- WACS protects against simulation and operational uncertainties.
- As an automatic control, WACS takes the burden off operators for rapid response to alarms (Figure 5). Following outages, operators can concentrate on restoration of out-of-service equipment.
- WACS caters to advances in IT (sensors, communications, and control computers, and control and AI technology). WACS could be further interfaced with control center LANs—for example with dynamic security assessment applications.

6 FURTHER DEVELOPMENT OF WACS

We expect to incorporate the PDC function in the WACS computer, or in a companion computer using software and hardware similar to WACS.

The next generation of phasor measurements will likely use a 60-packets/second rate, with similar WACS execution rate. This will reduce control system latency.

For operator alarms, we are investigating adding online modal analysis using the extensive signal processing and identification tools of the software platform. LabVIEW can also integrate MATLAB or other code if desirable.

As Figure 4 shows, other control actions are possible. For example, in a stressed situation, the voltage schedule of power plants with reactive power reserve could be increased. This could be implemented at BPA by interfacing WACS with the AGC digital message.

7 CONCLUSIONS

With best practices, blackout risk becomes very low. For various reasons (financial/commercial/regulatory, staff limitations, human error, etc.) best practices on a one-system basis are seldom completely followed. Industry trends, such as restructuring and cost pressures, may reduce reliability in the future.

Costs of some of the recent blackouts were several billions of dollars. WACS is a promising technology to improve reliability at relatively low cost as another “layer of defense.”

ACKNOWLEDGMENTS

Ken Martin, Dr. John Hauer, and Bill Mittelstadt are leading the phasor measurement (WAMS) development. Prof. Mani Venkatasubramanian and students (Washington State University) contributed to the WACS design, and are researching future enhancements.

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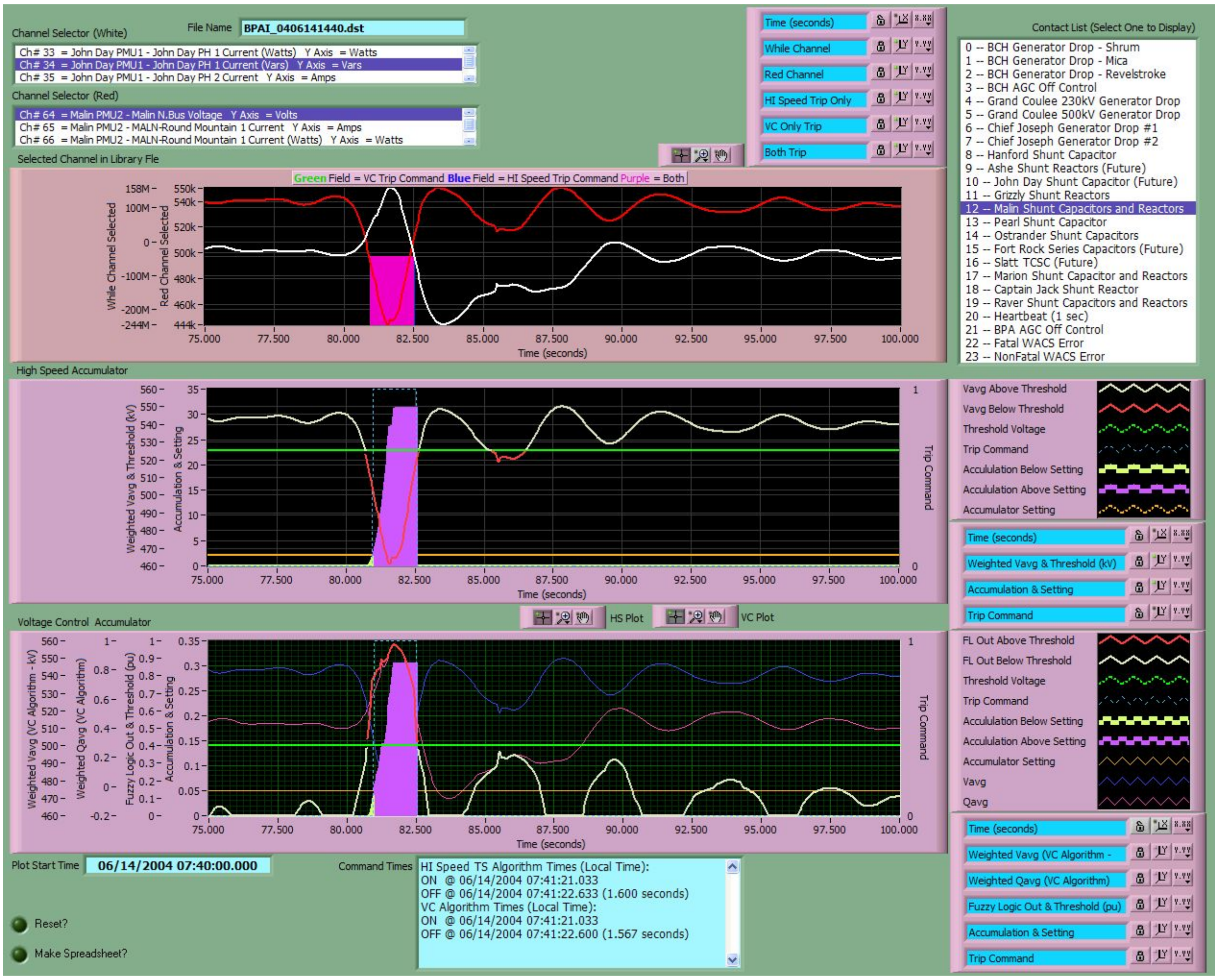

Channel Selector (White)

File Name BPAI_0406141440.dst

Ch# 33 = John Day PMU1 - John Day PH 1 Current (Watts) Y Axis = Watts
Ch# 34 = John Day PMU1 - John Day PH 1 Current (Vars) Y Axis = Vars
Ch# 35 = John Day PMU1 - John Day PH 2 Current Y Axis = Amps

Channel Selector (Red)

Ch# 64 = Malin PMU2 - Malin N.Bus Voltage Y Axis = Volts
Ch# 65 = Malin PMU2 - MALN-Round Mountain 1 Current Y Axis = Amps
Ch# 66 = Malin PMU2 - MALN-Round Mountain 1 Current (Watts) Y Axis = Watts

Selected Channel in Library Fle

Green Field = VC Trip Command Blue Field = HI Speed Trip Command Purple = Both

Contact List (Select One to Display)

0 -- BCH Generator Drop - Shrum
1 -- BCH Generator Drop - Mica
2 -- BCH Generator Drop - Revelstroke
3 -- BCH AGC Off Control
4 -- Grand Coulee 230kV Generator Drop
5 -- Grand Coulee 500kV Generator Drop
6 -- Chief Joseph Generator Drop #1
7 -- Chief Joseph Generator Drop #2
8 -- Hanford Shunt Capacitor
9 -- Ashe Shunt Reactors (Future)
10 -- John Day Shunt Capacitor (Future)
11 -- Grizzly Shunt Reactors
12 -- Malin Shunt Capacitors and Reactors
13 -- Pearl Shunt Capacitor
14 -- Ostrander Shunt Capacitors
15 -- Fort Rock Series Capacitors (Future)
16 -- Slatt TCSC (Future)
17 -- Marion Shunt Capacitor and Reactors
18 -- Captain Jack Shunt Reactor
19 -- Raver Shunt Capacitors and Reactors
20 -- Heartbeat (1 sec)
21 -- BPA AGC Off Control
22 -- Fatal WACS Error
23 -- NonFatal WACS Error

Plot Start Time 06/14/2004 07:40:00.000

Command Times

```
HI Speed TS Algorithm Times (Local Time):
ON  @ 06/14/2004 07:41:21.033
OFF @ 06/14/2004 07:41:22.633 (1.600 seconds)
VC Algorithm Times (Local Time):
ON  @ 06/14/2004 07:41:21.033
OFF @ 06/14/2004 07:41:22.600 (1.567 seconds)
```

Figure 9: WACS development PC computer plots for capacitor/reactor bank switching using June 14, 2004 archived data. The *top plot* shows selected representative input signals. The white channel is John Day PH Line 1 reactive power; negative is into the John Day switchyard. The red channel is Malin voltage. On the upper right, the selection of contact 12 for Malin shunt capacitors and reactors means that the middle and lower plots are for capacitor/reactor bank switching. The *middle plot* is for the voltage magnitude based algorithm. The white/red signal is the weighted average voltage (turns red when below threshold for volt-second accumulation). The green line is the threshold (525 kV). The yellow and purple signals are the accumulated volt-seconds, and the orange line is the accumulator setpoint; the small yellow area is the volt-second area to initiate control action (dashed blue line). The *lower plot* is for the voltage magnitude, generator reactive power fuzzy logic algorithm. The blue and orange signals are the weighted average voltage and weighted average reactive power inputs to fuzzy logic. The white/red signal is the fuzzy logic per unit crisp output (turns red when above threshold for per unit-second accumulation), and the green line is the accumulator setpoint (0.5 per unit). The yellow and purple signals are the accumulated per unit-seconds, and the orange line is the accumulator setpoint; the small yellow area is the per unit-second area to initiate control action (dashed blue line). The lower blue box gives WACS operation times.