Keeping an Eye on Power System Dynamics

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An interconnected power system is one of the largest and most complex of human achievements. It is maintained in a stable dynamic state only by tight control and protection, plus intelligent and diligent operation. Operating details are taken for granted by the general public; only when some catastrophic failure takes place is power system stability seen as newsworthy.

Faults occur on power systems, most often through natural phenomena beyond human control. However, a well designed system will, for the most common faults, recover automatically and continue power delivery with very little inconvenience to its customers. This level of performance is achieved at a high cost in terms of manpower and equipment. In the future, the market economy is likely to force power systems much closer to their limits of stable operation, and operating decisions will have to be based on accurate, online system information and simulations rather than the current practice of extensive offline simulation of a comprehensive set of possible system operating conditions.

The massive breakup experienced by the Western North American Power System on August 10, 1996, has focused national attention on the problem of power system dynamic security. The final breakup was caused by the unstable oscillation which started at about 725 s. This was the culmination of a number of automatic system protection actions that triggered following a fault on a 500-kV line. Post-mortem analysis of monitor records, such as that in Figure 1, suggests that potential oscillation problems may have been predictable. Such predictions will be essential if operators are to maintain system security close to the limit of system stability.

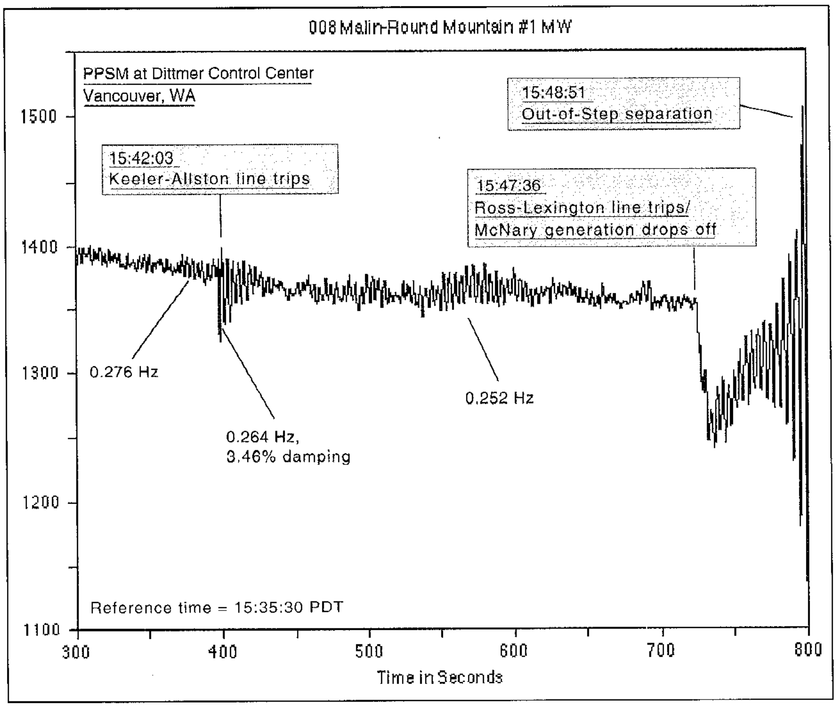

Figure 1. Oscillations on the WSCC system, August 10, 1996

The market economy forces systems closer to their stability limits, and operating decisions must be based on accurate, online system information and simulations

Using offline simulation studies, it is not possible to predict the behavior of a system under a sequence of faults outside the design criteria, such as the sequence that caused this Western Systems Coordinating Council (WSCC) breakup. Online simulation has reached neither the required level of speed nor the detail of modeling accuracy necessary for online dynamic security.

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An interim solution is to rely on continuous monitoring of the system dynamics. This can be viewed as a form of measurement-based dynamic security analysis. In the Western Power System, the technology and infrastructure that this requires are being developed as extensions of the Department of Energy/Electric Power Research Institute Wide-Area Measurement System (WAMS) Project and related efforts. These efforts are directed towards providing essential support for:

- Early detection of system problems, enabling cost reductions through performance-based maintenance and providing a safety check on network loading
- Refinement of planning, operation, and control processes to allow best use of transmission capability
- Real-time determination of transmission limits.

Any tools developed must be user friendly and allow ease of use under the stressed conditions of online operation. The infrastructure must also include adequate communication links so that information can be disseminated to and discussed by expert technical staff widely separated geographically.

Dynamic Information Technologies Package

Bonneville Power Authority (BPA) began to develop integrated monitoring and analysis tools to meet the need for accurate and coordinated dynamic power system information in 1990. The Dynamic Information Technology Package (DITPak) has evolved, and it now includes virtual instrumentation using LabVIEW software, modular and readily networked measurement hardware, streamlined analysis software in a MATLAB working environment, and optional use of familiar workstation tools for display and report generation (Figure 2).

It has been explicitly designed to accommodate future technology advances as they are introduced. Development of the package has been a collaboration between many individuals and organizations (principally BPA, the Pacific Northwest National Laboratory (PNNL), the Universities of Montana and Colorado, and key vendors). This has assured that the package meets the wide range of requirements likely to be necessary in future power system operations. The package consists of three elements:

- Portable Power System Monitor (PPSM). An interactive measurements workstation with an option for virtually continuous recording. Integration of multiple-site data is facilitated by optional use of satellite-synchronized precise time measurements.
- Power System Identification Toolbox (PSITools). A graphical user interface using MATLAB that allows access to advanced FORTRAN, multioutput Prony analysis, and conventional Fourier analysis. These may be combined with frequency domain options

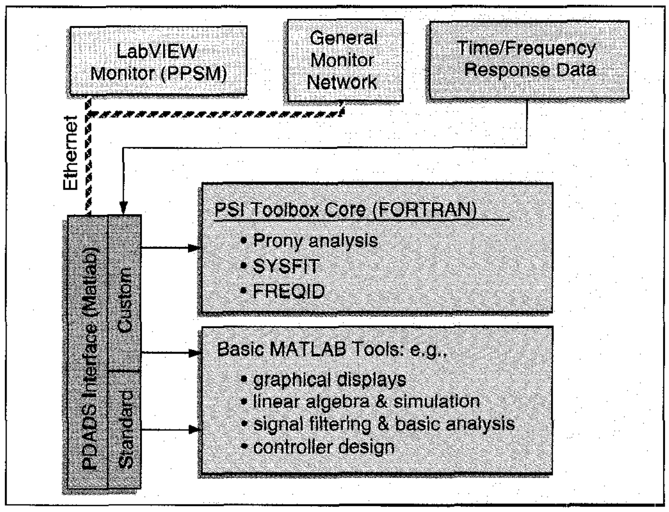

Figure 2. DITPak architecture

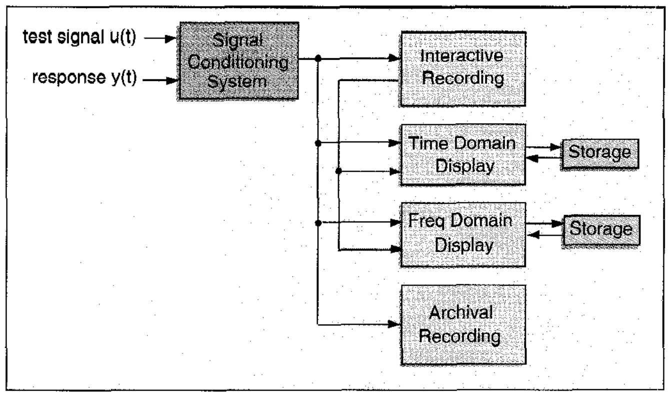

Figure 3. DITPak functionality

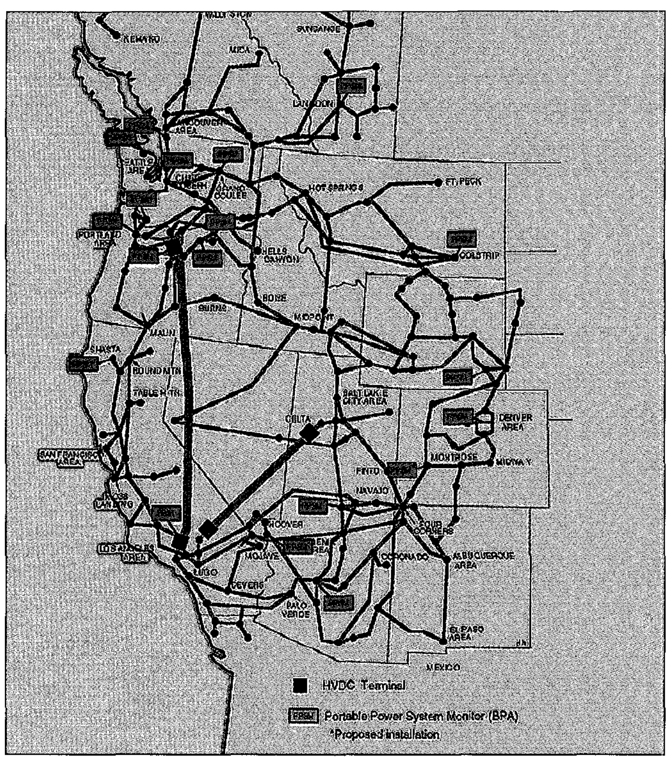

Figure 4. PPSM units in service in 1996

to fit models to observed system response. Modal analysis results are particularly useful for controller design and for refinement of computer models.

- Portable Dynamic Analysis and Design System (PDADS). Based on the widely used MATLAB script language, PDADS provides integrating tools and a user interface. It provides access to all MATLAB tools, together with control and data exchange interfaces to the PSI Toolbox and the PPSM. It also supports custom, menu-driven graphical interfaces for specific application environments.

DITPak was expressly engineered to extract dynamic information from sources such as:

- System disturbances

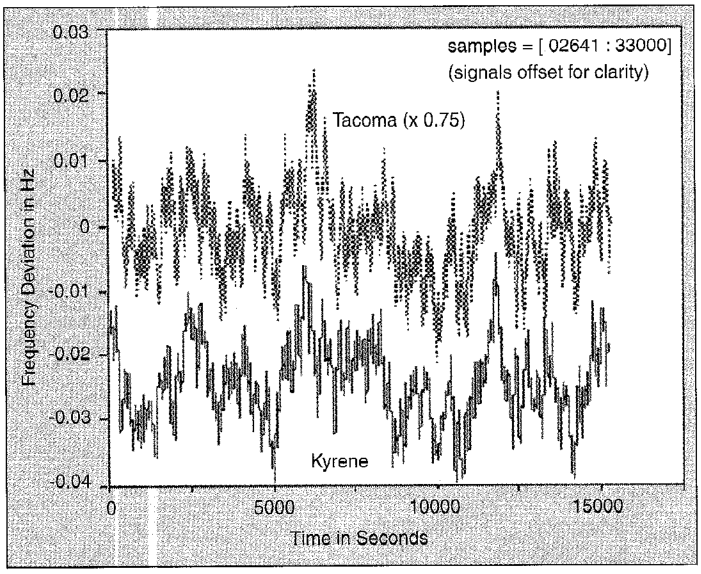

Figure 5. Ambient fluctuations in bus frequency, Tacoma and Kyrene substations, April 15, 1996

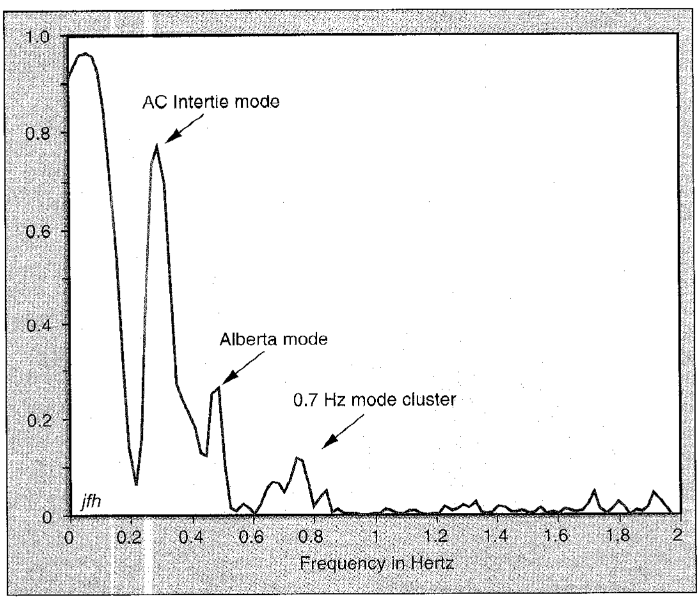

Figure 6. Coherency of ambient fluctuations in bus frequency, Tacoma and Kyrene substations, April 15, 1996

- Ambient system conditions using spectral signatures, correlation analysis, and open-loop/closed-loop spectral comparisons
- Direct tests with random low-level signal injections, network switching, and high-level pulse or step inputs.

Figure 3 shows the functionality of DITPak.

Measurements and Analysis of Events in the Western Interconnected System

At present, there are some 20 PPSM units in service across the western power system (Figure 4). Under the WAMS Project, these are being interfaced with critically placed measurement systems of other types, primarily those based upon phasor measurement technologies.

Ambient Data Analysis

Figures 5 and 6 show an example of wide-area correlation involving the bus frequency at the Kyrene substation in Phoenix, Arizona, and the bus frequency at the Tacoma substation, near Seattle, Washington. The Tacoma measurements were recorded at the central monitor at the Dittmer Control Center. The signals were obtained under ambient conditions from ordinary frequency transducers. The substations are about 1,000 miles apart, and Global Positioning System (GPS) synchronization was not used.

The coherency between the signal and other spectral functions shows the existence of particular oscillatory modes. Simulation models can be compared with these measured results for validation, and any subsequent changes in the spectral signature can be used to give warnings of system changes to system operators.

Response to Major Disturbances

Signals from major disturbances are a good source of information concerning the behavior of oscillatory dynamics and of the control systems that affect them. The response caused by a generator tripping at the Palo Verde plant near Phoenix is particularly useful in determination of the frequency and damping of the dominant north/south oscillatory mode across the Pacific ac intertie.

Figure 7 shows limiting cases among five trips during the winter of 1992-1993. From this figure, the following information about this north/south oscillation may be inferred:

- The frequency and damping of the mode vary considerably during normal conditions.
- The damping can reach values low enough to be considered potentially dangerous.
- The measured signal response is dominated by the mode. This mode-shape information indicates that Palo Verde is a good location for observing the effect of damping controls and suggests that Palo Verde itself may be a good location for controls to damp the mode.

Figure 7 is just one among many examples gathered through collective efforts of the WSCC system oscillation work groups and, more recently, through the WAMS project.

The August 10 breakup provided ample opportunity and incentive to examine such oscillations under more extreme conditions. Figure 8 shows PSITools being used to analyze PPSM records taken just prior to the final system breakup.

Low-Level Response Tests

Figure 9 shows the measurement scheme used to determine a model of a hydraulic turbine. Using system response fitting routines within PSITools, a model was determined that was able to represent the turbine characteristics much more faithfully than the normally used mathematical model. A comparison of the actual and model responses is shown in Figure 10.

Post-Disturbance Monitor Issues

A system upset on the scale of the August 10 disturbance triggers a number of actions among the concerned utilities. Questions like what happened, why it happened, and how to avoid it in future operations have to be answered as a matter of urgency. WAMS and DITPak were very useful in this postmortem analysis.

The next challenge is to recognize warning signs while there is still time to make changes and prevent such failures from occurring.

Acknowledgments

Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

MATLAB is a registered trademark of *The Mathworks Inc.*

LabVIEW is available from National Instruments Inc.

Contact any of the authors for more information about DITPak.

Further Reading

K.E. Stahlkopf, M. R. Wilhelm, "Tighter Con-

Monitoring and analysis tools must be user friendly and allow ease of use under the stressed conditions of online operation

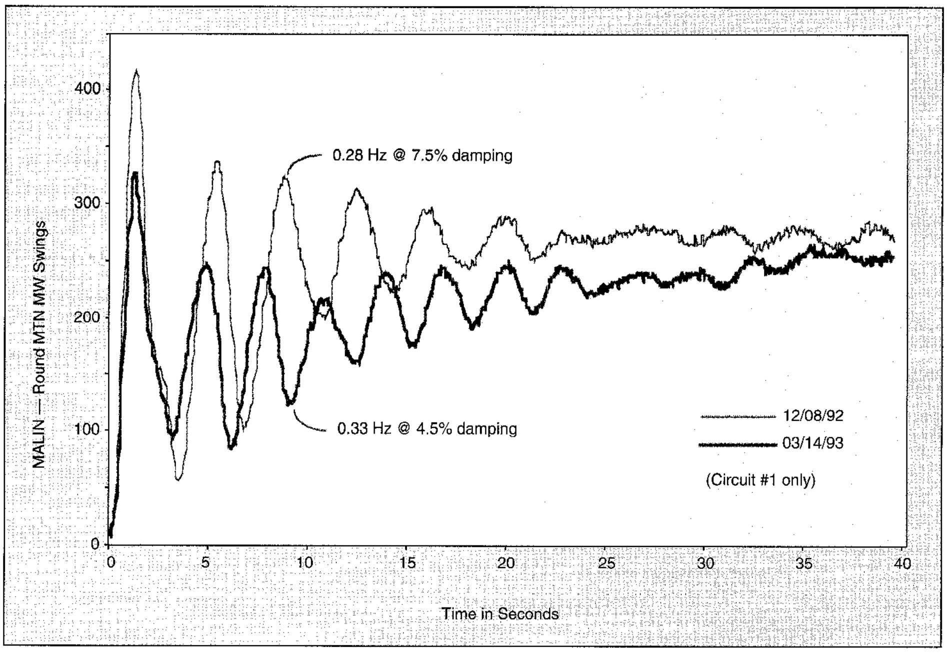

Figure 7. AC intertie response to Palo Verde unit trips, December 8, 1992, vs. March 14, 1994

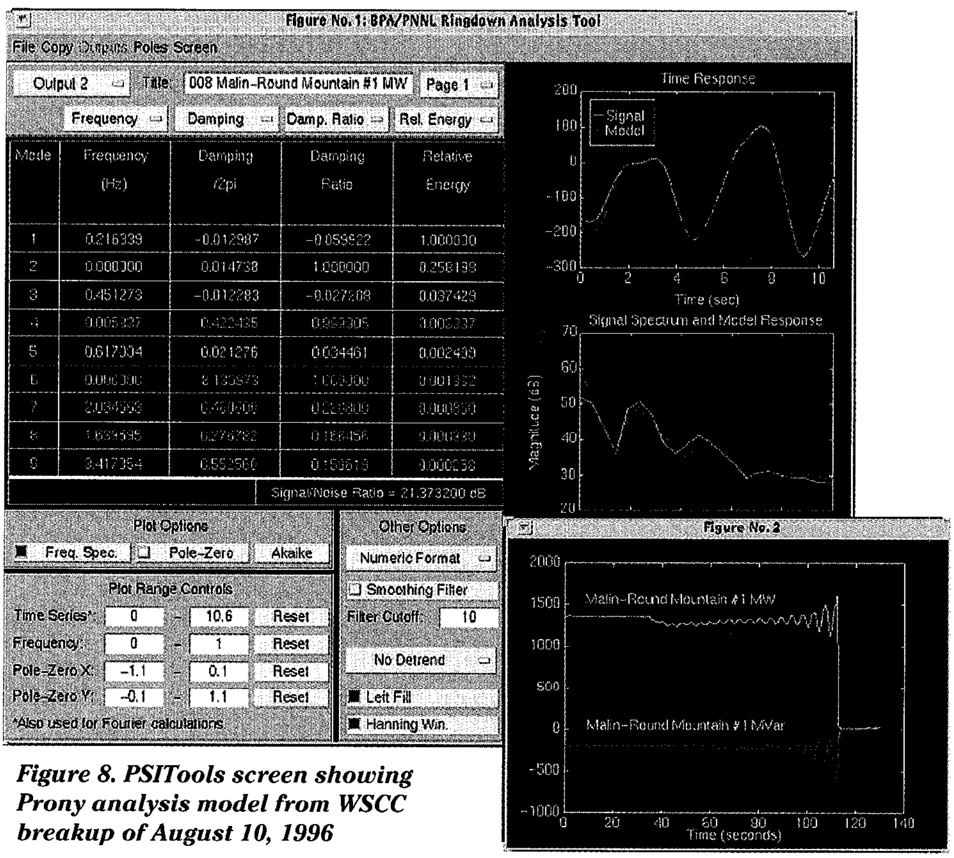

Figure 8. PSITools screen showing Prony analysis model from WSCC breakup of August 10, 1996

trols for Busier Systems," *IEEE Spectrum*, Volume 34, Number 4, pages 48-52, April 1997.

J.F. Hauer, "BPA Experience in the Measurement of Power System Dynamics," *Inter-Area Oscillations in Power Systems*, IEEE Publication 95 TP 101, pages 158-163, 1995.

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Carson Taylor, Dennis Erickson, "Recording and Analyzing the July 2 Cascading Outage," *IEEE Computer Applications in Power*, January 1997.

D.J. Trudnowski, M.K. Donnelly, J.F. Hauer, "Estimating Damping Effectiveness of BPA's Thyristor Controlled Series Capacitor by Applying Time and Frequency Domain Methods to Measured Response," *IEEE Transactions on Power Systems*, Volume 11, pages 761-766, May 1996.

D.J. Trudnowski, J.C. Agee, "Identifying a Hydraulic-Turbine Model from Measured Field Data," *IEEE Transactions on Energy Conversion*, December 1995.

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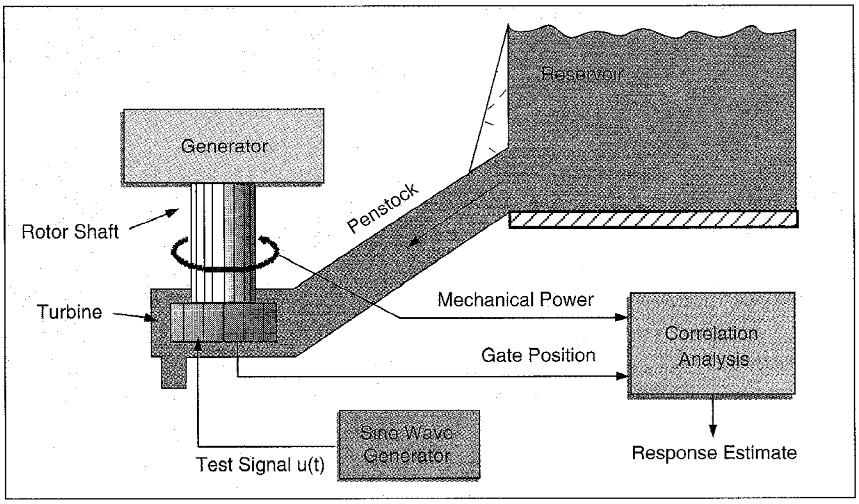

Figure 9. Hydro-turbine measurement quantities

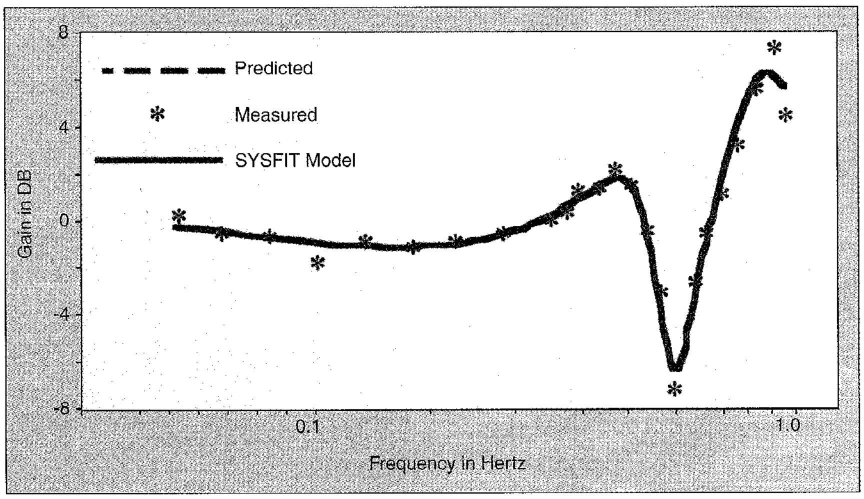

Figure 10. SYSFITmodel for Mt. Elbert pumped-storage plant

Biographies

John Hauer started his engineering career with the General Electric Company in 1961. This was followed by industrial work at Boeing Aerospace, a PhD at the University of Washington, and a faculty position at The University of Alberta. In 1975, he joined the Bonneville Power Administration and began a long involvement with identification, analysis, and control of power system dynamics. In 1994, he stepped down as BPA principal engineer for power system dynamics and assumed technical leadership of the Power Systems Group at the U.S. Department of Energy's Pacific Northwest National Laboratory in Richland, Washington. He is a Fellow of the IEEE.

Daniel J. Trudnowski received the BS degree in engineering science from Montana Tech in 1986, and MS and PhD degrees in electrical engineering from Montana State University (MSU) in 1988 and 1991, respectively. From 1991 to 1995, he was with Pacific Northwest National Laboratory (PNNL), where he was a senior research engineer working on control system and power system dynamic problems; since 1995 he has continued to serve PNNL as a consultant. He also served as an adjunct lecturer in the Electrical Engineering Department at Washington State University (Tri-Cities Campus) during this time. In 1995, he joined the Engineering Science Department at Montana Tech where he is currently an assistant professor in the Control Systems Engineering option. His research interests include system identification and application of advanced control to power systems and robotics. He is a member of the IEEE and its Control Systems, Signal Processing, and Power Engineering societies.

Graham Rogers has had a varied career in power system engineering education, research, and consulting, which spans over 35 years. He currently operates Cherry Tree Scientific Software, which provides computer programs for power system dynamic studies and advice on the analysis and control of power system dynamics. He is a Senior Member of the IEEE, and is an associate editor of *IEEE Transactions on Control Systems Technology*.

Bill Mittelstadt received his BS and MS degrees from Oregon State University in 1966 and 1968, respectively. He is the principal transmission planning engineer at Bonneville Power Administration, responsible primarily to provide technical leadership in intertie and transmission planning activities. He is a Fellow of the IEEE and past secretary of CIGRE Study Committee 38. He is a registered engineer in Oregon and is BPA's representative in the EPRI Grid Operations and Planning Business Unit Council.

Wayne Litzenberger is a senior electrical engineer with the Bonneville Power Administration (BPA) in Portland, Oregon. Following a brief period of employment with The Boeing Co. in the late 1960s, he has been employed by BPA in a variety of assignments, primarily in the area of power system controls. He has managed HVDC and SVC projects and for the past 2 years, the Wide Area Measurements Project. He is a member of the IEEE, where he chairs the DC and FACTS Subcommittee plus the Working Group on HVDC and FACTS Bibliography and Records.

Jeffrey M. Johnson received his BSEE degree in 1992 and MSEE degree in 1996 from Washington State University. Since 1994 he has been employed in the Thermal and Electric Systems Group at Pacific Northwest National Laboratory. His research interests include signal processing, control system analysis and design, and system identification. He is a member of Tau Beta Pi and an associate member of IEEE.