Position paper for NSF/DOE/EPRI Sponsored Workshop on
Future Research Directions for Complex Interactive Electric Networks
Washington D.C., 16–17 November 2000

Response-Based, Feedforward Wide-Area Control

Carson W. Taylor
Bonneville Power Administration
Transmission Business Line
Vancouver, Washington USA

Abstract: I suggest R&D directions for wide-area angle and voltage stability controls in large power systems. Existing wide-area stability controls are mostly event-driven discontinuous actions, and are termed special protection systems or remedial action schemes. More sophisticated controls act on the measured response (swing) of electrical variables to disturbances. I describe applications of response-based, feedforward (disturbance-rejecting) wide-area controls, including preliminary designs for stability and voltage controls in the Pacific Northwest portion of the western North American interconnected power system.

Power System Stability Control Challenges

Industry restructuring poses challenges in facilitating commerce over transmission networks while ensuring power system security against cascading outages [1]. There are many areas requiring R&D and technology deployment. Experience indicates technology deployment will likely lead to new areas for research.

Because of the difficulties and lack of incentives to expand transmission networks, transmission line loadings are increasing as load grows and commerce increases. The power system stress and potential for synchronous and voltage instability are increasing. There is pressure to relax reliability criteria, even to the point of operating to N-0 criterion. This means reliable and robust control actions will be required for many single contingencies. These control actions are often of the discontinuous, feedforward (disturbance-rejecting) type.

(Spinning reserve requirements and requirements for predisturbance load curtailment are already being replaced with load tripping in the event generation or import capability is actually lost.)

The high volatility in power prices challenges the industry to develop IT solutions for direct load control. Direct load control (air conditioners, space and water heating) also offers a painless way to shed load for power system stability, especially longer-term voltage stability.

With the digital/optical revolution in sensors, control and protection, and communications, system reliability can be greatly enhanced by replacement of legacy equipment. The challenge is to justify and prioritize these enhancements. Similar to transmission additions, attractive return on investment is required.

Restructuring, with formation of regional transmission organizations (transcos or ISOs), results in new control centers. This provides not only challenges, but “greenfield” opportunities for sophisticated wide-area control of large geographic coverage. Availability of fiber optic communication networks facilitate wide-area control.

Meeting the challenges of power system operation under higher stress requires fidelity in steady-state and dynamic simulation. Despite significant efforts, large discrepancies still exist between simulation and the real world. Reference 2 describes problems, but four years later we are encountering similar problems, especially in simulation of oscillation damping. There is justified concern that simulation fidelity is poor compared to reliability criteria safety margins.

Present Practice and State-of-the-Art in Stability Controls

Power system stability and voltage controls are mainly local feedback control at generating plants, such as automatic voltage regulators including power system stabilizers and prime mover controls. Other feedback controls exist at special substation power electronic devices such as static var compensators. These controls are usually continuous (smooth). The controls are now highly developed, and new controls are implemented digitally [3]. Nevertheless, technological progress continues, with reference 4 being one example. Power system dynamic performance could be enhanced with replacement of legacy equipment such as PSS with noisy speed or frequency transducers and low gains.

Power electronic devices, where justified, also offer powerful control performance (e.g., ref. 5). Further R&D is required for wide-area coordination of generator controls and transmission-level power electronic device controls [26].

Another class of controls, for both preventive and corrective actions, are mechanically-switched devices such as series and shunt capacitor banks. These are discrete (discontinuous controls), and the switching frequency is restricted. Circuit breaker operating time (two cycle opening, five cycle closing) are fast enough, for single operation, and can be fast enough for several bang-bang operations for control of low frequency oscillations (2–4 second period). Generator or load tripping are even more powerful discontinuous

Bonneville Power Administration - TOP/Ditt2, PO Box 491, Vancouver, WA 98666, USA, cwtaylor@bpa.gov.

control for stability enhancement.

At present, these discrete devices are mostly switched manually via SCADA, by simple local relays, or by event-driven wide-area controls (special protection systems/remedial action schemes).

The devices and controls are widely used, and are usually cost-effective compared to power electronic devices. Shunt capacitor banks are low cost and have virtually zero losses. Modern all-film fuseless capacitor banks increase cost-effectiveness [6,7]. New techniques for multiple-step banks are developed [8,9].

For perspective, Bonneville Power Administration has fourteen 500-kV capacitor banks (up to 460 MVAr at 550-kV), fifty-three 230-kV banks (up to 168 MVAr at 241-kV), and numerous 115-kV banks. BPA also has two large static var compensators and one thyristor controlled series capacitor, but this equipment is not cost-justified [10].

BPA and other power companies have very extensive wide-area, event-driven stability controls for generator and load tripping, and for shunt and series reactive power compensation switching. PLCs are used for logic decisions, and transfer trip over microwave radio is used for communications. Fault-tolerant control center computers perform central logic. Redundancy ensures no single component will cause scheme failure. Events detected are usually outages of 500-kV lines.

The event-driven wide-area stability controls, while very fast for transient stability and very reliable, have shortcomings. They obviously only operate for certain pre-determined disturbances within a portion of the transmission network. They are also expensive to install and modify. The complexity is such that BPA has a 24/7 “RAS Dispatcher.”

For slower switching of shunt compensation (preventive control for voltage stability) manual switching has disadvantages, and automation is desirable. System operation is becoming ever more complex, with rapid growth of transactions. Incorrect capacitor bank switching by operators contributed to a partial voltage collapse and loss of load on the Olympic Peninsula in January 1995.

More sophisticated wide-area control is now possible based on developments such as digital transducers and signal processing, fiber optic communications, and easy to program real-time control computers [3,11]. High accuracy, low noise digital transducers include synchronized positive sequence voltage and current phasor measurement and frequency measurement [12,13]. Fiber optic communications have reduced latency [3], and “relay to relay” transfer trip time can be as short as 6 ms [14]. BPA has recently installed over 2900 km of SONET fiber optic communications. A glut of fiber optic capacity may be developing [15]. An example of flexible, easy to program and modify real time control is LabVIEW Real Time which uses the G graphical, dataflow-driven, structured programing language [16]. The embedded computer is linked to a standard PC platform, and fault tolerance can be designed using two or more embedded computers.

Wide-area control is facilitated by control center application programs such as the emerging dynamic and voltage security assessment software. Industry restructuring results in larger control centers with larger databases and geographic scopes. Although hindered by legacy equipment, substation automation installations are emerging that also facilitate wide-area control, including geographically distributed control.

Also facilitating application of wide-area controls are developments in control theory, including intelligent controls [3].

Chapter 9 of reference 3 suggests areas for future work in the area of advanced stability controls.

Figure 1 shows the general control environment, with response-based feedforward control highlighted.

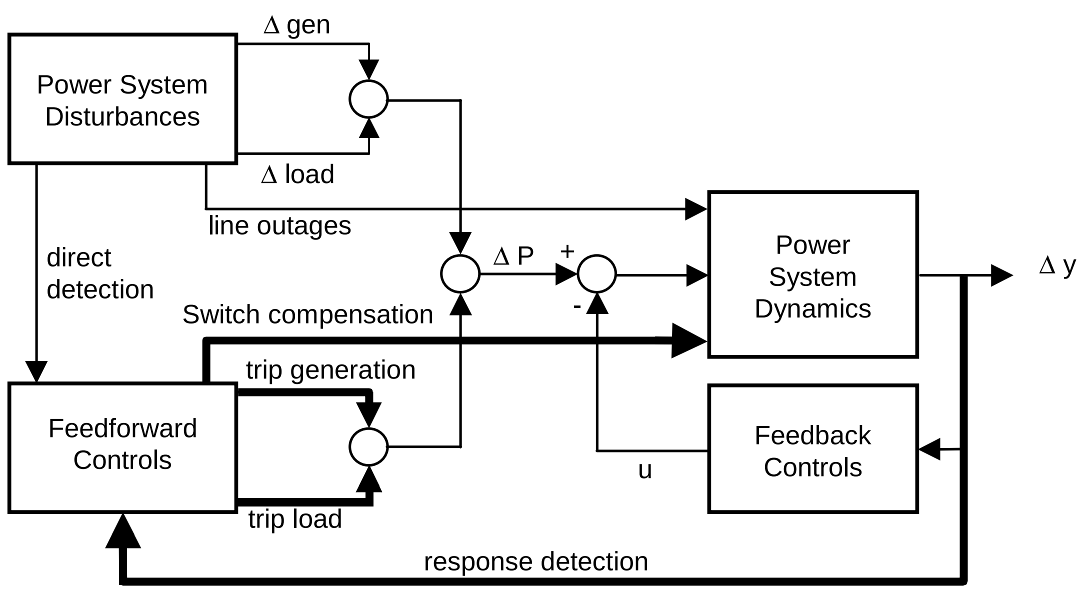


Fig. 1. General power system structure showing stability controls. Response-based feedforward controls are emphasized. Source: J. F. Hauer

BPA's Advanced Stability and Voltage Control Project

Before suggesting R&D directions, I'll describe a BPA project.

We are 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 collaboration with Washington State University. Reference 17 describes the project in more detail, and reference 18 provides additional background.

A principle benefit of the project is improved angle and voltage security. 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).

Figure 2 shows the overall control proposal. The project exploits "information age" technology in digital control and communications [3,11]. 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.

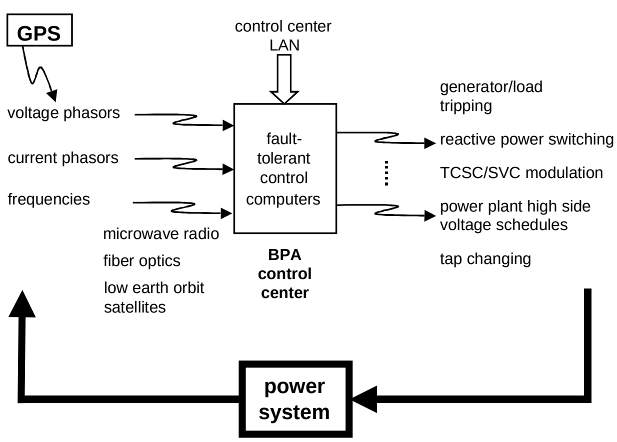


Fig. 2. Flexible wide-area control.

The project goals include:

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

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

3. 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. Fuzzy logic is a convenient means to combine reactive power and voltage magnitude measurements. For local areas without substantial generation, reactive power flow computed for the center of major support lines can replace generator reactive power. Reactive power is a much more sensitive indicator of voltage problems than voltage magnitude.

4. 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 reserves and boost transmission voltages, 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.

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

6. Evaluate benefits of automatic centralized control and improved local control. Hierarchal centralized and improved local control (distributed control) will be evaluated.

Many of the components shown on Figure 2 exist, including synchronized phasor measurements (seven 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.

Expansion of phasor measurements has been approved. Within a year or so, BPA phasor measurements available at the BPA control center will include 17 positive sequence voltage phasor and frequency measurements at eleven 500-kV buses and 4 measurements at 230-kV buses. Current phasors will be available for approximately 40 transmission lines and 22 generator lines. The additions will utilize BPA fiber optic communications. One existing phasor measurement location will be converted from analog microwave to fiber optic communication. Phasor measurements are also received from other WSCC utilities (notably Southern California Edison at present). Phasors and bus frequencies are telemetered 30 times per second.

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 [20,21].

Simulation results show cases where Pacific AC Intertie transfer capability can be increased over 600 MW by wide-area, response-based control for generator tripping [17].

An alternative strategy is to distribute some of the reactive power compensation control to substations (only simple local voltage relay supervision is used with central control). Figure 3 shows a substation controller used by at least two utilities [22,23]. In this distributed control the inputs V_{aux} are bias signals derived from remote reactive power and voltage measurements to make the control more sensitive and robust. For example, high reactive power output at nearby generators will cause faster capacitor bank insertion. Chapter 7 of reference 19 provides simulation results.

The wide-area stability and voltage control concepts exploiting information-age digital control and digital communication technology are ambitious and futuristic. Much work remains in simulation verification, control tuning, and real-time implementation.

R&D Directions: Wide-Area Control

The pieces are coming together!

What is most needed now is full-scale demonstration of the state-of-the-art in power system stability and voltage control. Ideally, this should be a partnership between practicing engineers and researchers. Researchers should be involved in the difficult practical work of overcoming barriers to implementation [25]. This often leads to meaningful new research areas.

As sophisticated response-based feedforward controls are deployed, attention can be brought to still more advanced concepts such as wide-area bang-bang and continuous feedback controls.

Synergy between control center applications and wide-area controls is needed. On-line security assessment provides an organized database for intelligent controls such as neural nets, decision trees, or adaptive fuzzy logic. Automated control system learning is possible

Likewise, synergy between substation automation and wide-area control is needed. Distributed and hierarchical control concepts require investigation and development as alternatives to centralized control. Multicast rather than point to point fiber optic communication is necessary for distributed control.

Longer range, and more abstract, real-time software concepts such as “agents” appear promising [24].

R&D Directions: Related Work

Starting from scratch, a new power system would have all digital/optical sensors, communications, and control and protection. How to prioritize and cost-justify the transition from legacy to 21st century equipment?

Given the preponderance of mechanically-switched equipment, controls approaching the sophistication of controls for equipment such as thyristor switched capacitor banks require development. Almost all of the available actuators are mechanical.

Power electronic devices will have a wider role to play as they become less costly. Where to locate: at loads, distribution, transmission? How to control and coordinate multiple devices? Optimal choice of type of device?

Direct load control for voltage and price stability is needed.

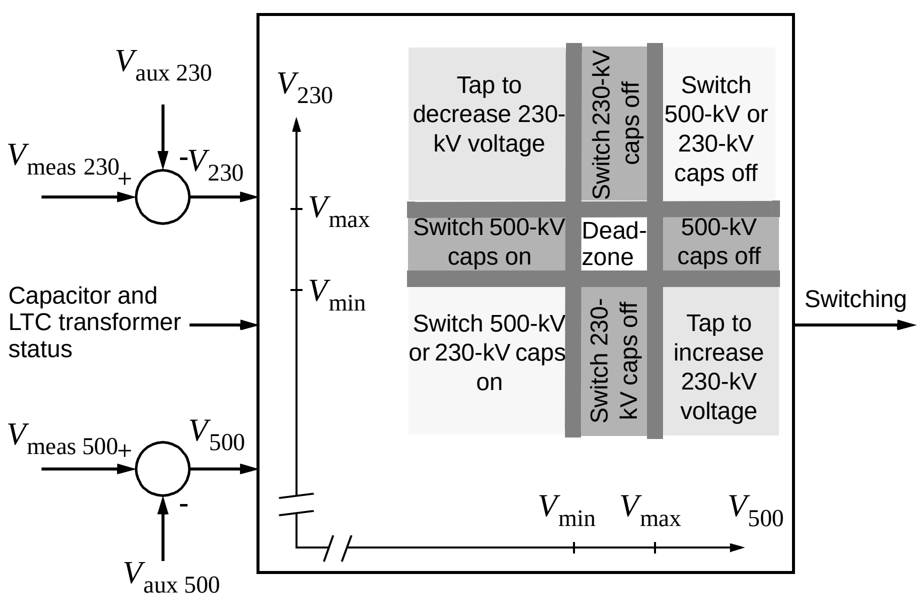


Fig. 3. Microprocessor-based substation voltage/reactive power controller with both 500-kV and 230-kV capacitor banks, and LTC autotransformer. Switching based on inverse-time criteria [19].

Direct load control for angle stability is also proposed.

Finally, the fidelity of simulations must be improved. This requires expansion of measurement equipment at power plants and load busses, as well as simulation software improvements. Wide-area measurements for system/equipment monitoring can also be used for wide-area control.

Finis

The state-of-the-art in power system stability controls, including many recommendations for research and development, are comprehensively described in two recent CIGRÉ reports [3,26].

Power system stability and security requires defense in depth (multiple lines or layers of defense). These layers include effective planning and operation, EMS applications, and state-of-the-art control and protection. State-of-art control and protection includes digital equipment and optical communications, single-pole switching, underfrequency and undervoltage load shedding, sensitive reactive power compensation control, and emergency controls for generator/load tripping and controlled islanding.

Wide-area, response-based control is a promising, but technically challenging, additional layer of defense. This layer becomes necessary as security margins are reduced to facilitate electric power commerce.

References

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

[2] 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.

[3] CIGRÉ TF 38.02.17, *Advanced Angle Stability Controls*, Brochure Number 155, April 2000 (available at http://www.transmission.bpa.gov/orgs/opi/index.shtm, summary in April 2000 issue of *Electra*).

[4] H. Kitamura, M. Shimomura, and J. Paserba, "Improvement of Voltage Stability by the Advanced High Side Voltage Control Regulator," *Proceedings of 2000 IEEE Power Engineering Society Summer Meeting*, 16–20 July 2000, Seattle, Washington (available at http://www.transmission.bpa.gov/orgs/opiindex.shtm under Power System Stability Controls Subcommittee).

[5] C. Gama, L. Ängquist, G. Ingeström, and M. Noroozian, "Commissioning and Operative Experience of TCSC for Damping Power Oscillation in the Brazilian North–South Interconnection," *CIGRÉ*, paper 14-104, 2000.

[6] P. H. Thiel, J. E. Harder, and G. E. Taylor, "Fuseless Capacitor Banks," *IEEE Transactions on Power Delivery*, Vol. 7, No. 2, pp. 1009–1015, April 1992.

[7] M. S. Dhillon, and D. A. Tziouvaras, "Protection of Fuseless Capacitor Banks Using Digital Relays," Proceedings of 26 Annual Western Protective Relay Conference, 26–28 October 1999, Spokane, Washington USA.

[8] C. W. Taylor and A. L. Van Leuven, "CAPS: Improving Power System Stability Using the Time-Overvoltage Capability of Large Shunt Capacitor Banks," *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, pp. 783–792, April 1996.

[9] D. Bruns, S. Miske, C. Taylor, G. Lee and A.-A. Edris, "Shunt Capacitor Bank Series Group Shorting (CAPS) Design and Application," IEEE paper PE-021PRD (07-2000), to appear in IEEE Transactions on Power Delivery.

[10] C. W. Taylor and M. K. Pal, discussions of "Voltage Stability of the Puget Sound System Under Abnormally Cold Weather Conditions," *IEEE Transactions on Power Systems*, Vol. 8, No. 3, pp. 1133-1142, August 1993.

[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] A. G. Phadke, J. S. Thorp, and M. G. Adamiak, "A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency, and Rate of Change of Frequency," *IEEE Transactions on Power Systems and Apparatus*, Vol. PAS-102, No. 5, pp. 1025-1038, May 1983.

[13] IEEE Power System Relaying Committee, "Synchronized Sampling and Phasor Measurements for Relaying and Control," *IEEE Transactions on Power Delivery*, Vol. 9, No. 1, pp. 442–452, January 1994.

[14] E. O. Schweitzer III, K. Behrendt, and T. Lee, "Digital Communications for Power System Protection: Security, Availability, and Speed," *CIGRÉ*, paper 34-104, 2000.

[15] M. Heinzl, "Operators of Fiber-Optic Networks Face Capacity Glut, Falling Prices," *Wall Street Journal*, page B1, October 19, 2000.

[16] National Instruments, www.ni.com/info/lvrt.

[17] C. W. Taylor, V. Venkatasubramanian, Y. Chen, "Wide-Area Stability and Voltage Control," *Proceedings of VII Symposium of Specialists in Electric Operational and Expansion Planning (VII SEPOPE)*, 21–26 May 2000, Curitiba, PR, Brazil (available at http://www.transmission.bpa.gov/orgs/opiindex.shtm under Power System Stability Controls Subcommittee).

[18] C. W. Taylor, "Line Drop Compensation, High-Side Voltage Control, Secondary Voltage Control—Why Not Control a Generator Like a Static Var Compensator?" *Proceedings of IEEE Power Engineering Society 2000 Summer Meeting*, 16–20 July 2000, Seattle (available at http://www.transmission.bpa.gov/orgs/opiindex.shtm under Power System Stability Controls Subcommittee).

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

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

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

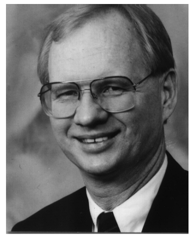
[22] S. Koishikawa, et al., "Adaptive Control of Reactive Power Supply Enhancing Voltage Stability of a Bulk Power Transmission System and a New Scheme of Monitor on Voltage Security," *CIGRÉ*, paper 38/39-01, 1990.

[23] M. C. Perdomo and G. P Arbeláez, "Voltage Reactive Power Control Strategy in the Columbian Transmission System: Control Philosophy, Application and Implementation," *VI Symposium of Specialists in Electrical Operational and Expansion Planning* (VI SEPOPE), Salvador, Brazil, 24–29 May 1998.

[24] C.-C. Liu, J. Jung, G. T. Heydt, V. Vittal, and A. G. Phadke, "The Strategic Power Infrastructure Defense (SPID) System," *IEEE Control Systems Magazine*, pp. 40–52, August 2000.

[25] D. S. Bernstein, "Control Experiments and what I Learned From Them: A Personal Journey," *IEEE Control Systems*, pp. 81–88, April 1998.

[26] CIGRÉ TF 38.02.16, *Impact of Interactions among Power System Controls*, Brochure Number 166, August 2000 (summary in August 2000 issue of *Electra*).



Carson W. Taylor (F'88) joined Bonneville Power Administration in 1969 after earning degrees from the University of Wisconsin and Rensselaer Polytechnic Institute. His current position is Principal Engineer in Transmission Operations and Planning. Mr. Taylor is a Fellow of the IEEE and chairs the IEEE Power System Stability Controls Subcommittee. He is a distinguished member of CIGRÉ and has convened three CIGRÉ task forces.

Mr. Taylor is the author of the EPRI-sponsored book *Power System Voltage Stability*. Mr. Taylor also operates Carson Taylor Seminars, a training and consulting company established in 1986.