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MODULATION AND SSR TESTS PERFORMED ON THE BPA 500 kV THYRISTOR CONTROLLED SERIES CAPACITOR UNIT AT SLATT SUBSTATION

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Modulation and SSR Tests Performed on the BPA 500 kV Thyristor Controlled Series Capacitor Unit at Slatt Substation

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***Abstract*–Field experience is reported for a thyristor controlled series capacitor (TCSC) recently commissioned at BPA's Slatt substation. Subsynchronous resonance tests show that TCSC interactions with shaft dynamics of PGE's Boardman steam generator are well understood and are effectively avoided by normal TCSC valve firing logic. Modulation tests, performed with the Boardman plant off line, show that the TCSC can be a powerful and responsive actuator for swing damping. Security considerations did not permit lightly damped operation of the controlled plant. Close analysis indicates that the TCSC damping contribution, though small, was measurable. The best estimate is that damping for the McNary mode is 7.33% and 8.55%, for the TCSC damper loop open and closed respectively. TCSC testing and monitoring is facilitated by an advanced interactive measurement network representing BPA's approach to the information requirements of major control systems.**

Keywords—TCSC, FACTS, network resonance, feedback control, power system monitoring.

I. INTRODUCTION

The Slatt Thyristor Controlled Series Capacitor (TCSC) project is part of the EPRI Flexible AC Transmission System (FACTS) effort [1], with the Bonneville Power Administration (BPA) as the host utility and General Electric (GE) as the prime contractor. The TCSC was sited for proximity to the Portland General Electric (PGE) 550 MVA Boardman generator, some 25 km away. Examination and control of TCSC interactions with Boardman shaft dynamics is a critical project objective, and PGE has been strongly involved in the project since its inception. This included workup of enhanced shaft instrumentation and protection, which was installed during a maintenance shutdown of the machine during May-June 1994. The shutdown also provided an opportunity to safely test TCSC damping capabilities, a secondary project issue, on June 6-7 1994. The generator returned to service a few days later, and subsynchronous resonance (SSR) testing was done on August 5-6.

This paper summarizes TCSC performance in damping control and in avoidance of SSR effects. It also describes the associated information systems, which are explicitly designed for staged tests and extended monitoring of major control systems. Some results draw upon mathematical software being developed under various BPA contracts and collaborations, primarily those with the Pacific Northwest Laboratory (PNL). PNL is operated for the U. S. Department of Energy by the Battelle Memorial Institute under contract DE-AC06-76RLO 1830.

II. TCSC AND SITE CHARACTERISTICS

A TCSC performs as a rapidly controllable series capacitor that minimizes the risk of subsynchronous resonance. Other advantages include modular construction and a substantial short-term overload capability. The Slatt TCSC, represented in Fig. 1, consists of six series modules that can each provide up to 4.0 ohms of compensation under thyristor control [2,3].

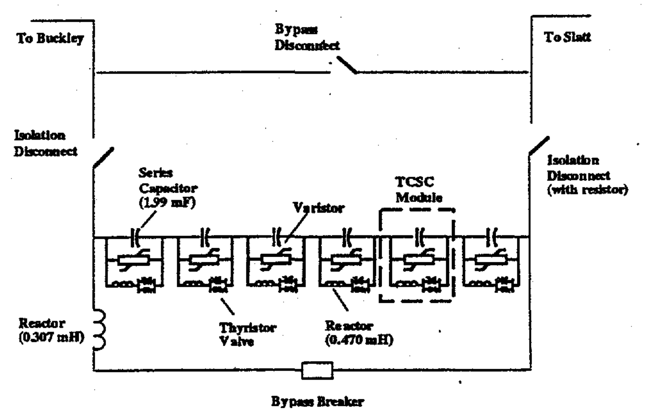

Fig. 1. General circuit for the Slatt TCSC

Slatt substation is located in north central Oregon on the eastern leg of the Pacific AC Intertie (Fig. 2). Depending upon operating conditions, the TCSC there may draw power from a number of large generator sites including John Day, Boardman, McNary and WNP#2 (Ashe). Network configuration was adjusted to accommodate different stages of the commissioning tests.

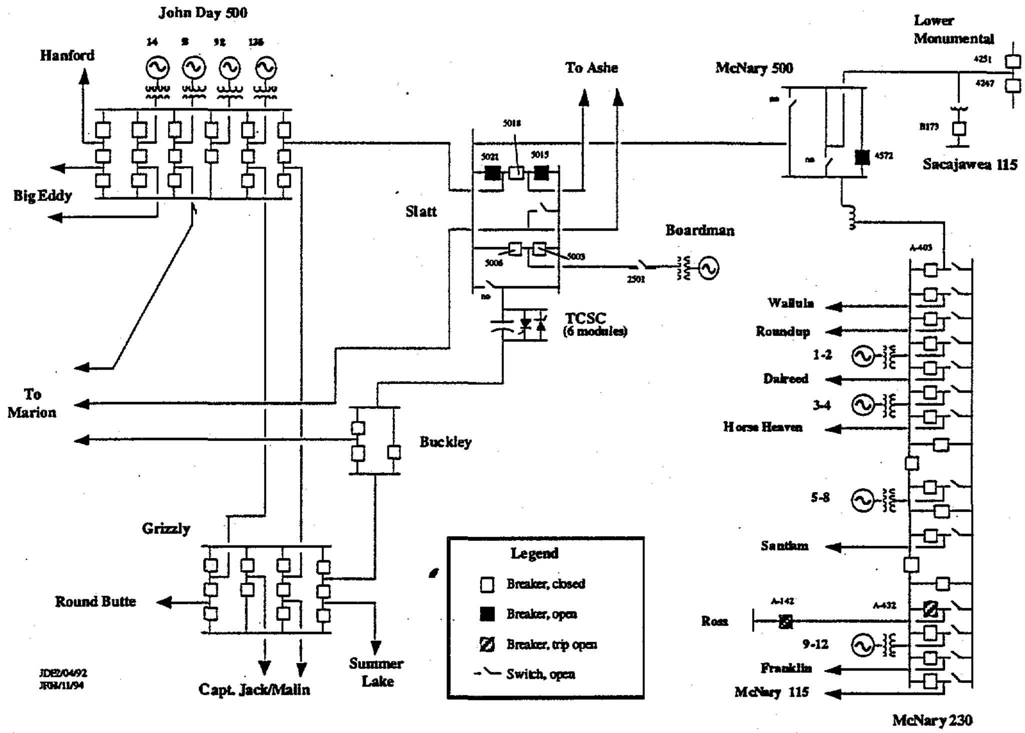

Fig. 2. Network configuration for TCSC modulation tests

III. TCSC MODULATION TESTS OF JUNE 6-7, 1994

Modulation tests of the Slatt TCSC, accompanied by scheduled trips of the McNary-Ross line, were performed on June 6 and 7 with the Boardman plant off line. The test team consisted of personnel from BPA, GE, and PNL plus U. S. Corps of Engineers operations staff at the McNary plant. Extensive data recordings were made on BPA monitor facilities at Slatt, McNary, and the Dittmer control center. Data storage and backup was controlled via the monitor network from the TCSC control house, the Slatt relay house, BPA's Vancouver Labs, and BPA's Portland Headquarters.

The data reported here focuses upon TCSC response to modulation signals and its effects upon the electrical system local to Slatt. The signals of primary interest are TCSC actual ohms, power on the Slatt-Buckley line, TCSC synthesized angle, and the output of the TCSC damping loop. These are taken from points E, F, G, and H in Fig. 3.

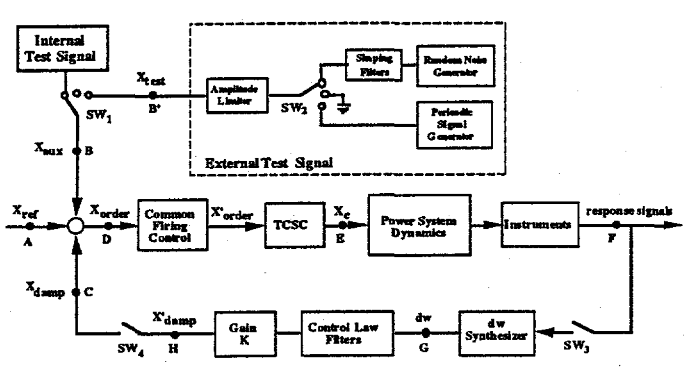

Fig. 3. Test points for TCSC damping control tests

Testing on June 6 determined an upper limit for feedback gain and resulted in some adjustments to the test procedure. Fig. 4 shows typical responses local to the TCSC for step inputs. The curves have been offset for better clarity .

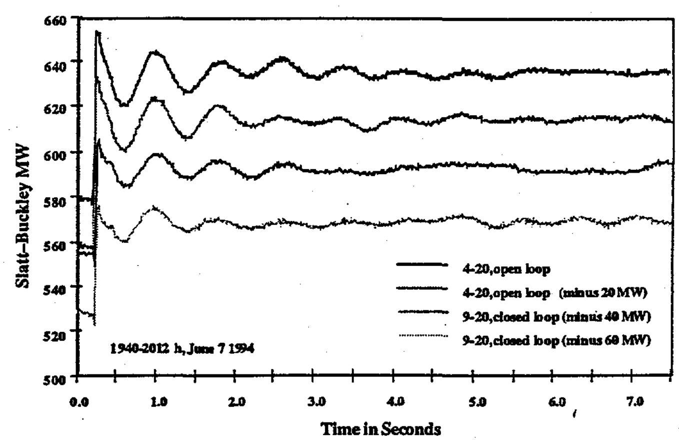

Fig. 4. Buckley line response to positive TCSC steps (detail)

Figs. 5-6 show results for successive trips of the McNary-Ross 230 kV line. McNary plant swings are well damped without TCSC action. (Analysis during the tests indicated damping values near 7.5% and a frequency of 1.27 Hz). Such strong damping, together with substantial ambient system activity, masks the small contribution the TCSC was expected to make.

Though the directly available information is different, the adverse noise environment can be countered through sustained frequency domain correlations. Fig. 7 depicts an ambient spectrum for fluctuations in Slatt-Buckley line power. In addition to the familiar range of interarea modes

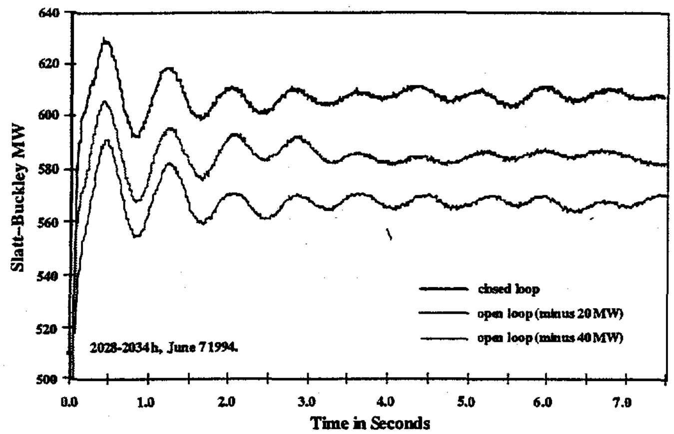

Fig. 5. Buckley line response to tripping of McNary-Ross line (detail)

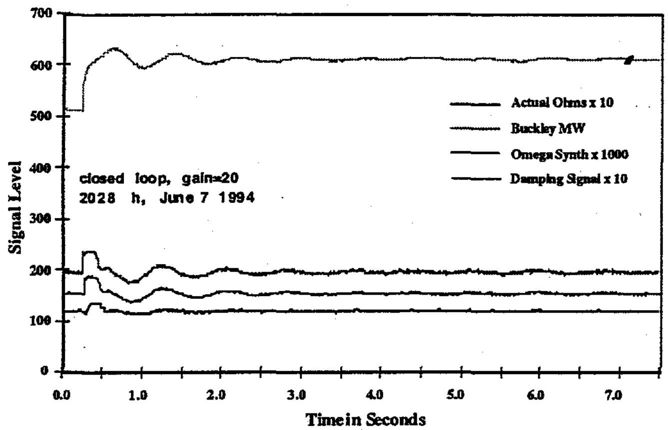

Fig. 6. Local response signals for tripping of McNary-Ross line

below 1.0 Hz, it indicates three closely spaced plant modes between 1.2 Hz and 1.5 Hz plus a sharp peak of undetermined origin near 2.2 Hz. The TCSC was operating with the damper loop open at this time; closed loop operation made no obvious differences in the spectrum.

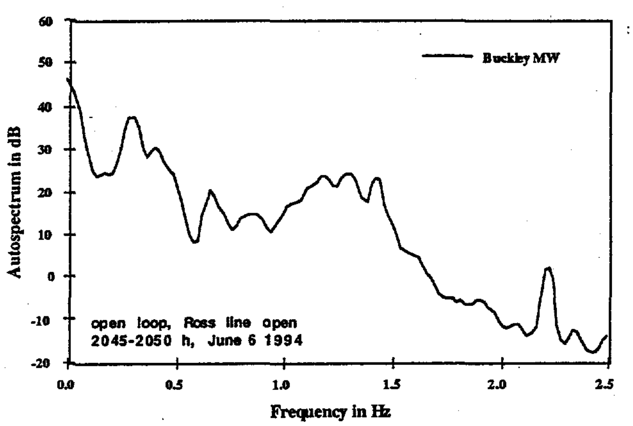

Fig. 7. Ambient spectrum for Slatt-Buckley line power

The results of correlation tests using TCSC noise modulation are summarized in Figs. 8A-B. The Slatt-Buckley line power tracks the TCSC modulation signal so well that the relationship between them seems more algebraic than dynamic. This is borne out by the frequency

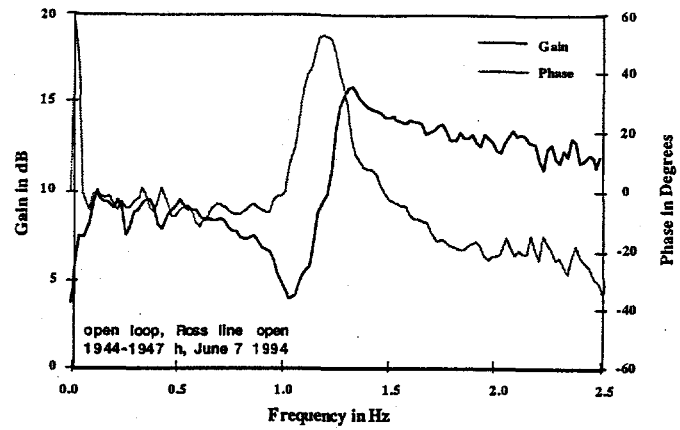

Fig. 8A. Frequency response of Slatt-Buckley line MW to TCSC modulation signal

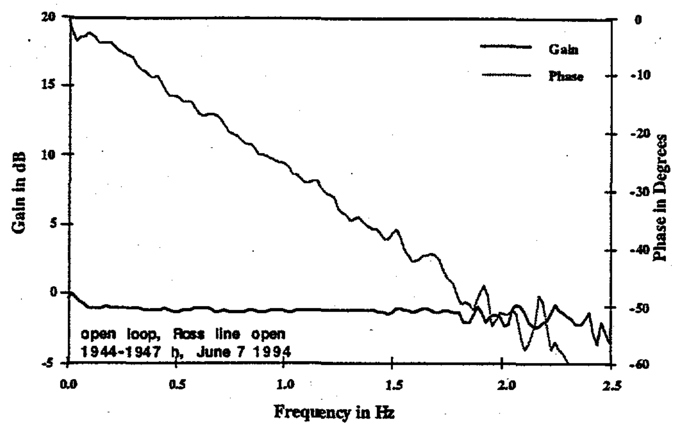

Fig. 8B. Frequency response of actual TCSC ohms to TCSC modulation

response in Fig. 8A, which has a modest dynamic range and very little peaking. Fig. 8B indicates that the TCSC tracks modulation inputs accurately, though with an apparent delay of some 70 msec. About 30 msec is required to bring the actual ohms signal out of the controller for analog access. Thus the true delay is 30 to 40 msec., which adds some 20 degrees to the phase compensation needed near the McNary plant mode.

Close analysis of the modulation tests indicates that the TCSC damping contribution, though small, was measurable [4]. The best estimate is that damping for the McNary mode is 7.33% and 8.55%, for the TCSC damper loop open and closed respectively. Overall, test results show that the TCSC is a good actuator for swing damping, and that it could be effective in the present application were McNary plant swings less strongly damped.

A full explanation as to why TCSC leverage over system dynamics is so devoid of modal resonances, in comparison to some model studies, would be useful. It may be that the strong power fluctuations on the Slatt-Buckley line were reapportioned among parallel branches, and were not attended by comparable swings in angle at McNary or other plants. Alternatively, the lack of a distinct McNary response peak in Figure 8A may just result from coupling among regional plants. Correlation analysis of Dittmer measurements, together with post-test model studies, may narrow these uncertainties and further quantify TCSC damping performance.

IV. SHAFT INTERACTION TESTS OF AUGUST 1994

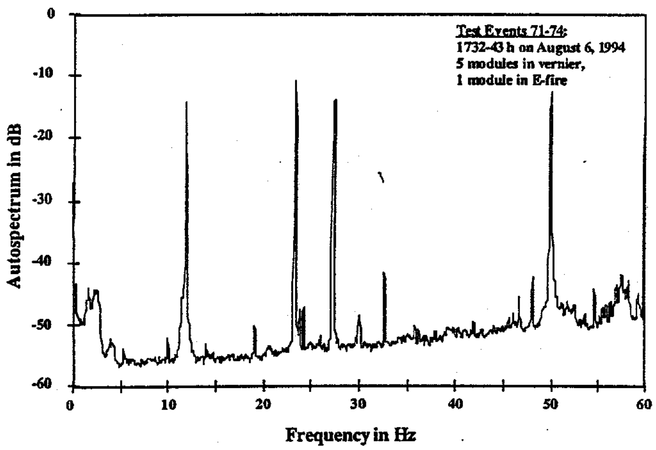

Fig. 9. Composite autospectrum for shaft speed deviations (rear sensor)

Examination of SSR interactions between the TCSC and the Boardman generator involved some 96 test events. The basic procedure was to sinusoidally modulate the TCSC at a selected shaft torsional frequency, remove the stimulus while switching the TCSC to the desired operating condition, and then record the ringdown in shaft speed [5]. Fig. 9 shows composite autospectra for sequential testing of the four shaft modes. Their observed frequencies are 11.91 Hz, 23.32 Hz, 27.32 Hz, and 49.95 Hz.

Figs. 10 -12 show rear speed ringdowns following stimulus of mode 4. The data was collected on Slatt monitor facilities at 400 samples per second, after 120 Hz lowpass filtering. The records were subsequently bandpassed through a 10th order Chebychev filter with corners at 44 Hz and 56 Hz. The TCSC was bypassed for Fig. 10, and the linear decline indicates exponential speed decay.

For Fig. 11 the TCSC was set at 5.25 ohms and the capacitors were allowed to resonate with mode 4. This involved five modules blocked (i.e., inserted as conventional series capacitors) and 1 module in continuous bidirectional gating (E-fire). Initial ringdown is slow, with a trend of form $te^{-\alpha t}$. Longer records show that the activity does not decline much farther and that an SSR condition exists. Fig. 12 differs in that the five modules are operating in normal vernier mode. The trend is essentially identical to that of Fig. 11, demonstrating that vernier operation effectively decouples the TCSC from Boardman shaft dynamics. Like results were obtained for many other TCSC operating configurations.

Prony analyses indicate a frequency near 49.92 Hz and a damping of 0.12%-0.14% for the first 2 seconds of all ringdowns shown. Similar results are obtained graphically, despite some activity not associated with mode 4. Displays with this activity removed are readily produced via sliding Fourier or Prony windows. GE test personnel produced these in real time with the aid of special filters and a dynamic signal analyzer [5]. These readily established the minimum stimulus needed for good test results.

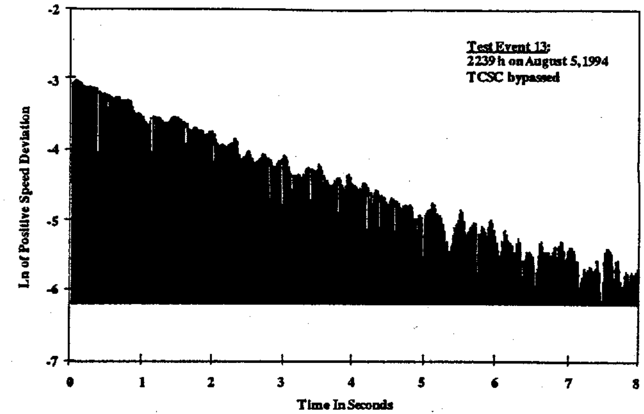

Fig. 10. Ringdown from mode 4 energization, TCSC bypassed

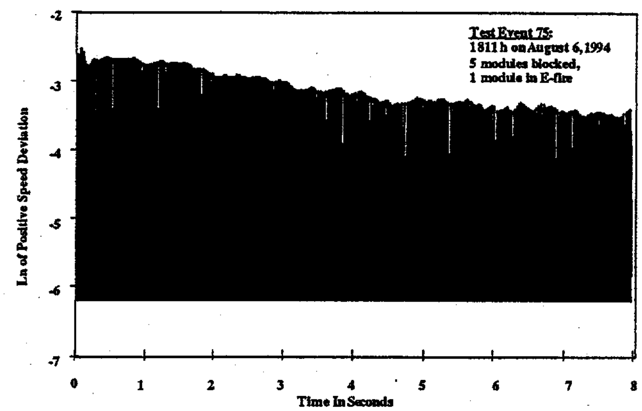

Fig. 11. Ringdown from mode 4 energization, TCSC in resonance with shaft

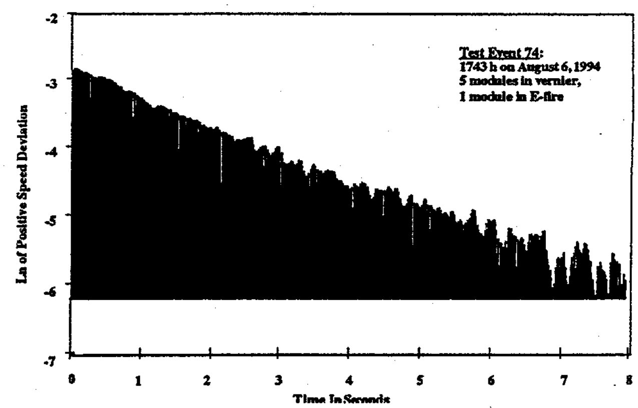

Fig. 12. Ringdown from mode 4 energization, TCSC decoupled from shaft

Because of the conclusive results at full load, tests were not performed at partial loadings of the generator. Supplemental information will be obtained through the monitoring of system disturbances.

V. TCSC INFORMATION SYSTEMS

The information requirements of wide area control [6,7] are a major issue in EPRI's FACTS program. The interactions and other side effects that may result from modulating a power electronics device are numerous, and often subtle [8,9]. They should be examined as far as possible during commissioning tests, and monitored during subsequent operation. It should

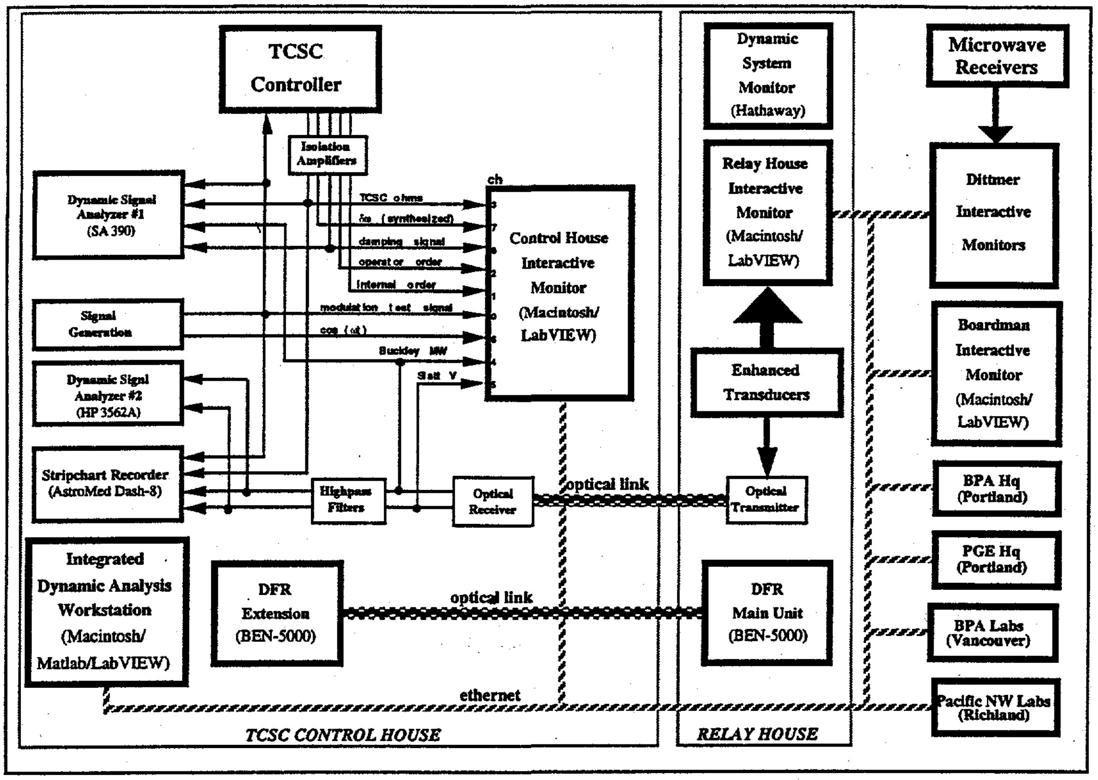

Fig. 13. Slatt instrumentation for TCSC modulation tests of June 6-7, 1994

be recognized, however, that if adverse effects do occur they may be intermittent and less conspicuous at the controller than at other locations.

A further characteristic of tests on a major control system is that the results must be continually analyzed and evaluated during the test itself. This is done to verify that operating conditions are appropriate for continued testing, and to balance data quality against operational stress. The supporting information system must have the *signal access* to observe all significant controller effects, the *dynamic range* to accommodate both large and small signals, the *bandwidth* to track fast dynamics, the *recording capability* for long-term correlation analysis, and the *processing intelligence* needed to extract and display critical information. The following functions are generic requirements:

- ***Signal conditioning***, to assure the measurement quality and prompt observability of important signal features.
- ***Archival recording***, to assure safekeeping of test results. This should be as comprehensive as possible, and include all phases of testing that involve switching operations or application of test signals.
- ***Interactive recording***, to permit prompt examination of test data that cannot be displayed and/or analyzed in real time. It also provides local backup recording of high priority signals.
- ***Time domain display***, to permit frequent review of signal waveforms for evidence of data quality and emerging trouble on the power system.
- ***Frequency domain display***, to permit frequent review of signal spectra for evidence of data quality and emerging trouble on the power system.

The TCSC modulation tests drew upon an advanced interactive measurement network (Fig. 13) that represents BPA's approach to meeting these information requirements. The basic element in this network is BPA's Portable Power System Monitor (PPSM), which permits interactive display and analysis concurrently with high performance monitoring [7]. Signal conditioning needs are minimized by use of 16 bit digitization throughout. In the modulation tests, regional archiving was provided by continuous 20 samples per second (sps) recording on the Dittmer PPSM. Local archiving was done continuously at 100 sps, on PPSM's in the TCSC control house and the relay house. This rate is consistent with the 20 Hz bandwidth of the relay house enhanced transducers. Locally collected data were periodically transmitted over the ethernet to Portland-area facilities for backup, and reviewed in the dedicated signal analysis workstation. Continuous surveillance over key signals was performed with a combination of stripchart recorders and dynamic signal analyzers (DSA's). Backup recording for switching events was provided by a Hathaway Dynamic System Monitor (DSM) and a BEN-5000 digital fault recorder (DFR). A further PPSM, not on the ethernet, was temporarily installed at the McNary plant for data collection on June 6.

For SSR tests the modulation signal was produced at Boardman and transmitted to Slatt. Testing focused more narrowly, on higher speed local signals, and PPSM acquisition rates there were reset to 400 sps and 900 sps respectively. The Slatt DFR was manually triggered for accessory data collection, at 10K sps. Continuing development of the Slatt local area network (LAN) will permit the Slatt PPSM's, DSM, and DFR to cross-trigger one other, or to be remotely triggered for examination of the TCSC operating environment.

The information technology deployed in the Slatt TCSC project represent a sustained BPA effort to deal systematically with the measurement and signal processing needs involved in wide area control [7]. It evolved from test experience with the HVDC modulation system at Celilo, and is being applied at a number of other sites. These include BPA's recently completed SVC stations at Maple Valley and Keeler substations, the Dittmer control center, the Pacific HVDC Intertie, and various remote points where high quality dynamic data is needed.

VI. CONCLUSIONS

The subsynchronous resonance tests summarized here show that TCSC interactions with shaft dynamics of PGE's Boardman steam generator are well understood and are strongly suppressed by the TCSC's normal valve firing logic. Modulation tests, performed earlier with the Boardman plant off line, show that the TCSC can be a powerful and responsive actuator for swing damping. Security considerations did not permit lightly damped operation of the controlled plant, however, so complete demonstration of the TCSC damping function was not feasible. TCSC performance over a wider range of operating conditions is desirable through post-test modeling [10], and through a sustained program of monitoring together with non-intrusive testing. This activity, like the tests reported here, is facilitated by an advanced interactive measurement network representing BPA's approach to the information requirements of major control systems.

ACKNOWLEDGMENT

The Slatt TCSC Project is a broad team effort linking numerous organizations. The majority of credit is due the many individuals who made it possible and successful but, because they are so numerous, are not indicated in the author list.

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BIOGRAPHY

John F. Hauer [redacted] He achieved his Bachelors degree at Gonzaga University, in 1961, and his Ph.D. degree at the University of Washington in 1968. Both are in electrical engineering. Prior to graduate studies he worked with the General Electric Company, in the area of nuclear reactor controls, and developed spacecraft navigation and guidance methods at the Boeing Company. From 1968 to 1975 he was a member of the Computing Science faculty at the University of Alberta, with activities centered upon constrained optimization of dynamic systems. In 1994 he stepped down as Principal Engineer for Power System Dynamics at the Bonneville Power Administration, where he has served since 1975, and assumed similar duties at Battelle, Pacific Northwest Laboratories. Dr. Hauer is a member of the Power Engineering and Control System societies.

William A. Mittelstadt [redacted] He received his Bachelor's degree from Oregon State University in 1966 and his Master's degree there in 1968. As Principal Engineer for Transmission System Planning at the Bonneville Power Administration, he is their primary source of technical guidance for intertie and main grid transmission planning. He is currently on the Electric Power Research Institute Power System Operations Business Unit. Mr. Mittelstadt is also a member of CIGRE and has served as Secretary of CIGRE Study Committee 38.

Richard J. Piwko (SM '85) a native of Massachusetts, received the BSEE and MSEE degrees from Worchester Polytechnic Institute in 1974 and 1976. He joined the General Electric Company in 1976, and is presently a Consulting Engineer in the Power Systems Engineering Department. He is involved in design and performance analysis of turbines, generators, HVDC systems, static var systems, and thyristor controlled series capacitors, plus the analysis and mitigation of torsional interactions among such devices. Mr. Pwiko is active on several IEEE working groups, subcommittees and committees in the HVDC, FACTS and system dynamic performance areas.

Ben Damsky [redacted] He received BS and MS degrees in Physics from Princeton and the University of Pennsylvania respectively. At the General Electric Company he worked on vacuum and gas circuit breakers, thyristors, HVDC equipment, and fuses. Mr. Damsky has been with EPRI as Project Manager since 1984, working in such areas as FACTS, amorphous core transformers, battery monitoring and software development.

James D. Eden [redacted] After receiving the BS degree in Electrical Engineering from Oregon State University in 1979, he joined Portland General Electric Co. and is presently their Principal Planning Engineer. His responsibilities have included long-range transmission planing, generation project integration, regional planning, and broad use of dynamic analysis and control. Mr. Eden is a registered Professional Engineer in the state of Oregon and holds memberships in IEEE, NSPE, Eta Kappa Nu and Tau Beta Pi.