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# Wide-Area Stability and Voltage Control

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## Summary

Bonneville Power Administration is investigating wide-area stability and voltage control. The control provides a flexible platform for rapid implementation of generator tripping and reactive power compensation for voltage support and stability. Features include phasor measurements, digital fiber optic communications, and fuzzy logic control. The control includes both fast and slow subsystems. The controls are being developed in close collaboration between Bonneville Power Administration and Washington State University.

A principle benefit of the project is improved voltage security because of better preventive and corrective countermeasures. For preventive and slow corrective countermeasures, the control can automate actions of an alert and experienced operator. Other benefits include reduced losses, reduced future compensation needs because of better use of existing compensation, and automation for the future when operators may be less experienced.

We expect synergy between the wide-area control and other control center applications. For example, on-line security assessment can be used for controller tuning and adaptation. There will also be synergy between wide-area control and substation automation (e.g., intelligent electronic devices, digital control and protection).

We present simulation results showing improved voltage support and transient stability for major disturbances limiting intertie transfer capability.

**Keywords:** voltage control, voltage stability, reactive power, power system stability, fuzzy logic

## 1. Pacific Northwest Power System

The Pacific Northwest power system in western North American is characterized by high spring and summer power exports to California, and winter peaking of load. The major load centers are on the west side of the Cascade Mountains, and include the Vancouver B.C., Seattle/Tacoma, and Portland metropolitan areas, and the Willamette River Valley between Portland and Eugene, Oregon.

Generation concentrations are along the Columbia River on the east side of the Cascade Mountains. Some power plants are far more distant in northern British Columbia, eastern Montana, and Wyoming. Figure 1 shows a portion of the Pacific Northwest 500-kV power system. Most of the transmission shown is owned by the Bonneville Power Administration (BPA).

For the past decade, wintertime voltage stability has been a major concern [1,2]. System additions have included many large 230-kV and 500-kV capacitor banks.

In the summer of 1996, two major power failures occurred in the western U.S., attributed in part to insufficient voltage support for the Pacific Intertie [3–5]. The Pacific Intertie between the Pacific Northwest and Southern California consists of a ±500-kV, 3100 MW bipolar HVDC link, and a 500-kV AC intertie of 4800 MW capacity. Measures taken to prevent power failure reoccurrences included addition of large capacitor banks (again), and many stability controls to trip generation and insert series and shunt capacitor banks following detection of line outages.

As in other parts of the world, the Pacific Northwest power companies are undergoing restructuring. In this highly competitive environment, reliability must be maintained and repeats of the summer 1996 failures will not be tolerated. Information-age technology is a key in balancing reliability with low-cost transmission service.

We describe wide-area controls to improve both wintertime voltage stability, and spring/summer voltage support for high power exports on the Pacific Intertie. The controls are response-based, rather than event-based, meaning controls

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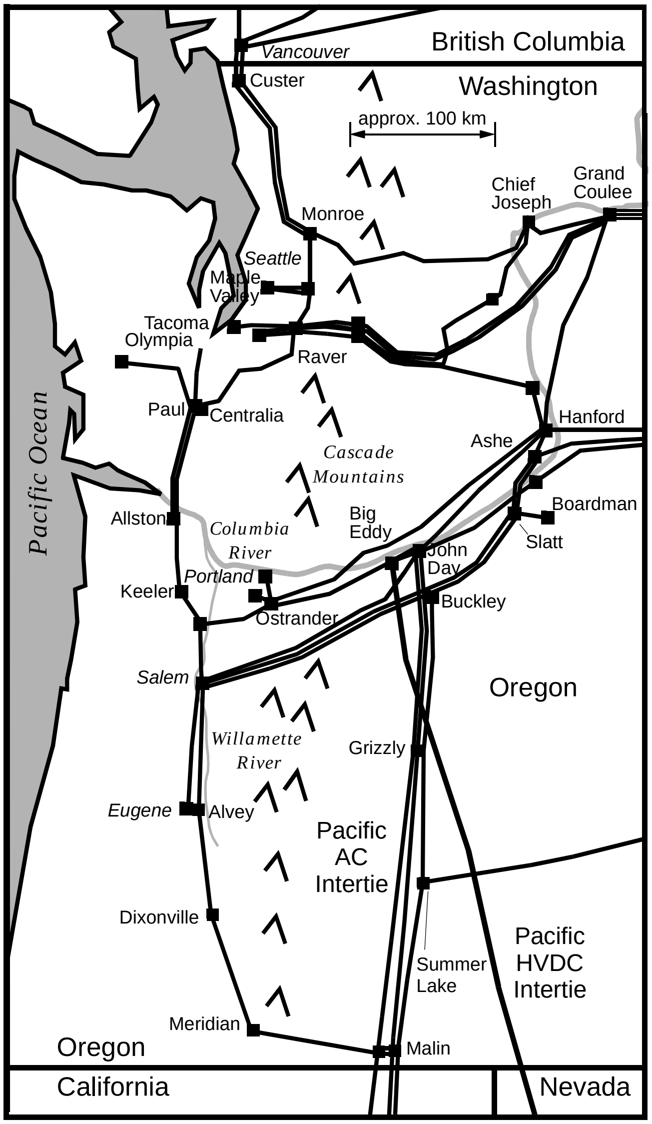



Fig. 1. Pacific Northwest 500-kV transmission network.

detect significant change of measured variables rather than events such as opening of an important transmission line.

## 2. BPA Existing Stability and Voltage Control

Before describing advanced control we briefly describe relevant existing control.

### 2.1 Remedial action schemes

Remedial action schemes, also termed special protection systems, are pre-planned feedforward controls that detect certain outages (events) and send signals for actions such as generator tripping or reactive power compensation switching [6]. For transient stability, the actions occur in a fraction of a second.

Following the summer 1996 outages, BPA feedforward stability controls related to voltage support have been greatly expanded. This is because of more stringent planning criteria, and the need to maximize transfer capabilities.

The event-driven feedforward controls only operate for certain pre-selected outages and are quite expensive. Redundancy in sensing, communications, and control logic is required since the basic reliability requirement is that failure a single component will not cause instability [7].

### 2.2 Slower voltage control

Slower controls for voltage and reactive power operate in a time frame of seconds, tens of seconds, or minutes. During normal operation, reactive compensation switching is mainly by SCADA operators. For voltage changes of several per cent or more, voltage relays with seconds of time delay will initiate compensation switching. With dozens of transmission-level shunt capacitor banks and shunt reactors, good coordination of control is challenging. To help guide operators in compensation switching, we installed a monitor of power plant reactive power reserve [8].

BPA autotransformers (500/230-kV and 230/115-kV) have under-load tap changers, but control is by SCADA operators. Tap changing has lower priority than reactive power compensation switching. Switching frequency is restricted to several tap changes per day because tap changer failure results in transformer outage.

Voltage schedules are published for power plant switchyards and for substations. Most power plants have automatic SCADA to maintain transmission-side voltage to the desired schedule, and to balance reactive power among the plant generators. In many cases this control is slow and not very predictable. Faster (10–20 second time frame) feedback controls [9,10] are proposed.

BPA SCADA voltage measurements are single phase and power measurements use two element watt/var transducers. Most measurements are telemetered over analog microwave channels. BPA, however, has recently installed over 2900 km of SONET fiber optic communications.

## 3. BPA's Advanced Stability and Voltage Control Project

BPA has a development project for "Advanced Stability and Voltage Control" (Figure 2). The project exploits "information age" technology in digital control and communications [6,11]. Input signals are from positive sequence synchronized phasor measurements and from SCADA. Control action is centralized at the BPA control center and most of the control actions are discrete. Flexibility for rapid, low-cost implementation of new control requirements is a key attribute.

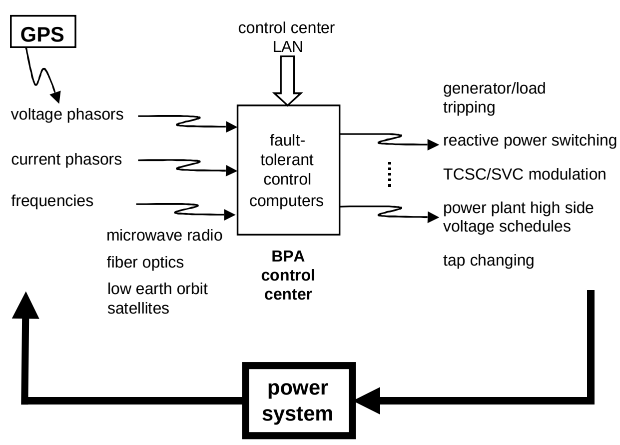



Fig. 2. Flexible wide-area control.

The project goals include:

1. Provide fast response-based control (generator tripping and reactive power compensation switching) to maintain Pacific Intertie stability for disturbances occurring anywhere in the interconnection. Voltage magnitudes along the Pacific ac intertie are the primary input signals, but voltage phase angle, frequency, and active and reactive power measurements are available. Eventually the control may replace remedial action schemes based on direct detection of certain outages.

2. Initiate reactive compensation switching for voltage stability and voltage control. Control is based on voltage magnitudes and generator/static var compensator reactive power outputs using fuzzy logic.

3. Provide high-side voltage schedules (setpoints) to power plants. In a voltage emergency, power plants with reactive power reserve can be sent a higher schedule to activate reserve and boost transmission voltage, thus reducing reactive power losses, and increasing line charging and shunt capacitor bank outputs. The control may also be used to equalize reactive power output of closely-coupled plants. The BPA automatic generation control (AGC) digital message is used to transmit the voltage schedules.

4. Automate autotransformer tap changing, preventing circulating reactive power/current between parallel transformers at different stations and improving voltage stability.

5. Provide a flexible platform for rapid, low-cost addition of stability controls. The phasor measurement inputs allow control based on voltage magnitude and angle, active power, reactive power, and frequency.

6. Evaluate benefits of automatic centralized control and improved local control. We envision hierarchal centralized and improved local control. For example, see §7.5 of reference 1.

Many of the components shown on Figure 2 exist, including synchronized phasor measurements (7 locations in the states of Washington and Oregon), outgoing transfer trip signals for generator tripping and compensation switching, SCADA, AGC telemetry, and control center LAN. For the fast stability control, some of the phasor measurements require replacement of analog microwave communications with digital fiber optics. With many input measurements and many outgoing signals, brute force redundancy is not planned. Failure of a single input signal or outgoing signal may degrade control, but not cause failure.

The wide-area control can be categorized as fast control to ensure transient stability following major disturbances, and slower control for wintertime voltage stability. Slower controls also provide reactive power “management” during normal operation. The fast controls are *corrective countermeasures* taken in less than one second following a disturbance. The slower controls are either corrective countermeasures taken in a time frame of tens of seconds following a disturbance, or *preventive countermeasures* ensuring security for potential disturbances [12,13].

The principle benefit of the project is improved voltage security because of better preventive and corrective countermeasures. For preventive countermeasures, control can automate actions of an alert and experienced operator. Other benefits include reduced losses, reduced future compensation needs because of better use of existing compensation, and automation for the future when operators may be less experienced.

### 3.1 A premise

Generator and static var compensator (SVC) reactive power outputs are sensitive indices of voltage security. For example, voltage magnitudes can be within normal values but voltage security will be low if reactive power reserves are low. Voltage control can be made more sensitive using generator/SVC reactive power measurements in addition to voltage magnitude measurements. An alternative for corrective control is to base action on *change* of voltage magnitudes and reactive power using washout (high pass) filters.

Fuzzy logic is a convenient means to combine reactive power and voltage magnitude measurements. However, as described in Section 4, simpler control is appropriate for transient stability voltage support.

### 3.2 Measurements and communications

The main input measurements are synchronized positive sequence phasors. As substation automation proceeds, this advanced digital measurement technology will be more common. Phasor measurements are more accurate because all three phases are used, providing an averaging effect. Since real-world accuracy of capacitive voltage transformer measurements is around ±1% (±5.5 kV for 550-kV), averaging is highly desirable. Averaging of several three-phase measurements per substation might be feasible as legacy transducers are replaced with IEDs (intelligent electronic devices).

Communication speed is critical for fast control. Most existing BPA phasor measurements are telemetered to the control center data concentrator over analog microwave using modems, but digital fiber optics is used for one substation. The latency of fiber optic digital communication is around 38 ms, while latency using modems over analog microwave channels is over 80 ms. Our conclusion is that digital communication is needed for wide-area transient stability control. At present we do not envision multiple (bang-bang) switching.

Fiber optic communication is installed in *self-healing* ring configuration; if the path is cut, the communication is redirected around the ring within around 100 ms.

### 3.3 Fuzzy logic control

Fuzzy logic controllers are popular for discrete high-level control, with many successful applications. They have several advantages [6,14,15,19]. They are a generalized expert system which can emulate human reasoning, such as what an experienced operator would do after observing voltage and reactive power measurements. Intermediate values beyond the yes or no of a relay are used. For equal performance and robustness, a few fuzzy logic rules can replace many expert system (relay logic) rules. Appendix 1 provides application considerations and rules of thumb.

Modern real-time controllers include fuzzy logic tools and graphical interfaces for controller tuning.

The controller described and uses the most common fuzzy logic methods. Terminology and nomenclature are not standardized for fuzzy logic—we generally follow the terminology and nomenclature of reference 15.

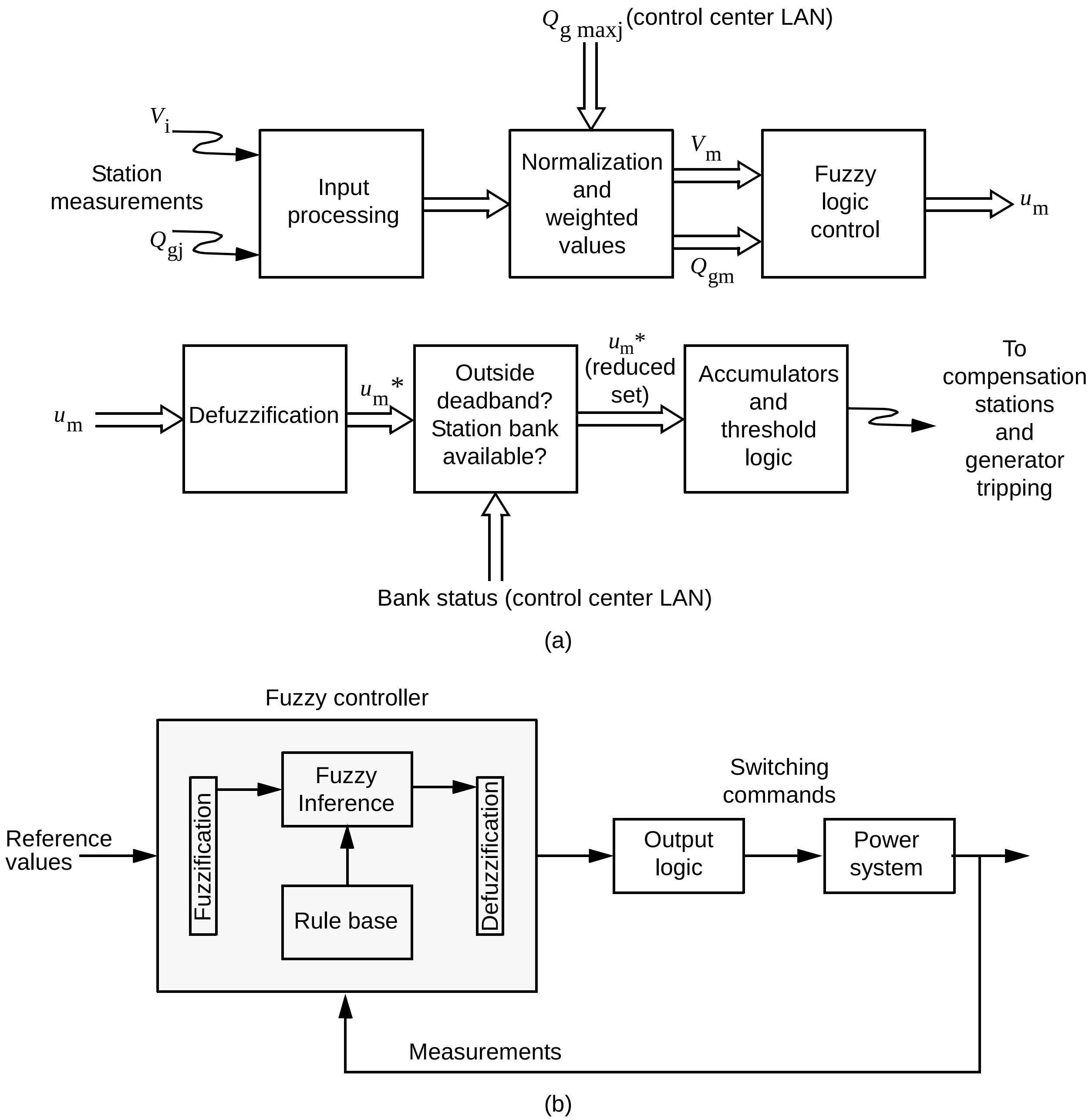



Fig. 3. Overall control scheme for based on voltage magnitude and generator reactive power measurements.

### 3.4 Basic control scheme

Figure 3, an expansion of Figure 2, shows the control. Input processing includes signal validation and computation of variables such as reactive power from the voltage and current phasors. Logic can be included to block operation for momentary voltage dips caused by short circuits. A real-time phasor data concentrator developed at BPA can be modified for these purposes.

Except possibly for high speed control, the basic scheme is to combine voltage measurements and generator reactive power measurements using fuzzy logic. For example, low voltage and high reactive power will result in capacitor bank insertions as either preventive or corrective countermeasures.

For a voltage control "zone," weighted voltage measurements from several substations, and weighted and normalized reactive power measurements from several power plants will be combined.

**Rules.** The controller uses rules based on the weighted voltage and weighted generator reactive power measurements (premise or input variables). The fuzzy control output for compensation switching or generator tripping is $u_m$. The linguistic variables are:

- LOv, low
- HIv, high
- PLq, positive large
- PMq, positive medium
- PSu, positive small
- ZEu, zero
- NSu, negative small, etc.

The lower case letters v, q, and u identify voltage, reactive power, and control linguistic variables.

The rules (computed for compensation or generator tripping station m) are:

1. If $V_m$ is LOv and $Q_{gm}$ is PLq, then $u_m$ is PLu
2. If $V_m$ is LOv and $Q_{gm}$ is PMq, then $u_m$ is PMu
3. If $V_m$ is LOv and $Q_{gm}$ is OKq, then $u_m$ is PSu
4. If $V_m$ is OKv and $Q_{gm}$ is PLq, then $u_m$ is PMu
5. If $V_m$ is OKv and $Q_{gm}$ is PMq, then $u_m$ is PSu
6. If $V_m$ is OKv and $Q_{gm}$ is OKq, then $u_m$ is ZEu
7. If $V_m$ is OKv and $Q_{gm}$ is NMq, then $u_m$ is NSu
8. If $V_m$ is OKv and $Q_{gm}$ is NLq, then $u_m$ is NMu
9. If $V_m$ is HIv and $Q_{gm}$ is NLq, then $u_m$ is NLu
10. If $V_m$ is HIv and $Q_{gm}$ is NMq, then $u_m$ is NMu
11. If $V_m$ is HIv and $Q_{gm}$ is OKq, then $u_m$ is NSu

$V_m$ is the weighted voltage magnitude of measurements for compensation station m and $Q_{gm}$ is the weighted generator reactive power measurement for compensation station m. Figure 4 shows the voltage/reactive power switching plane.

There are alternative fuzzy logic methods, but rules based on a combination of voltage and reactive power measurements (Figure 4 switching plane) are intuitively appealing.

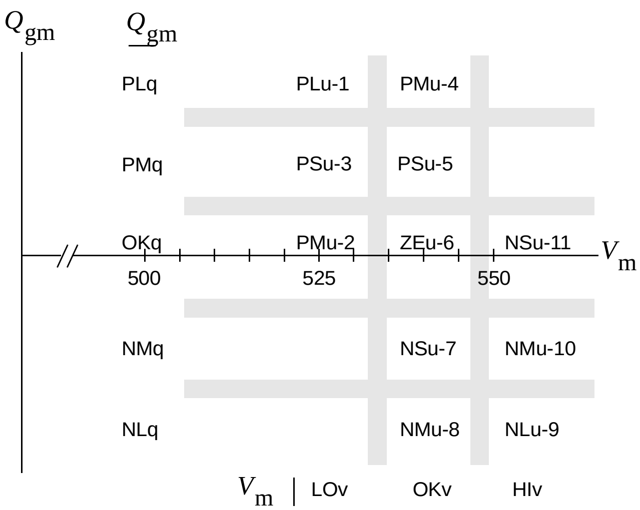



Fig. 4. Switching plane. The rule numbers follows the linguistic variable.

Similar rules can be developed for autotransformer tap changing where the inputs are voltages and transformer reactive power or reactive current.

**Membership functions and fuzzy sets.** The membership value, μ, of a linguistic variable is between zero and one. For small and moderate values, we use isosceles triangle membership functions. For large values, we use the end functions shown on Figures 5–7.

Figures 5–7 show example fuzzy sets for the two inputs and the output. The output domain is ±1. The settings are tuned based on simulation and operating experience, and are different for different output control actions.

**Fuzzy inference.** We use the so-called min-max logic. In the rules, *and* corresponds to the minimum of voltage or reactive power membership. If more than one rule affects the output variable, the maximum value is used. In fuzzy logic, *and* corresponds to a minimum operation and *or* corresponds to maximum operation.

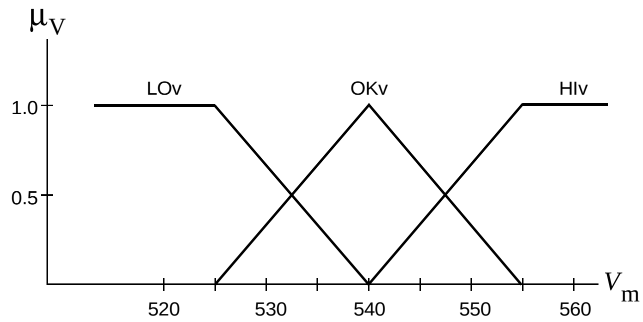



Fig. 5. Example voltage input fuzzy set.

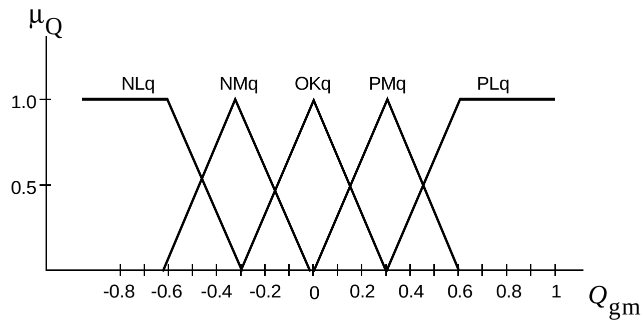



Fig. 6. Example generator reactive power fuzzy set.

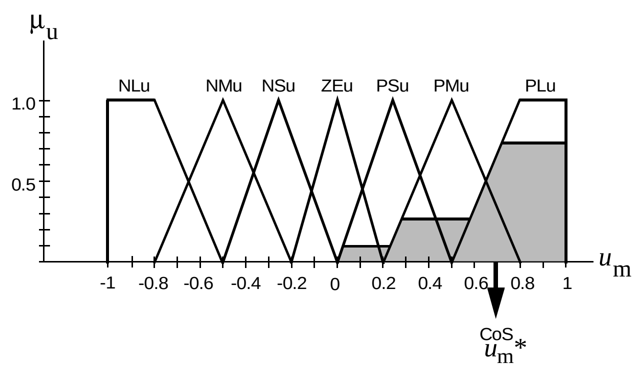



Fig. 7. Example output fuzzy set. Shading and crisp output is for the Appendix 2 example.

**Defuzzification.** The output variable must be converted from a fuzzy value to a crisp value. We use the center of sums method [15]. It's similar to center of area (gravity) except that overlapping areas are taken twice. It's easier to compute and has other advantages.

Center of sums computation is a bit complex and numerically intensive. It's akin to numerical integration over the output fuzzy set. Faster but less robust methods are available. Logic can be used to reduce computation—for example if output variables PL or PM are non zero but compensation is not available at station m to boost voltage (capacitor banks already on), then defuzzification is not necessary.

Appendix 2 provides a calculation example for fuzzy inference and defuzzification. Reference 16 provides more detail, including fuzzy logic pseudo code

**Output logic.** Defuzzification produces a crisp control output, $u_m$*. $u_m$* with domain ±1 is computed for each reactive power compensation station, and also for generator tripping. If $u_m$* is outside a deadband (perhaps ±0.2), and if compensation station m is available for switching in the right direction, switching will be commanded after an accumulated $u_m$*-seconds threshold is reached. Thus the station with the largest sustained values of $u_m$* will be commanded to switch first (inverse-time control).

If $u_m$* is close to ±1, switching could be commanded after only two compute cycles using trapezoidal accumulation/integration (average of two consecutive $u_m$* computations multiplied by compute cycle time).

Once switching or generator tripping is commanded for one or several stations, the stations with smaller $u_m$* should not be switched until the effect of the first switching is evident. With five cycle closing time circuit breaker, three cycle transfer trip and auxiliary relay time, and four cycle margin, the delay time for further switching should be about 12 cycles or 0.2 seconds. This delay can be realized by the threshold of the accumulators or by other logic.

For stations with multiple capacitor or reactor banks, SCADA data is required to determine the pre-disturbance status of each bank, and to select the appropriate bank. Alternatively, the selection logic could be at the compensation station. For nearby stations, logic should, for low voltage problems, switch reactors off before switching capacitor banks on. Vice versa for high voltage.

Accumulators reset when the input is inside the deadband. Additional resetting logic following switching commands might be desirable. If voltage/reactive changes rather than magnitudes are used, resetting will tend to occur as the changes are washed out.

Logic is required to prevent excessive switching or hunting due to some failure or algorithm deficiency. A maximum of, say, three switchings per bank per time period could be enforced, or the deadband could be automatically increased if hunting occurs.

A more sensitive ("trigger-happy") threshold could be used for series capacitor switching. Undesirable switching of series compensation is more benign than undesirable shunt compensation switching.

As in the remedial action schemes, local voltage measurement should supervise the switching command. For example, allow no switching to boost voltage if voltage is above 540 kV.

## 4. Simulation of Transient Stability Control

The first evaluation of the advanced response-based control is for fast transient stability stabilization [17,18]. This is the most demanding application. The critical disturbance, which imposes a limit on north-to-south Pacific Intertie transfer, is outage of two nuclear units at Palo Verde near Phoenix, Arizona in the south portion of the western North American interconnection. Control actions simulated are insertion of series and shunt capacitor banks along the Pacific AC intertie, and up to 800 MW of generator tripping. The series capacitor insertion is on the lines between Grizzly and Malin (Figure 1) and the shunt capacitor banks are two 200 MVAr 500-kV banks at Malin. The generator tripping is either at Grand Coulee and Chief Joseph (Figure 1), or farther north in British Columbia.

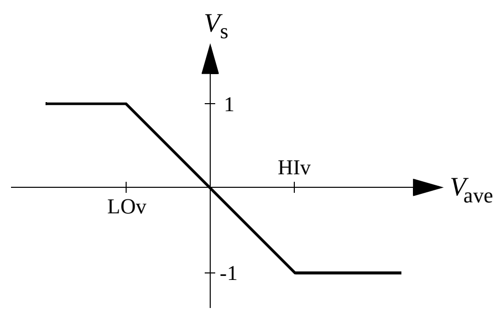
The control time delays represented are 4 cycles delay for receiving the measurements and input processing, 4 cycle delay for control logic including ensuring sustained stress for more than one compute cycle, and 6 cycle delay for output transfer trip signals and circuit breaker operation.

We used the EPRI ETMSP program for simulation. We developed user-defined models for the central control, and enhanced the program to allow the generator tripping and series and shunt capacitor bank switching.

The fuzzy logic control described above was simulated. Also investigated was a proportional control based on weighted voltage magnitudes only. For transient stability, this approach proved to be simpler, easier to tune, more predictable, and faster than the fuzzy control.

### 4.1 Voltage magnitude based control

The inputs to the control scheme are the positive sequence 500-KV voltage measurements from Malin, John Day, Ashe, Slatt and Summer Lake. A weighted average of the five measurements $V_{ave}$ is calculated. The weights are set individually for each control device, and we set higher weights for the Malin and Summer Lake bus voltages since these voltages are more sensitive to severe contingencies affecting the AC Intertie. From the weighted voltage $V_{ave}$, a proportional control signal $V_s$ is calculated for each device as shown in Figure 8.




ig. 8. Proportional control scheme.

The control signal $V_s$ is proportional to $V_{ave}$ if LOv<$V_{ave}$<HIv. Two threshold values $V_{si}$ and $V_{so}$ are also to be set. $V_{si}$ is for switching in of capacitor banks and/or tripping of generators. These actions are initiated if $V_s > V_{si}$. $V_{so}$ is for switching out of capacitors, which is initiated if $V_s < V_{so}$. We can set values for $V_{si}$ and $V_{so}$ for different devices by prioritizing when capacitor banks are to be switched in or out. For choosing between multiple switching actions, the device which has the longest time-period with $V_s$ beyond the switching threshold is switched first.

### 4.2 Simulation results

We describe large-scale simulation results using a summer peak load case. For summer conditions with high Canada to U.S. power transfer, generator tripping is most effective in British Columbia. Using an automated search procedure, we determine Pacific AC intertie transfer limit at the Oregon–California border for several control assumptions (the transfer limit is from transient stability reliability criteria).

Performance of either control scheme depends on the settings. Referring to Figure 5 (fuzzy control) and Figure 8 (voltage magnitude control), the settings are from 500 kV to 580 kv for generator tripping and from 520 kV to 560 kV for capacitor bank switching. Referring to Figure 6, the settings are from -0.5 to +0.5 for generator tripping and -0.4 to +0.4 for capacitor bank switching. Referring to Figure 7, the fuzzy control threshold, $u_m$* is around 0.5. For voltage magnitude based control, the control threshold, $V_{si}$, is around 0.7.

We describe results for the outage of two Palo Verde units (2700 MW).

**Case 1, existing controls.** The Pacific AC Intertie transfer limit is *4175 MW.* The existing controls are voltage relays at Malin that insert series and shunt capacitor banks after time delay. See Figure 8a.

**Case 2, series and shunt capacitor bank switching by fuzzy control.** The transfer limit is *4325 MW.*

**Case 3, series and shunt capacitor bank switching by proportional control.** The transfer limit is *4375 MW.* See Figure 8b.

**Case 4, series and shunt capacitor bank switching, and 800 MW generator tripping in British Columbia by fuzzy control.** The transfer limit is above *4800 MW.*

**Case 5, series and shunt capacitor bank switching, and 800 MW generator tripping in British Columbia by proportional control.** The transfer limit is above *4800 MW.* Stability margin is somewhat greater than Case 4. See Figure 8c.

**Summary.** The transient stability transfer limit can be increased over 600 MW by the proposed controls, which include generator tripping. For transient stability, the voltage magnitude based approach is simpler, easier to tune, more predictable, and faster than the fuzzy control. A difficulty for transient stability with the fuzzy approach that combines voltage magnitude and generator reactive power is the phase lag in the reactive power. For slower preventive and corrective control, the fuzzy logic approach allows more sensitive control.

## 5. Conclusions and Outlook

The wide-area stability and voltage control concepts exploiting information-age digital control and digital communication technology are ambitious and futuristic. While we described the concepts, much work remains to be done in simulation verification, control tuning, and real-time implementation.

The principle benefit of the project is improved voltage security because of better preventive and corrective countermeasures. For preventive countermeasures, control can automate actions of an alert and experienced operator. Other benefits include reduced losses, reduced future compensation needs because of better use of existing compensation, and automation for the future when operators may be less experienced. Also important is the availability of a flexible platform for rapid, low-cost implementation of new control requirements.

We expect synergy between the wide-area control and other control center applications [19]. For example, on-line security assessment can be used for controller tuning and adaptation, and, ultimately, automated learning. There will also be synergy between wide-area control and substation automation (e.g., intelligent electronic devices, digital control and protection).

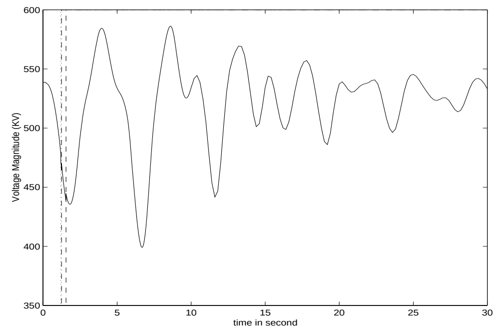



Fig. 8a. Malin 500-kV voltage for double Palo Verde unit outage with 4175 MW transfer. Existing controls with series capacitors inserted at 1.0 seconds, Malin shunt capacitor banks at 1.05 and 1.35 seconds.

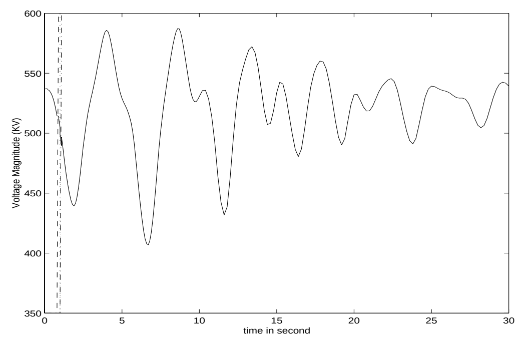



Fig. 8b. Malin 500-kV voltage for double Palo Verde unit outage with 4375 MW transfer. Voltage magnitude based control with series capacitors inserted at 0.8 seconds, Malin shunt capacitor banks at 0.7 and 0.9 seconds.

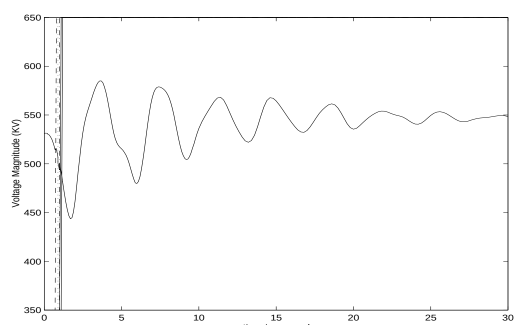



Fig. 8c. Malin 500-kV voltage for double Palo Verde unit outage with 4800 MW transfer. Voltage magnitude based control with series capacitors inserted at 0.69 seconds, Malin shunt capacitor banks at 0.58 and 0.79 seconds, and generator tripping at 0.89 and 0.99 seconds.

There is a gradual improvement and maturing of phasor measurement technology. Much more rapid is the technical development and deployment of fiber optic communication. Also important is the availability of real-time digital controls with graphical interface and support tools such as for fuzzy logic.

Although BPA supports the R&D, and the overall concepts, implementation depends on detailed benefits and cost considerations.

**Acknowledgment:** Ken Martin is the BPA developer of synchronized phasor measurements including a phasor data concentrator, and is responsible for communication latency tests.

## 6. References


[1] C. W. Taylor, *Power System Voltage Stability*, McGraw-Hill, 1994.

[2] C. W. Taylor, G. L. Comegys, F. R. Nassief, D. M. Elwood, and P. Kundur, "Simulation and Implementation of Undervoltage Load Shedding for Pacific Northwest Voltage Stability," *CIGRÉ*, paper 38–103, 1994.

[3] C. W. Taylor and D. C. Erickson, "Recording and Analyzing the July 2 Cascading Outage," *IEEE Computer Applications in Power*, Vol. 10, No. 1, pp. 26–30, January 1997.

[4] C. W. Taylor, "Improving Grid Behavior," *IEEE Spectrum*, pp. 40–45, June 1999.

[5] D. M. Kosterev, C. W. Taylor, and W. A. Mittelstadt, "Model Validation for the August 10, 1996 WSCC System Outage," *IEEE Transactions on Power Systems*, Vol. 14, No. 3, pp. 967–979, August 1999.

[6] CIGRÉ TF 38.02.17, *Advanced Angle Stability Controls*, December 1999.

[7] North American Electric Reliability Council, *NERC Planning Standards*, September 1997, http://www.nerc.com/~filez/pss-psg.html.

[8] C. W. Taylor and R. Ramanathan, "BPA Reactive Power Monitoring and Control following the August 10, 1996 Power Failure," *Proceedings of VI Symposium of Specialists in Electric Operational and Expansion Planning*, Salvador, Brazil, May 24–29, 1998.

[9] D. Brandt, R. Wachal, R. Valiquette, and R. Wierckx, "Closed Loop Testing of a Joint VAR Controller Using a Digital Real-Time Simulator," *IEEE Transactions on Power Systems*, Vol. 6, No. 3, pp. 1140–1146, August 1991.

[10] C. V. Thio and J. B. Davies, "New Synchronous Compensators for the Nelson River HVDC System - Planning Requirements and Specification," *IEEE Transactions on Power Systems*, Vol. 6, No. 2, pp. 922–928, April 1991.

[11] J. F. Hauer, W. A. Mittelstadt, W. H. Litzenberger, C. Clemans, D. Hamai, and P. Overholt, *Wide Area Measurements for Real-Time Control and Operation of Large Electric Power Systems: Evaluation and Demonstration of Technology for the New Power System*. Report prepared for U.S. Department of Energy by Bonneville Power Administration and Western Area Power Administration, April 1999. The report and attachments are available from BPA on compact disk.

[12] CIGRÉ TF 38.02.12, *Criteria and Countermeasures for Voltage Collapse*, Brochure Number 101, October 1995.

[13] CIGRÉ TF 34.08, *Protection against Voltage Collapse*, Brochure Number 128, 1998

[14] Earl Cox, "Fuzzy Fundamentals," *IEEE Spectrum*, pp. 58–61, October 1992.

[15] D. Driankov, H. Hellendoorn, and M. Reinfrank, *An Introduction to Fuzzy Control*, Springer–Verlag, 1993.

[16] C. W. Taylor, *BPA Advanced Voltage and Reactive Power Contro*l, BPA report, 31 March 1998. Available from author.

[17] V. Venkatasubramanian and K. W. Schenider, *Summary of BPA SVC/TCSC/HVDC Modulation Studies at WSU*, Washington State University report for BPA, February 1998.

[18] V. Venkatasubramanian, Y. Chen, and J. Li, *BPA Advanced Voltage Control Evaluation*, Washington State University report for BPA, November 1999.

[19] C. W. Taylor, "The Future in On-Line Security Assessment and Wide-Area Stability Control," *Proceedings of IEEE Power Engineering Society 2000 Winter Meeting*, 23–27 January 2000, Singapore.

[20] S. Chiu, "Using Fuzzy Logic in Control Applications: Beyond Fuzzy PID Control," *IEEE Control Systems*, pp. 100–104, October 1998.


## Appendix 1: Fuzzy Logic Applications

**When to use fuzzy logic.** Fuzzy logic is attractive for high level, discrete control. The following ideas and quotes are taken from the literature:

Fuzzy logic is an effective way of including engineering judgment in the form of qualitative rules. Fuzzy logic is useful for human-like decision making requiring the use of heuristic reasoning and learning from past experience. Intelligent controls have an ability to emulate human capabilities such as planning, learning and adaptation.

Fuzzification handles uncertainty in a very natural way.

Measurements include noise so there is inevitable fuzziness in the interpretation of sensor data. Fuzzy logic is useful where redundant measurements are not highly accurate.

Fuzzy logic provides graded transition from one control action to the next. It's less prone to chattering or limit cycles than bivalent control. Interpolation among rules is important for being able to implement a rule system without inducing limit cycles.

Fuzzy logic is an attractive technique for the control of an ill-defined or parameter-variant plant.

Fuzzy logic is good when a mathematical model of the process does not exist, or exists but is too difficult to encode, or is too complex to be evaluated fast enough for real time operation, or involves too much memory. It's useful when high ambient noise levels must be dealt with or it is important to use inexpensive sensors and/or low-precision microcontrollers.

Intelligent control systems are designed to maintain satisfactory closed-loop system performance and integrity over a wide range of operating conditions.

Processes that are significant for intelligent control are, in general, large-scale and hybrid in nature and may be described by differential or difference equations, discrete event models or both.

Learning is required when the complexity of a problem or the uncertainty thereof prevents a priori specification of a satisfactory solution.

A system considered optimal according to an analytic measure is not necessarily optimal according to human judgement. The use of fuzzy logic to express optimality measures is perhaps the most valuable benefit that fuzzy logic brings to control applications. *The essence of fuzzy logic is that it lets you express what's on your mind.* [20]

**Rules of thumb for membership functions.** Number of linguistic labels associated with a variable should generally be an odd number between 5 and 9.

Each label should overlap somewhat with its neighbors. The overlap should be between 10 and 50 percent of the neighboring space, and the sum of the vertical points of the overlap should always be less than one. A cross point level of 0.5 is usually best.

The density of the fuzzy sets should be highest around the optimal control point of the system and should thin out as the distance from that point increases.

## Appendix 2: Fuzzy Logic Calculation Example

The example for the 460 MVAr, 550-kV John Day capacitor bank. The control settings are those of Figures 5–7.

Assume the voltages at John Day, Big Eddy, and Hanford are 525 kV, 528 kV, and 530 kV respectively (Figure 1). The assumed corresponding weights are 0.6, 0.3, and 0.1. All other weights are zero. The weighted voltage is 526.4 kV.

The normalized reactive power at John Day, Big Eddy, McNary, and Ashe are 0.6, 0.5, 0.4, and 0.4. The corresponding weights are 0.5, 0.2, 0.15, and 0.15. Using equation 2, the weighted reactive power is 0.52.

Using Figure 5, voltage is LOv with membership (540 - 526.4)/(540 - 525) = 0.907. Voltage is OKv with membership (526.4 - 525)/(540 - 525) = 0.093.

Using Figure 6, reactive power is PMq with membership (0.6 - 0.52)/0.3 = 0.267. Reactive power is PLq with membership (0.52 - 0.3)/0.3 = 0.733.

Therefore rules 1, 2, 4, and 5 fire. Rule 1 says that output is PLu = min (0.907,0.733) = 0.733. Rule 2 says that output is PMu = min (0.907,0.267) = 0.267. Rule 4 says that output is PMu = min (0.093,0.733) = 0.093. Rule 5 says that output is PSu = min (0.093,0.267) = 0.093. Combining rules 2 and 4 gives PMu = max(0.267,0.093) = 0.267.

Figure 7 shows the fuzzy control output.

Using center of gravity, the crisp control output value is $u_m^* = 0.7$. Using center of sums, $u_m^* = 0.69$.

Calculations could be repeated assuming failure of some measurements or telemetry.