ESTIMATING DAMPING EFFECTIVENESS OF BPA'S THYRISTOR
CONTROLLED SERIES CAPACITOR BY APPLYING TIME AND
FREQUENCY DOMAIN METHODS TO MEASURED RESPONSE

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Estimating Damping Effectiveness of BPA's Thyristor Controlled Series Capacitor by Applying Time and Frequency Domain Methods to Measured Response

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Abstract--Recently, a 500-kV thyristor controlled series capacitor (TCSC) was installed in the Bonneville Power Administration system in the northwestern United States. Extensive field testing has included modulation experiments to determine the effect of the TCSC on low-frequency oscillations. This paper discusses modulation procedures, analysis methods, and results for estimating the damping effectiveness of the TCSC. Modulation methods include driving the TCSC with step and random noise, and analysis techniques include time (Prony analysis) and frequency-domain identification. Results indicate that: 1) the TCSC can have significant impact on system dynamics; and 2) under a very small feedback gain, the TCSC provides measurable added damping.

I. INTRODUCTION

The first 500-kV thyristor controlled series capacitor (TCSC) was recently commissioned at the Bonneville Power Administration (BPA) C. J. Slatt substation in north-central Oregon in the United States. The TCSC was constructed and installed by the General Electric Company (GE) as part of a collaborative research effort between the BPA, GE, the Electric Power Research Institute (EPRI), and Portland General Electric [1]. A primary objective of the TCSC is to safely enable higher and more flexible power transmission. Critical to fulfilling this objective is proper control of the TCSC to mitigate possible electromechanical stability problems.

Recent field tests have included modulating the TCSC and conducting line-switchings under various system configurations to evaluate the dynamic performance. The

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overall testing procedure and initial results are reported in [2]. Security considerations did not permit lightly-damped operation of the system, therefore, performance of the TCSC as an oscillation damper was not immediately obvious. The analysis presented here provides detailed results and insights to the effectiveness of the TCSC under the limited testing conditions. This paper extends general discussion in [2] with a detailed presentation of the modulation procedures, analysis methods, and results for estimating the damping effectiveness of the TCSC. Probing methods include driving the TCSC with step and random noise, and analysis techniques include time (Prony analysis) and frequency-domain identification.

The system configuration and testing procedures are described in section II. Section III summarizes analysis methods used to estimate the damping effectiveness from field test data, and detailed testing and analysis results are provided in section IV.

II. SYSTEM CONFIGURATION AND TEST PROCEDURES

A. System and TCSC Characteristics

The Slatt TCSC has been described in detail in previous literature [3,4]. For the purposes of this paper, it suffices to describe the device as a controllable reactance placed in series in the 500-kV Slatt-Buckley transmission line. The reactance of the device is variable with a range from 1.2 ohms inductive to 24.0 ohms capacitive. The reader is referred to the literature for further information.

The Slatt substation is a 500-kV switchyard serving generation resources from four locations. Of these, the U.S. Army Corps of Engineers' McNary power plant is of interest for the TCSC low-frequency oscillation testing. During testing, the power plant consisted of 12 identical hydro turbines rated at 72 MW each. The entire plant was producing roughly 600 MW for the duration of these tests.

Original project studies indicated that, with all four of the Slatt generation resources connected at the Slatt substation, it may not be possible to adequately test the potential of the TCSC as a damping actuator [4]. Therefore, for oscillation testing the system was configured according to the simplified one-line diagram in Fig. 1. This configuration leaves the TCSC substantially radial to the McNary power

plant to facilitate interactions between the TCSC modulation and McNary plant oscillations. In further attempts to approximate a radial connection, a separate 500-kV line (McNary-Lower Monumental) and, for most of the testing, a 345-kV line (Ross-McNary) were opened at McNary. The remainder of the McNary transmission lines are at 230-kV and below, leaving the McNary bus with a relatively weak system connection apart from the McNary-Slatt 500-kV line.

Fig. 1. Test system configuration.

B. Low-Frequency Oscillation Testing

Extensive TCSC modulations and some McNary-Ross line switches were used to initiate McNary swings. The majority of tests were conducted with the McNary-Ross line open.

Fig. 2 shows the modulation test configuration. The external test signal (X_{test}) was used to modulate the TCSC impedance (X_c) in both open-loop and closed-loop operation. Primarily two types of probing signals were used: 1) step functions, and 2) random Gaussian noise. The feedback control law was fixed at values determined from simulation studies and the feedback gain (K) was adjusted during field tests. Security considerations limited extensive closed-loop tests to a relatively low feedback gain of $K = 20$.

Fig. 2. Modulation test configuration.

TCSC steps and line switches were used to investigate the system's response to a sudden discontinuity; this enables an understanding of the TCSC's effects on transient (first-swing) and small-signal dynamics. To obtain quality data, the steps were made large enough to cause significant system swings well above system noise.

Random noise modulation was used to excite the small-signal dynamics of the system. Typically, the TCSC was driven with a low-level signal for several minutes, and the system response analyzed to accurately assess the small-signal characteristics. Such an approach allows one to primarily excite the linear dynamics. Also, low-level probing can result in less system stress than step testing because no significant oscillations occur. Advantages of noise probing are discussed in more detail in [5].

III. ANALYSIS METHODS

Evaluation of low-frequency oscillation interaction requires an understanding of how the TCSC affects the swing characteristics. Assuming a linear oscillation model, the swing mode can be identified using time-domain analysis of a ringdown (Prony analysis) or frequency-domain analysis (spectrum analysis with frequency-domain fitting) of noise response tests. Both approaches have advantages and disadvantages that make them complimentary and allow for cross validation of analysis results. The techniques described here are part of an extensive software package being developed by the Pacific Northwest Laboratory and the BPA [6].

A. Dynamic Model

It is well known [5,7,8] that the electromechanical dynamics of a power system can be linearized at an operating point, and the transfer function from a given input u to a given output y can be written in Laplace domain as

$$G(s) = \frac{Y(s)}{U(s)} = \sum_{i=1}^n \frac{R_i}{s - p_i} \quad (1)$$

where $U(s)$ and $Y(s)$ are the Laplace transforms of u and y , respectively; and the p_i 's are the system eigenvalues with residue R_i 's.

For the testing configuration, the dominant eigenvalue is the McNary plant mode. Step and noise response data are analyzed assuming the model structure (1). From the analysis, the McNary plant mode is identified for various operating and testing conditions.

B. Prony Analysis

Prony analysis is used to identify the McNary mode from TCSC step responses. It is a method of fitting a linear model in the form of (1). Development of Prony analysis for power system applications includes variations and advances discussed in [9,10,11]. It has demonstrated uses in field-data analysis [8,12], transient stability simulation analysis [11], and control system design [13,14].

C. Noise Response Analysis

The analysis procedure proposed in [5] is used to identify the McNary mode from the noise response tests. With this approach, spectral density estimation and frequency-domain identification are used to estimate the McNary mode. Simulation tests indicate that this approach provides a more accurate mode estimate than ringdown analysis [6], but it requires several minutes of data. The system mode is identified by

1. Apply a random probing signal at X_{test} and measure the real-power response on the McNary-Slatt line. Estimate the system's frequency-response $G(j\omega)$ from analysis of the TCSC actual ohms (X_c) and the McNary-Slatt line flow.
2. Fit a parametric model to $G(j\omega)$ using frequency-domain fitting (the model contains the estimated mode).

Spectral estimation methods [15] are used to calculate the estimated frequency response using

$$G(j\omega) = \frac{S_{uy}(\omega)}{S_{uu}(\omega)} \quad (2)$$

where $S_{uy}(\omega)$ is the estimated cross-spectral density between X_c and McNary-Slatt line power at frequency ω , and $S_{uu}(\omega)$ is the estimated auto-spectral density function for X_c . S_{uy} and S_{uu} are calculated using the well-established periodogram averaging method (often termed the Welch method [16]). Periodogram averaging consists of sliding discrete Fourier transform operations on the modulation responses.

The accuracy of estimates S_{uy} and S_{uu} depend on the length of the noise probing, the amplitude and frequency content of the probing signal, and periodogram averaging parameters. The objective in choosing these parameters is to make $G(j\omega)$ accurately represent the actual frequency response. The quality of $G(j\omega)$ is judged using the estimated coherency function, defined as [15]

$$\gamma_{yy}^2(\omega) = \frac{|S_{uy}(\omega)|^2}{S_{uu}(\omega)S_{yy}(\omega)} \quad (3)$$

If $G(j\omega)$ is accurate, γ_{yy}^2 will settle close to 1. If γ_{yy}^2 does not settle close to 1, analysis parameters and/or the probing signal are adjusted. Details on choosing these parameters for power-system modal analysis are discussed in [5].

Given $G(j\omega)$, a parametric model $G(s)$ is identified using frequency-domain identification. This is done in two

steps. First, initial model parameters are estimated using the least-squares curve-fitting routine in [17]. The second step improves the initial parameter estimates by forcing the model's response to optimally match the measured data using a nonlinear search algorithm, which is part of the computer program described in [18]. Application of this approach has been demonstrated in solving other power system problems in [6].

IV. TCSC TEST RESULTS

The primary field tests were conducted with the McNary-Ross line open to facilitate interactions between TCSC modulations and McNary swings. System operating conditions were adjusted to maintain a steady-state flow near 600 MW on the McNary-Slatt line. Then the TCSC was driven using step and random probing. Security considerations limited closed-loop gains to be relatively small.

Under open-loop conditions, the TCSC was driven with several step functions. Fig. 3 shows the McNary-Slatt line-flow response to three 4-to-20 ohm steps. Slight variations in the responses are typical and are likely caused by the random variations in the system operating conditions. Prony analysis results of five open-loop responses are shown in Table I. The average identified McNary mode is 1.266 Hz at 7.84% damping (damping ratio $\times 100$) with standard

Fig. 3. McNary-Slatt open-loop responses to three for 4-to-20 ohm TCSC steps.

Table I: Identified modes from open-loop TCSC step responses.

TCSC-step size	Identified Mode	
	Damp (%)	Freq (Hz)
4-to-20 ohm	7.57	1.226
20-to-4 ohm	8.70	1.274
4-to-20 ohm	7.90	1.266
20-to-4 ohm	7.57	1.287
4-to-20 ohm	7.44	1.279
Average	7.84	1.266
Std. Deviation	0.51	0.024

Fig. 4. Prony model fits to 4-to-20 ohm and 20-to-4 ohm open-loop step responses.

deviations of 0.024 Hz and 0.51% damping. Approximately the first 2 seconds of a ringdown are used for the Prony analysis because portion of the data exhibits a relatively high signal-to-noise (SNR) oscillation. Past 2 seconds, the noise tends to degrade the Prony fit. Fig. 4 shows typical Prony fits to two ringdowns.

Because of limitations in the TCSC controller during testing, closed-loop step responses were only obtained for three 20-to-9 ohm steps. The system response is shown in Fig. 5 for the steps, and the TCSC internal (X'_{order}) and actual (X_c) ohms are shown in Fig. 6 for one of the responses. The damping signal from the TCSC exhibited in Fig. 6 is relatively weak because of the small feedback gain. Prony analysis results are shown in Table II. In this case, the identified mode is 1.258 Hz at 9.64% damping with standard deviations of 0.016 Hz and 0.089% damping. Comparison of the open-loop and closed-loop Prony results indicates an average increase of 1.80% in damping.

Fig. 5. McNary-Slart closed-loop responses to three 20-to-9 ohm TCSC steps.

Fig. 6. TCSC internal and actual response to a closed loop 20-to-9 ohm command.

Table II: Identified modes from closed-loop TCSC step responses.

TCSC-step size	Identified Mode	
	Damp (%)	Freq (Hz)
20-to-9 ohm	9.73	1.243
20-to-9 ohm	9.55	1.256
20-to-9 ohm	9.65	1.258
Average	9.64	1.258
Std. Deviation	0.089	0.016

Fig. 7 shows the open-loop noise probing responses. For the signals shown in Fig. 7, the random driving signal applied at X_{test} (see Fig. 2) was adjusted so that X_c had a mean of 12 ohms and a variance of 2.12. To limit unnecessary interactions, X_{test} is filtered to be bandlimited from 0 Hz to 2 Hz. Signals of larger magnitude were also applied with similar results. Fig. 8 shows the estimated coherency function for the signals in Fig. 7. The near unity coherency indicates that an accurate frequency response can be calculated. The estimated frequency response is shown in Fig. 9 along with the response of a 2nd-order model obtained using frequency-domain identification. Frequency response data at the peak of the gain (between 1.15 Hz and 1.6 Hz) are used for the identification because this portion of the response contains the maximum information about the mode. Table III summarizes the identified modes from three different open-loop noise tests. The average identified mode is 1.256 Hz at 7.33% damping with standard deviations of 0.005 Hz and 0.16% damping.

Closed-loop noise probing results are summarized in Figs. 10 and 11, and Table IV. The X_c probing signal in Fig. 10 has a mean of 11 ohms and a variance of 3.34. The average identified mode for two tests is 1.252 Hz at 8.55% damping with standard deviations of 0.003 Hz and 0.10% damping. Comparison of the open-loop and closed-loop noise probing results indicate an average increase of 1.22% in damping.

Fig. 7. Open-loop response to TCSC noise modulation.

Fig. 8. Coherency estimate for open-loop noise modulation.

Fig. 9. McNary-Slatt open-loop estimated frequency response and identified 2nd-order model response.

Table III: Identified modes from open-loop TCSC noise modulation responses.

TCSC-noise test number	Identified Mode	
	Damp (%)	Freq (Hz)
1	7.49	1.252
2	7.17	1.261
3	7.34	1.254
Average	7.33	1.256
Std. Deviation	0.16	0.005

Fig. 10. Closed-loop response to TCSC noise modulation.

Fig. 11. McNary-Slatt closed-loop estimated frequency response and identified 2nd-order model response.

Table IV: Identified modes from closed-loop TCSC noise modulation responses.

TCSC-noise test number	Identified Mode	
	Damp (%)	Freq (Hz)
1	8.62	1.254
2	8.48	1.250
Average	8.55	1.252
Std. Deviation	0.10	0.003

V. CONCLUSION

Results presented here indicate that: 1) the TCSC can have significant impact on system dynamics, and 2) under a very small feedback gain, the TCSC provided measurable

added damping. Analysis of TCSC step responses indicate that the McNary damping improved from 7.84% open loop to 9.64% under a small feedback gain. Noise-probing analysis indicates the damping improved from 7.33% to 8.55% under open-loop and closed-loop conditions, respectively.

The differences in the measured dampings from step and noise modulation tests is likely caused by the nature of the tests. Past simulation studies have indicated that noise modulation results in a more accurate mode estimate. Both step and noise tests indicate an improved damping of approximately 1.5%.

Security considerations did not permit lightly-damped operation of the system; therefore, performance of the TCSC as an oscillation damper was not immediately obvious. The analysis in this paper has provided detail results and insights to the effectiveness of the TCSC under limited testing conditions. To completely judge the effectiveness of the TCSC, more testing is required under more lightly-damped and strenuous conditions.

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REFERENCES

- [1] J. Douglas, ed., "The Future of Transmission - Switching to Silicon," *EPRI Journal*, pp. 5-13, June 1989.
- [2] J. Hauer, et al., "Test Results and Initial Operating Experience for the BPA 500 kV Thyristor Controlled Series Capacitor Unit at Slatt Substation, Part II - Modulation, SSR, and Performance Monitoring," Flexible AC Transmission System (FACTS 3) Conference, Sponsored by the Electric Power Research Institute, Baltimore, Maryland, October 1994.
- [3] J. Urbanek, R.J. Piwko, E.V. Larsen, B.L. Damsky, B.C. Furumasa, W.A. Mittelstadt, and J.D. Eden, "Thyristor-Controlled Series Compensation - Equipment Design for the Slatt 500 kV Substation," *IEEE Trans. on Power Delivery*, vol. 8, no. 3, pp. 1460-1469, July 1993.
- [4] R.J. Piwko, C.A. Wegner, B.C. Furumasa, B.L. Damsky, and J.D. Eden, "The Slatt Thyristor-Controlled Series Capacitor Project - Design, Installation, Commissioning and System Testing," CIGRE, Report No. 14-104, Paris, 1994.
- [5] D.J. Trudnowski, M.K. Donnelly, and J.F. Hauer, "A Procedure for Oscillatory Parameter Identification," *IEEE Transactions on Power Systems*, vol. 9, no. 4, pp. 2049-2055, November 1994.
- [6] D.J. Trudnowski, *Power System Identification Toolbox: Phase Two Progress*, PNL-9456, Pacific Northwest Laboratory, Richland, Washington, August 1994.
- [7] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill, Inc., 1994.
- [8] J.F. Hauer, C.J. Demeure, and L.L. Scharf, "Initial Results in Prony Analysis of Power System Response Signals," *IEEE Transactions on Power Systems*, vol. 5, pp. 80-89, February 1990.
- [9] D.A. Pierre, D.J. Trudnowski, and J.F. Hauer, "Identifying Linear Reduced-Order Models for Systems with Arbitrary Initial Conditions using Prony Signal Analysis," *IEEE Transactions on Automatic Control*, vol. 37, no. 6, pp. 831-835, June 1992.
- [10] D.J. Trudnowski, "Order Reduction of Large-Scale Linear Oscillatory System Models," *IEEE Transactions on Power Systems*, vol. 9, no. 1, pp. 451-458, February 1994.
- [11] I. Kamwa, et al., "A Minimal Realization Approach to Reduced-Order Modelling and Modal Analysis For Power System Response Signals," Paper No. 92SM490-3PWRs, IEEE/PES Summer Power Meeting, Seattle, Washington, 1992.
- [12] J.F. Hauer, "The Use of Prony Analysis to Determine Modal Content and Equivalent Models for Measured Power System Response," *IEEE Symposium on Eigenanalysis and Frequency Domain Methods for System Dynamic Performance*, Paper No. 90TH0292-3-PWR, pp. 105-115, 1989.
- [13] D.J. Trudnowski, J.R. Smith, T.A. Short, and D.A. Pierre, "An Application of Prony Methods in PSS Design for Multimachine Systems," *IEEE Transactions on Power Systems*, vol. 6, no. 2, pp. 118-126, February 1991.
- [14] M.K. Donnelly, J.R. Smith, R.M. Johnson, J.F. Hauer, R.W. Brush, and R. Adapa, "Control of a Dynamic Brake to Reduce Turbine-Generator Shaft Transient Torques," *IEEE Transactions on Power Systems*, vol. 8, no. 1, pp. 67-73, February 1993.
- [15] J. Bendat and A. Piersol, *Engineering Applications of Correlation and Spectral Analysis*, New York: John Wiley & Sons, 1980.
- [16] A. Oppenheim and R. Schaffer, *Digital Signal Processing*, Englewood Cliffs, New Jersey: Prentice-Hall, Inc. 1975.
- [17] J.M. Johnson and D.J. Trudnowski, "Frequency-Domain Transfer-Function Identification using Chebychev Polynomials," *Proceedings of the 32nd IEEE Conference on Decision and Control*, vol. 4, pp. 3510-3511, San Antonio, Texas, December 1993.
- [18] D.J. Trudnowski, *Frequency Domain Transfer Function Identification Using the Computer Program SYSFIT*, PNL-8455, Pacific Northwest Laboratory, Richland, Washington, December 1992.

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