Robust Damping Controls for Large Power Systems

John F. Hauer

ABSTRACT: This paper offers a perspective on the need for robust damping controls in the extensive power system that serves western North America. Key issues include the dynamics of the power system, known threats to controller robustness, and the information-poor environment in which major damping controllers must be designed and operated.

Introduction

Control system robustness is emerging as an issue of strategic importance to the engineering and operation of large power systems. Problems are especially acute in the western North American power system, where geography and climate have combined to produce an unusually complex system with long transmission paths and widely variable patterns of operation [1], [2]. In the damping of electromechanical modes, this is a matter of perennial interest and present concern [3].

The problems associated with damping of power system dynamics resemble those for damping control of a large space structure [4], [5]. Most of the concepts—and some of the methods—evolving to meet that highly visible aerospace need have direct counterparts in power system engineering. There are essential differences, however. The worst damping problems forecast for the western power system occur during severe system disturbances. These involve large control actions and significant changes in system structure, some of which are neither predictable nor communicated to major controllers. Structural changes compound the radical effects that even simple operating-point changes can produce in linearized system dynamics. Further complications are introduced by sharply resonant exogenous signals at frequencies close to those of critical system modes.

Control specialists will recognize the situation as information-starved, both on-line and off-line. This raises special problems in the development of trustworthy, high-performance stability controls. As the power system becomes more complex, there is also an increasing risk of unanticipated interactions among ordinary control systems. An instructive example of this occurred on March 3, 1987, when a simple controller in central Utah destabilized a mode near 0.7 Hz. This produced severe oscillations throughout the system before the controller disengaged, as illustrated in Fig. 1. The underlying causes of such behavior are discussed in [2], [6], and in later sections of this paper.

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Western Power System

The western power system extends some 2800 km from central British Columbia southward into Mexico, and from the Pacific Ocean eastward to the Dakotas (Fig. 2). Overall generating capacity is roughly 145 GW. Much of this capacity serves distant loads, and it is of several types. The Northwest is rich in hydroelectric generation, with seasonal surpluses during "good water years." The eastern half of the system makes extensive use of coal reserves there. The southwest portion (essentially California) contains a mixture of generation, but is heavily reliant on energy imports from other regions.

A simplified diagram of major system elements is shown in Fig. 3. There are four important transmission links to Southern California: the Pacific Alternating Current (AC) Intertie, the Pacific High Voltage Direct Current (HVDC) Intertie (Celilo-Sylmar), the relatively new Intermountain Power Project HVDC Intertie, and a set of AC ties

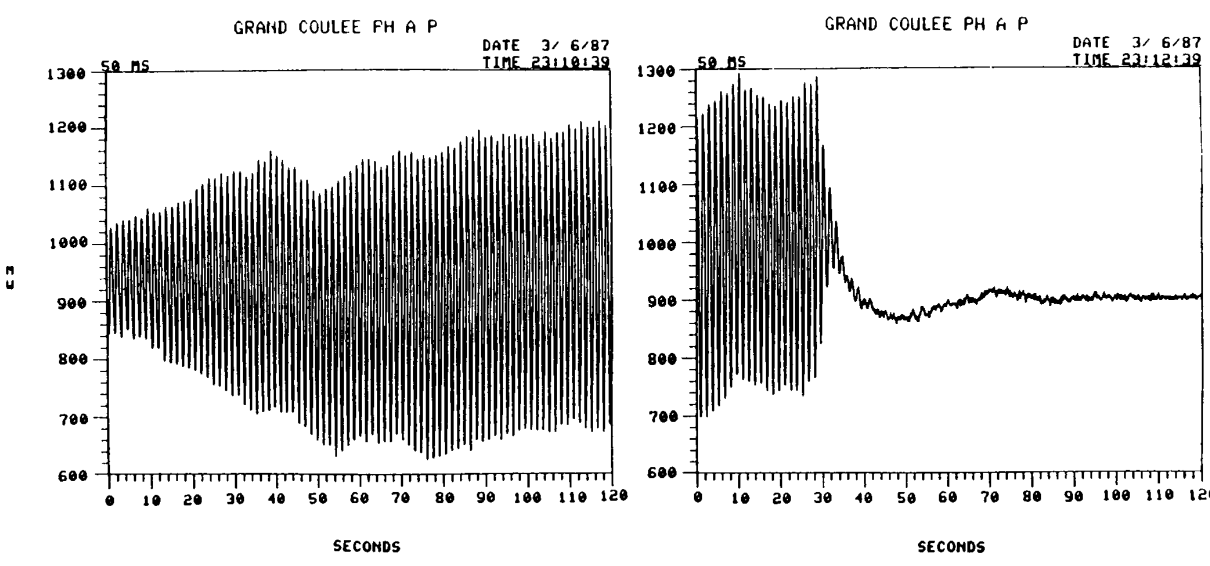

Fig. 1. Participation of Grand Coulee Powerhouse in western system oscillations of March 3, 1987.

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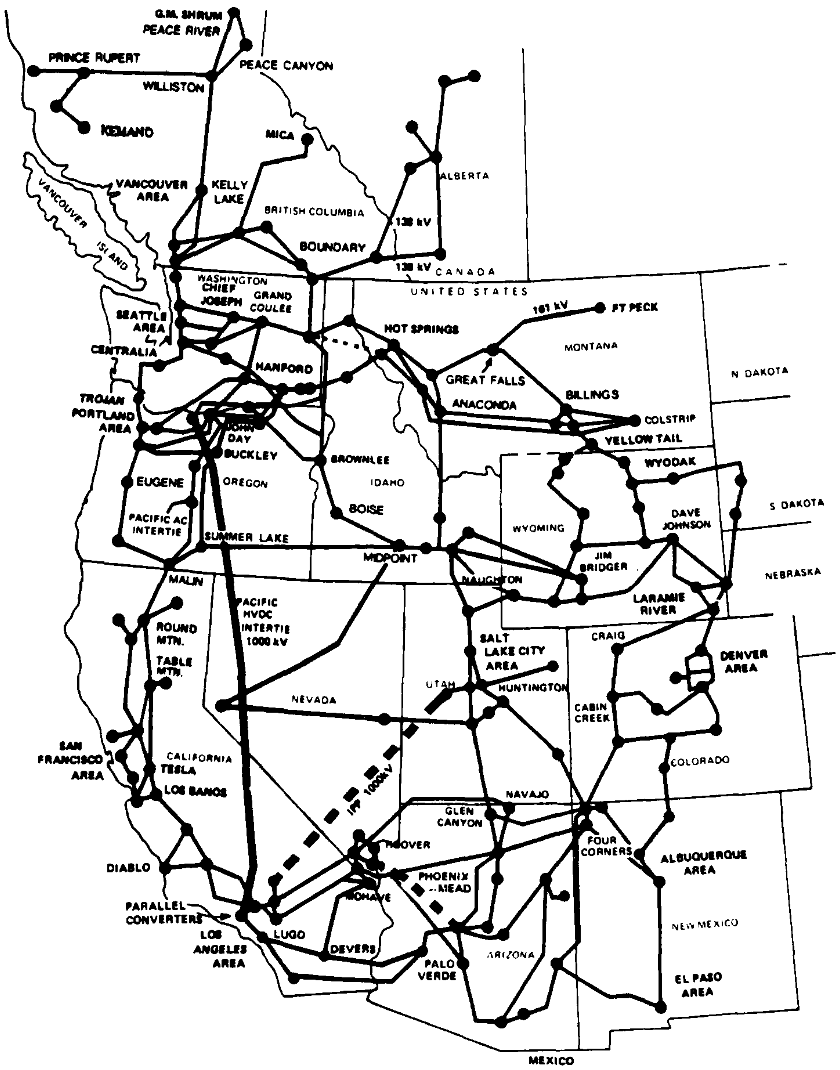

Fig. 2. General structure of the western North America power system.

from Arizona/New Mexico. The Pacific HVDC Intertie is shown as a four-terminal bipole system. This includes two new terminals that, when completed in 1989, will bring intertie capacity to 3100 MW, from its present level of 2000 MW. Capacity of the intermountain line is 1920 MW.

The fundamental dynamics of the system have become more complicated over the past decade, and more variable. These effects have not yet been quantified to the degree that would be desired for the design of robust controllers. Figure 4 illustrates the sort of anecdotal information that is becoming increasingly abundant, however. Each curve that appears was obtained by Fourier analysis of a "ringdown" signal, illustrated in Fig. 5. The test input was a 0.5-sec, 1400-MW pulse applied by means of the dynamic braking resistor at the Chief Joseph Powerhouse (near Grand Coulee).

The response for May 8, 1985, is typical of test and computer simulation results extending back to 1977. The peaks near 0.35 and 0.70 Hz represent fundamental system dynamics. The first peak is associated with a strong north-south mode, which was once prone to serious instabilities. In 1976, a modulation system was installed at the Celilo terminal of the Pacific HVDC Intertie as a partial remedy to this [7], [8]. That system, which employs a simple pole-shifting regulator strategy, is still in service and has a maximum capability of ± 140 MW.

During initial operation, it was found that HVDC modulation occasionally reduced the damping of one or more modes near 0.7 Hz. This was traced to intermittent nonminimum-phase response of the regulated quantity (AC intertie power), and the controller was detuned to achieve the needed robustness. System dynamics near 0.7 Hz have since developed into a very troublesome enigma.

In addition to seasonal effects near 0.7 Hz, the three tests performed in 1987–1988 consistently show a strong new response peak near 0.47 Hz. It is visible at many other points in the system, and there is evidence that it was intermittently present as early as 1985. The author has found no computer study that reflects this behavior.

Power System Stability Control

Power system conventions distinguish among several types of stability problems. The most important of these is to promptly restore an adequate balance between generation and load following large disturbances. If "first swing" stability is not achieved, then vital equipment will trip off through protective action and cascading outages may very well lead to a major loss of electrical services. At the other extreme, "dynamic" or small-signal stability has been a recurrent problem on the western system. This is usually characterized by spontaneous oscillations that increase slowly from an initially low level. It has, however, been displaced by the more difficult one of transient damping.

Computer models predict that, within very few years, some disturbances may be followed by strong, ill-damped oscillations near 0.7 Hz—even though predisturbance damping is adequate. The risk of such oscillations may impose costly constraints on system operation and growth unless reliable countermeasures are developed or the problem is shown to be a modeling fiction.

At this point, a brief summary of power system electromechanics will be used to establish some helpful terminology. Let us start with the generators. Each of these obeys the second-order swing equation, where θ describes the phasor angle for the generator, M and D are mass and damping coefficients, P_m is the mechanical power applied by the prime mover, and P_e is the (real) electrical power produced:

$$M\ddot{\theta} + D\dot{\theta} = P_m - P_e \qquad (1)$$

The flow of that power along transmission lines, when losses are neglected, can be described by the power-angle equation where $V_i \angle \theta_i$ is the phasor voltage at bus i:

$$P_{ij} = B_{ij} V_i V_j \sin(\theta_i - \theta_j) \qquad (2)$$

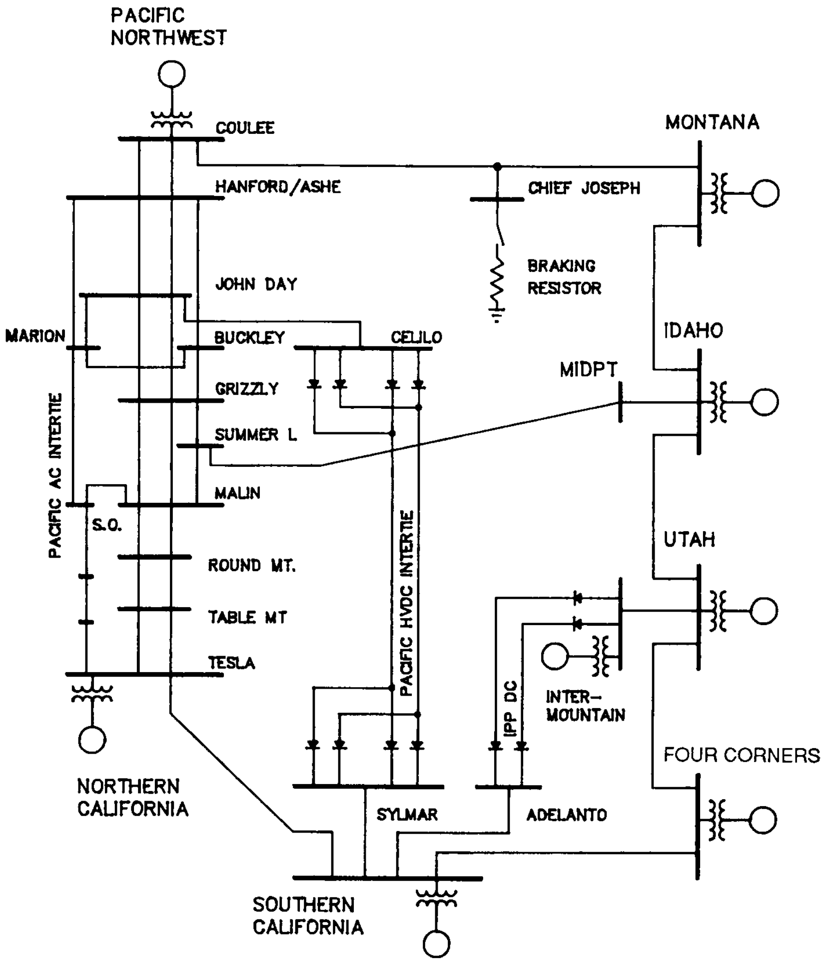

Fig. 3. Major elements in the western North America power system.

The consumption of that power is described by a load model such as shown, where P_{0v}, α_p, and P_{0f} parameterize load sensitivity to bus voltage and frequency deviation:

$$P_{\text{load}} = P_{0v}V^{\alpha_p} + P_{0f}(\Delta\dot{\theta}) \qquad (3)$$

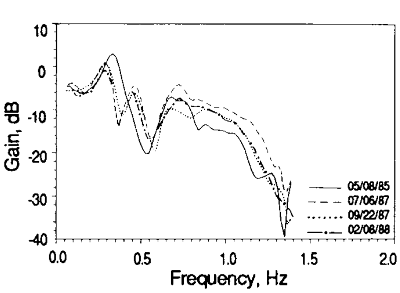

Fig. 4. Frequency response of Pacific AC Intertie line power determined by energization of the Bonneville Power Administration 1400-MW dynamic brake.

The generation, flow, and consumption of reactive power Q are governed by similar relations. This overall set of equations is intercoupled extensively by machine details and controller effects that introduce further nonlinearities and differential equations.

The equations shown thus far are basic to the stability and stability control of a power system. Equations (1) and (2), for example, indicate that the incremental restoring forces that generators exchange through the transmission system decline as the line angles θ_i-θ_j increase toward 90 deg. Control of series capacitance on a line would modulate B_{ij} in Eq. (2), and control of shunt capacitance would modulate some V_i (through reactive-power relations).

The major stability controls for dealing with a system disturbance are feedforward in nature, as illustrated in Fig. 6. They attempt to rebalance the system through preset actions that depend on sensor-based pattern recognition. The control laws are usually discrete (e.g., breaker-actuated) due to high power requirements. Adverse side effects often can be tolerated because control action is brief. In contrast, most feedback controllers operate under general system conditions, are continuously actuated, and use local information to address local objectives. With some notable exceptions for HVDC systems, such control tends to involve low gain/bandwidth products.

Transient damping problems require a much more integrated approach. It may be that, under some conditions, the feedforward controls used to catch the "first swing" overstimulate the critical mode (or modes) there. They may also need adjustments or extensions that bring the transdisturbance trajectory into a region with better damping. It could be that generator damping controls need revision. These issues—and that of model validity—are under very active investigation. Even so, after all options for oscillation avoidance have been developed, it still may be necessary to develop a large-scale transient damper for oscillation quenching.

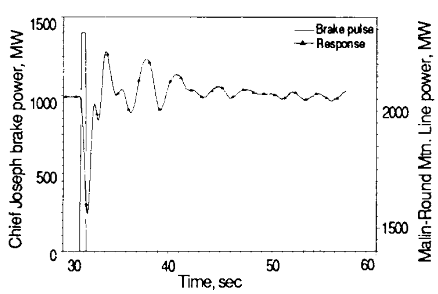

Fig. 5. Time response of Pacific AC Intertie power to dynamic brake test of February 8, 1988.

Reactive-Power Modulation in the Malin Area

The Malin substation is toward the middle of the AC intertie, on the Oregon–California border. It is a promising site for stability controllers that manipulate series and/or shunt reactance. This section presents some small-signal effects of such control.

The response curves shown in Fig. 7 were obtained by methods similar to those for Fig. 4, except that the ringdown signals were obtained by computer simulation. The frequency range of interest, from 0.02 to 2.0 Hz at most, is rather narrow. This, and the tendency of modes to become spaced more closely as frequency increases, makes the linear-frequency display more convenient than the log-frequency display used in a conventional Bode plot.

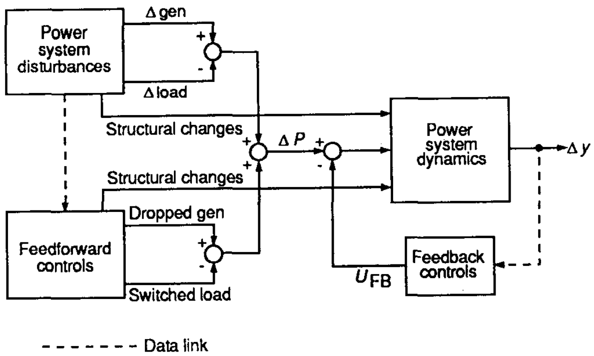

Fig. 6. General structure of power system stability controllers.

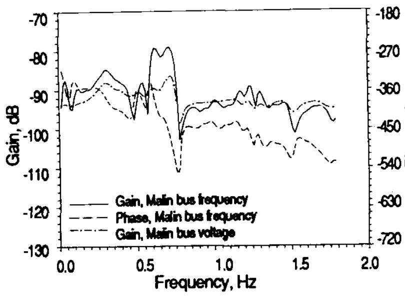

Fig. 9. Response of Malin bus quantities to transdisturbance control of shunt reactance.

The figure compares the potential effectiveness of three different control quantities: series compensation on the Malin-Round Mountain line, reactive load at Malin, and reactive load at Table Mountain. On a per-megavar basis (written Mvar, where var equals volt amps reactive), line response to control of series compensation is some 12 dB higher than it would be to control of shunt reactance at either site by, say, a static-var compensator. Examination of such line-flow responses shows that for many, perhaps all, the phase response varies strongly with system conditions [1]. Right half-plane (RHP) zeros tend to occur at frequencies such as 0.60 Hz and 0.80 Hz—very close to the mode requiring stabilization.

Turning to bus quantities, in Fig. 8 we see that Malin frequency merits consideration (though it too is sometimes nonminimum phase). The flat response of Malin voltage is a major deficiency in this signal—e.g., information about system dynamics would be very difficult to extract under field conditions [9]. Examination of other sites and other conditions suggests that this may be an extreme case, however.

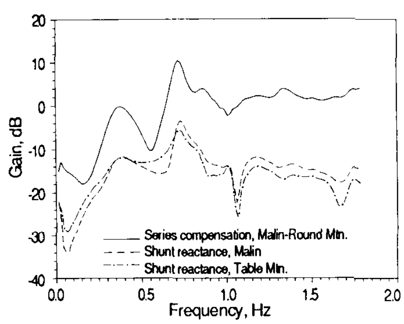

Fig. 7. Response of Malin-Round Mountain real power to control of various reactive-power quantities in the Malin/Table Mountain area.

Small-Signal Response During System Disturbances

The flat response of Malin bus voltage indicates that the plant poles have been canceled effectively by response zeros. These limit the usefulness of the voltage signal to an ordinary pole-shifting ambient damper. Even so, model simulations argue that this signal is effective for transient damping. This is reasonable, because voltage-support systems generally are less effective during major disturbances. In some sense, one may visualize the "voltage-support zeros" moving away from their ambient positions as the disturbance evolves. It would be possible to generate a time-varying linear model for system response to transient stabilizer action and then examine the trajectories of the poles and zeros of that model. Mathematical software for this is not yet available. A limited alternative is to numerically introduce a suitable control variation into a disturbance simulation and then submit the trajectory changes to the same Fourier processing used to examine response under ambient conditions. Figure 9 shows such results for a shunt reactance pulse applied after loss of 3100 MW on the expanded Pacific HVDC Intertie [1].

One must not read too much into such a lumped measure of frequency content. In this case, however, the results are certainly credible. Rational models [10], [11] obtained by fitting the data indicate poles consistent with those for ambient conditions, but with less damping; they are much more accessible to controller action. Most significantly, the responses for transient conditions are markedly different from those calculated or measured under ambient conditions.

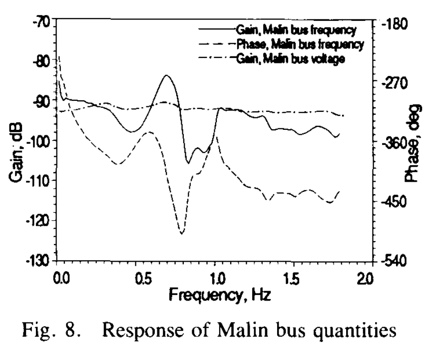

Fig. 8. Response of Malin bus quantities to shunt reactance control.

This poses difficulties in developing and validating the control law for a high-level transient damper. To minimize operational risks, such dampers should probably operate only when there is a clear need to do so. System conditions then are defined more clearly, and the dangers of incorrect control action should be outweighed by those of the disturbance itself.

System Dynamics Tests at the Celilo HVDC Terminal

The HVDC Modulation System at Celilo has provided a valuable window on power system dynamics since 1976. Tests performed in 1977, together with a frequency-domain model-fitting program developed for such applications [10], [11], confirmed that RHP zeros occasionally were present in system response. This had been deduced earlier from intermittent 0.7-Hz oscillations reported in [7], [8].

In May 1985, tests provided the first direct measurements of marginally stable activity near 0.7 Hz. These measurements are summarized in Figs. 10–12, which show data initially acquired with a Hewlett-Packard 5423A signal analyzer and that has since been checked with other instruments and software. Figure 10 shows input and output autospectra for 1405 to 1435 hours on May 7.

Placement of activity peaks for line current is typical, but the peak at 0.75 Hz is unusually strong and sharp. Estimated transfer functions for this period and for 1325 to 1410 hours are shown in Figs. 11 and 12. Important differences exist in the 0.75-Hz

Table 1
Model Fit to Response Data of 1325–1410 hr, 5/7/85
(Gain Coefficient = −0.086356955)

Zeros	Poles
−0.16801571 ± j3.4715102	−0.26713122 ± j2.2087741
0.22321208 ± j4.6615988	−0.64775160 ± j4.2735036
−0.78010254 ± j3.6659154	−0.45450944 ± j4.0709892
−0.00237467 ± j5.1109571	−0.21151249 ± j4.7678455
−0.26886083 ± j5.4116773	−0.14416853 ± j5.1427274
−0.84304012 ± j7.9678249	−0.91009437 ± j6.6721409
−1.09448730 ± j10.025241	−0.49816978 ± j8.7467103

Table 2
Model Fit to Response Data of 1405–1435 hr, 5/7/85
(Gain Coefficient = −0.088165064)

Zeros	Poles
−0.26681155 ± j3.4715102	−0.24306402 ± j2.2087741
0.25566699 ± j4.6615988	−0.76711482 ± j4.2735036
−0.62520335 ± j3.6659154	−0.25687441 ± j4.0709892
0.09378524 ± j5.1109571	−0.05726362 ± j4.7678455
−0.39959746 ± j5.4116773	−0.42668523 ± j5.1427274
−0.71736009 ± j7.9678249	−0.89674118 ± j6.6721409
−1.16386810 ± j10.025241	−0.50773745 ± j8.7467103

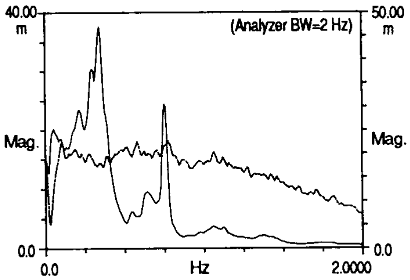

Fig. 10. Autospectra for HVDC current variations (broken line) and Malin-Round Mountain current response (solid line), 1405 to 1435 hr, 5/7/85 (unscaled).

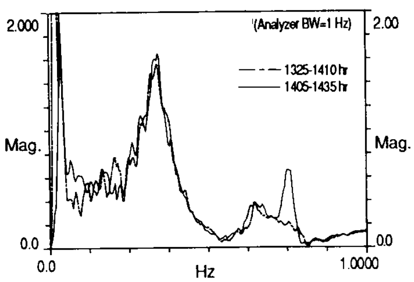

Fig. 11. Gain response of Malin-Round Mountain line current to HVDC modulation, 5/7/85 (unscaled).

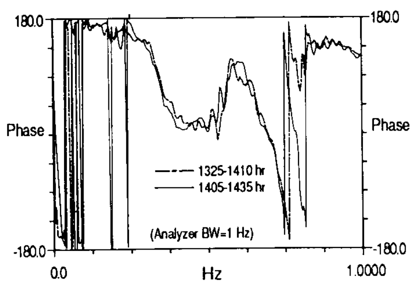

Fig. 12. Phase response of Malin-Round Mountain line current to HVDC modulation, 5/7/85 (unscaled).

region. Phase response indicates a RHP zero near 0.7 Hz for both cases, and a further RHP zero near 0.8 Hz for the condition of light 0.75-Hz damping.

Tables 1 and 2 give the parameters for a composite rational model fit to these transfer functions. The model contains two local modes, at 1.06 Hz and 1.40 Hz. These are consistent with results of wider-band signal analysis, as in Figs. 13 and 14 (with phase unwrapped). The poles of the two model response paths have been constrained to lie at the same frequencies, but were allowed different damping values, for the two time intervals. The model itself is of lowest order,

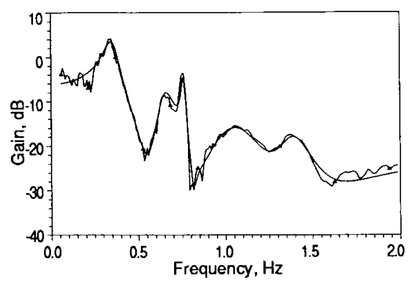

Fig. 13. Gain fit for model of Table 2.

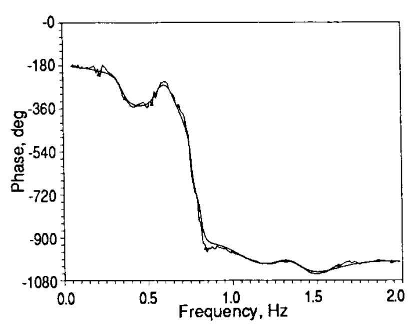

Fig. 14. Phase fit for model of Table 2.

which affords reasonable structure for observed phenomena. These somewhat severe constraints were imposed so that the results would be as simple as possible. A pure time delay of 0.1236 sec, not shown in the tables, enhanced the phase fit and is attributed to filter effects.

Both tables show a 0.74-Hz zero that is well into the RHP. Damping for the pole at 0.76 Hz is small for Table 2, roughly 1 percent. This does not fully account for the very sharply peaked 0.76-Hz activity in Fig. 10. The (estimated) coherency function indicates that approximately 35 percent of the power in this peak is due to the test input. It is likely, but not proven, that the remainder is associated with water-column activity at one of several hydrogenerators that sometimes oscillate at such frequencies (similar effects are noted in [12]).

Whatever their source, such critically placed "autonomous modes" [13] would be very unwelcome controller inputs—especially if the controller relied on identification or self-tuning logic. They would probably mandate use of a probing signal and degrade tracking performance, at least under ambient conditions.

HVDC Modulation and Interactions

High-capacity HVDC systems are attractive for stability control. Economic considerations favor their use in long-distance applications, so they tend to bridge and thus strongly influence dominant system modes. They are highly responsive, and supplemental stability controls are relatively inexpensive. These features bring risks, however. The HVDC current controller has high gain and a bandwidth on the order of 10–15 Hz. This encourages interactions among widely separated dynamic processes. HVDC modulation generally produces both real- and reactive-power injections at every terminal [1]. The reactive injections, and their effects, change markedly with operating conditions.

The new Intermountain Power Project line has a particularly high potential for AC/DC interactions that, at present, cannot be modeled reliably and are not well instrumented. Figure 15 shows some of the systemwide effects that might result from its real-power modulation. The intertie response metered at Malin indicates much stronger 0.7-Hz effects than are obtained there by HVDC modulation at Celilo, and weaker effects at 0.35 Hz. Response is also strong at Grand Coulee and at Kemano (in western British Columbia). Other studies indicate that the Kemano generator may sometimes be the most responsive in the system, with gains approaching unity in the 0.6–0.7-Hz range.

This figure also shows substantial response on the Celilo–Sylmar line. Study conditions represent low generation in Southern California, which intensifies AC system variations coupling the Sylmar and Adelanto terminals. It appears that, for these conditions, about half of the response at Grand Coulee is produced by propagation of these effects along the Pacific HVDC Intertie. They are reduced substantially by increased generation or by using extinction-angle control to fix DC voltage at Sylmar.

We are now in a position to discuss briefly the circumstances that produced the oscillations shown in Fig. 1. The Intermountain schedule controller forces the HVDC line to track the output level of project generation. Its bandwidth was about 1 Hz. Near the oscillation frequency (0.67–0.69 Hz) these

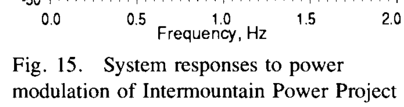

Fig. 15. System responses to power modulation of Intermountain Power Project HVDC line.

generators may furnish less than half of the line power [6]. The remainder comes from the system at large, so that the Intermountain generators act as rather uncertain transducers for dynamic effects that are otherwise beyond the range of local instrumentation. Controller bandwidth has since been reduced to a value that should avoid provocation of modes in the 0.7-Hz cluster.

This incident highlights the potential effectiveness—and the risks—of HVDC damping controls in the southwest. Their potential benefits are laid out in [14], which well illustrates the formidable issues confronting western system planners. The challenges to control engineers are no less formidable.

Summary and Conclusions

The expanse and complexity of the western power system are serious impediments to comprehensive understanding of the damping problems that confront it. Even so, momentum is developing toward installation of large-scale damping controls that directly target 0.7-Hz dynamics. There may be no good alternative.

Emerging control methods might compensate for some of the plant information that is now lacking—and that may never be fully available. The problems are difficult, however, and of forms not usually researched. For transient damping at Malin, one might wish for a discretely actuated self-tuning controller that uses a feedforward signal-canceling logic to minimize bandwidth, with the ability to simultaneously suppress perhaps three modes in the 0.62–0.78-Hz range. Robustness must, of course, be achieved and demonstrated. Developing this controller would be no small task.

Factoring robustness needs directly into controller site selection might yield more immediate benefits. This, too, is not readily done. The information environment should improve at sites close to critical generators—or at the generators themselves. This approach tends toward high-dimensional multiple-input/multiple-output problems that, in the western system, would probably necessitate intercontroller communications that are contrary to utility standards of practice. Establishing robustness would be rather difficult without fully validated system models.

Overall, the damping problems confronting the western utilities are just marginally within their resources' capabilities. The necessary actions are apparent [1], [3], [15], [16], but difficult. The situation provides many opportunities for cross-technology exchanges of information and methods.

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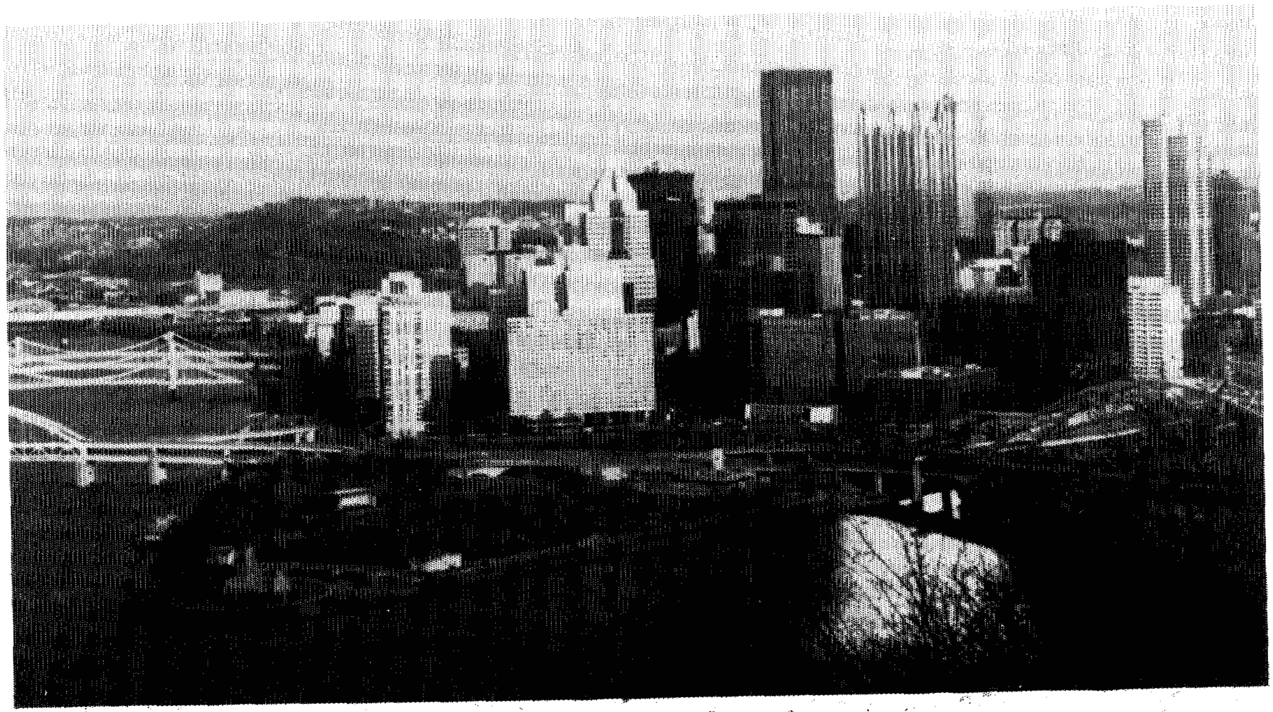
1989 ACC

The American Automatic Control Council will hold the eighth American Control Conference (ACC) on June 21-23, 1989, at the Pittsburgh Hilton and Towers, Pittsburgh, Pennsylvania. This conference will bring together people working in the fields of control, automation, and related areas.

The technical program will cover a wide range of topics relevant to the theory and practical implementation of control and industrial automation, and to university education in controls. Topics of interest will include linear and nonlinear systems, identification and estimation, signal processing, multivariable systems, large-scale systems, robotics and manufacturing systems, guidance and control, sensors, simulation, adaptive control, optimal control, expert systems, and control applications. Both contributed and invited papers will be included in the program of this conference.

For further information, contact the General Chairman: H. Vincent Poor, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, 1101 West Springfield Ave., Urbana, IL 61801; phone: (217) 333-6449.



Downtown Pittsburgh, situated at the confluence of two major rivers.