Final Report for DOE/EPSCoR Laboratory Partnership Grant "Advanced Techniques for Power System Identification from Measured Data"

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Overview of project outcomes:

Time-synchronized measurements provide rich information for estimating a power-system's electromechanical modal properties via advanced signal processing. This information is becoming critical for the improved operational reliability of interconnected grids. A given mode's properties are described by its frequency, damping, and shape. Modal frequencies and damping are useful indicators of power-system stress, usually declining with increased load or reduced grid capacity. Mode shape provides critical information for operational control actions. This project investigated many advanced techniques for power system identification from measured data focusing on mode frequency and damping ratio estimation.

Investigators from the three universities coordinated their effort with Pacific Northwest National Laboratory (PNNL). Significant progress was made on developing appropriate techniques for system identification with confidence intervals and testing those techniques on field measured data and through simulation. Experimental data from the western area power system was provided by PNNL and Bonneville Power Administration (BPA) for both ambient conditions and for signal injection tests. Three large-scale tests were conducted for the western area in 2005 and 2006. Measured field PMU (Phasor Measurement Unit) data was provided to the three universities. A 19-machine simulation model was enhanced for testing the system identification algorithms. Extensive simulations were run with this model to test the performance of the algorithms.

University of Wyoming researchers participated in four primary activities: 1) Block and adaptive processing techniques for mode estimation from ambient signals and probing signals, 2) confidence interval estimation, 3) probing signal design and injection method analysis, and 4) performance assessment and validation from simulated and field measured data. Subspace based methods have been use to improve previous results from block processing techniques. Bootstrap techniques have been developed to estimate confidence intervals for the electromechanical modes from field measured data. Results were obtained using injected signal data provided by BPA. A new probing signal was designed that puts more strength into the signal for a given maximum peak to peak swing. Further simulations were conducted on a model based on measured data and with the modifications of the 19-machine simulation model. Montana Tech researchers participated in two primary activities: 1) continued development of the 19-machine simulation test system to include a DC line; and 2) extensive simulation analysis of the various system identification algorithms and bootstrap techniques using the 19 machine model. Researchers at the University of Alaska – Fairbanks focused on the development and testing of adaptive filter algorithms for mode estimation using data generated from simulation models and on data provided in collaboration with BPA and PNNL. There efforts consist of pre-processing field data, testing and refining adaptive filter techniques (specifically the Least Mean Squares (LMS), the Adaptive Step-size LMS (ASLMS), and Error Tracking (ET) algorithms). They also improved convergence of the adaptive algorithms by using an initial estimate from block processing AR method to initialize the weight vector for LMS. Extensive testing was performed on simulated data from the 19 machine model.

This project was also extensively involved in the WECC (Western Electricity Coordinating Council) system wide tests carried out in 2005 and 2006. These tests involved injecting known probing signals into the western power grid. One of the primary goals of these tests was the reliable estimation of electromechanical mode properties from measured PMU data. Applied to the system were three types of probing inputs: (1) activation of the Chief Joseph Dynamic Brake, (2) mid-level probing at the Pacific DC Intertie (PDCI), and (3) low-level probing on the PDCI. The Chief Joseph Dynamic Brake is a 1400 MW disturbance to the system and is injected for a half of a second. For the mid and low-level probing, the Celilo terminal of the PDCI is modulated with a known probing signal. Similar but less extensive tests were conducted in June of 2000. The low-level probing signals were designed at the University of Wyoming. A number of important design factors are considered. The designed low-level probing signal used in the tests is a multi-sine signal. Its frequency content is focused in the range of the inter-area electromechanical modes. The most frequently used of these low-level multi-sine signals had a period of over two minutes, a root-mean-square (rms) value of 14 MW, and a peak magnitude of 20 MW. Up to 15 cycles of this probing signal were injected into the system resulting in a processing gain of 15. The resulting measured response at points throughout the system was not much larger than the ambient noise present in the measurements. Thus the low-level probing was only a small disturbance to the system, yet because of the processing gain, positive results were obtained in estimating the electromechanical modes.

The next section lists the significant findings and accomplishments from this project. References are given to published papers which are listed later in the report.

Significant Findings /Accomplishments:

A. Design of new probing signal – a low amplitude long duration wide bandwidth signal with a favorable crest factor. [6, 13]
B. Establishment of confidence intervals on mode estimates from measured ambient data using Bootstrap techniques for Yule Walker and Subspace Algorithms. [3, 14, 16]
C. Combined model of input/output relationship and noise model developed from measure data. [3]
D. For the 19-machine simulation model, a DC line was added between buses 26 and 27. This included a noise modulation input at both the rectifier ends. This required working with Graham Rogers at Cherry Tree Scientific Software to develop a modified version of the PST Toolbox allowing linearization of a system with a DC line and control input. [1, 4]
E. The accuracy of the linear models compared with a detailed nonlinear simulation has been studied.

F. Testing of adaptive filter LMS algorithms on field measured data using ARMA to give a better initial weight vector for the LMS algorithm. [11, 19]
G. Designed new low-level multi-sine probing signals with amplitudes of 20 MW and durations of up to 40 minutes. These signals were modulated on the Pacific DC Intertie at Celilo during WECC system wide tests in September 2005, June 2006, and August 2006. Extensively involved in the planning of each hour long test sequence. [13]
H. Analyzed PMU measurement data from WECC system tests from 2000, 2005, and 2006. Electromechanical Mode Frequencies and Damping Ratios were estimated. Results from ambient data, probing data, and Chief Joseph Dynamic Brake provided comparable estimates. [9, 13, 17]
I. Studied the change in accuracy of the mode estimates as a function of probing signal amplitude and duration. Found that the standard deviation of the mode estimates is approximately inversely proportional to the time aperture and that as the amplitude of the probing signal increases the standard deviation decreases. [3, 14, 16]
J. Developed new signal processing algorithm for Estimation of Autoregressive Parameters by the Constrained Total Least Square Algorithm Using a Bootstrap Method. [15]
K. Performed a study of the computational burden of mode estimation algorithms. [3, 18]
L. Performed a comparison of Time-Domain and Frequency-Domain LS Prediction Error Methods for Power System Mode Estimation. [8]
M. Developed a new algorithm for short duration pseudo-random signals. [2, 7]
N. Developed computationally efficient weighted update algorithms for statistical parameter estimates for time-varying signals. These algorithms have application to mode frequency, damping and shape estimation. [3]
O. Developed adaptive algorithms which recursively update the estimates of mode frequency and damping ratio. [1, 4, 5, 11, 12, 19]
P. Investigated the mode behavior over a forty eight hour period using ambient PMU data provided by Bonneville Power Administration. [3]
Q. Achieved improved adaptive mode estimation performance using adaptive step size least mean squares (ASLMS). [12]

Graduate Students, Undergraduate Students and Postdoctoral Fellows:

Number of Undergraduates: 1

Dustin Carruthers, University of Wyoming

Number of Graduate Students: 8

<u>Ph.D. Students</u>
Mike Anderson, University of Wyoming
Ning Zhou, University of Wyoming
Frank Tuffner, University of Wyoming

<u>MS Students</u>
Ashish Subramanian, University of Wyoming

Travis Makela, Montana Tech
Debbie Harvey, Montana Tech
Mr. Ashok, University of Alaska – Fairbanks
Mr. Trivikram, University of Alaska – Fairbanks

Graduate Student Summer Internships at Government Facilities
Ning Zhou, Pacific Northwest National Laboratory (PNNL)
Frank Tuffner, Bonneville Power Administration (BPA)

Graduate Students Hired into Fulltime Positions at PNNL upon Graduation
Ning Zhou
Frank Tuffner

Number of Postdoctoral Fellows: None

Other Funding Awards Attributable to DOE EPSCoR support:

"Development of Dynamic Security Assessment Tools for Synchronized Real-Time Phasor Data in the Eastern Interconnection," Power System Research Consortium (PSRC – AEP, PJM, NYISO, NEISO, First Energy), $190,000, September 2006 – September 2009.

"Power System Identification Using Injected Probing Signals," Bonneville Power Administration (BPA), $99,000, December 2003 through September 2006.

Publications (19):

1. N. Zhou, D. Trudnowski, J. W. Pierre, W.A. Mittelstadt, "Electromechanical Mode On-line Estimation Using Regularized Robust RLS Methods," *IEEE Trans on Power Systems*, vol. 24, no. 4, pp. 1670-1680, November 2008.

2. Zhou, N. and J.W. Pierre, "Time-Limited Perturbation Waveform Generation by an Extended Tim-Frequency Domain Swapping Algorithm," *Proc. 51st IEEE International Midwest Symposium on Circuits and Systems*, Knoxville, Tennessee, August 10-13, 2008.

3. Tuffner, Frank K., "Computationally Efficient Weighted Updating of Statistical Parameter Estimates for Time Varying Signals with Application to Power System Identification," *Ph.D. Dissertation*, University of Wyoming, August 2008.

4. Zhou, N., J.W. Pierre, D. Trudnowski, R. Guttromson, "Robust RLS Methods for On-line Estimation of Power System Electromechanical Modes," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1240-1249, August 2007.

5. Wies, R.W., A. Balasubramanian, and J.W. Pierre, "Adaptive Filtering Techniques for Estimating Electromechanical Modes in Power Systems," *Proceedings of the IEEE Power Engineering Society General Meeting*, June 2007.

6. Zhou, N., J.W. Pierre, and D.J. Trudnowski, "A Bootstrap Method for Statistical Power System Mode Estimation and Probing Signal Selection," *Proceedings of PSCE*, pp. 172-178, October 2006.

7. Zhou, N. and J.W. Pierre, "Waveform Generation of Time-Limited Pseudo-Random Signals," *Proceedings of the IEEE 12th DSP Workshop*, pp. 197-202, September 2006.

8. Subramanian, A. and J.W. Pierre, "Basic Frequency and Time Domain Least Squares Methods for System Identification," *Proceedings of North American Power Symposium (NAPS)*, September 2006.

9. Zhou, N., J.W. Pierre, J.F. Hauer "Initial Results in Power System Identification from Injected Probing Signals Using a Subspace Method, " *IEEE Transactions on Power Systems*, Vol. 21, no. 3, pp. 1296-1302, August 2006.

10. Zhou, N., J.W. Pierre, and D.J. Trudnowski, "A Bootstrap Method for Statistical Power System Mode Estimation and Probing Signal Selection," *Proceedings of the IEEE Power Engineering Society General Meeting*, June 2006.

11. Wies, R.W., A. Balasubramanian, and J.W. Pierre, "Combining Least Mean Squares Adaptive Filter and Auto-Regressive Block Processing Techniques for Estimating the Low-Frequency Electromechanical Modes in Power Systems," *Proceedings of the IEEE Power Engineering Society General Meeting*, June 2006.

12. Wies, R.W., A. Balasubramanian, and J.W. Pierre, "Using Adaptive Step-size Least Mean Squares (ASLMS) for Estimating Low-frequency Electromechanical Modes in Power Systems," *Proceedings of the 9th International Conference on Probabilistic Methods Applied to Power Systems(PMAPS)*, Stockholm, Sweden, June 2006.

13. Zhou, Ning, "Subspace Methods of System Identification Applied to Power Systems," *Ph.D. Dissertation*, University of Wyoming, December 2005.

14. Anderson, M.G., N. Zhou, J.W. Pierre, and R.W. Wies, "Bootstrap-based Confidence Interval Estimates for Electromechanical Modes from Multiple Output Analysis of Measured Ambient Data," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 943-950, May 2005.

15. Zhou, N. and J.W. Pierre, "Estimation of Autoregressive Parameters by the Constrained Total Least Square Algorithm Using a Bootstrap Method," *Proceedings of the IEEE International Conference in Acoustic, Speech and Signal Processing (ICASSP)*, March 2005.

16. Anderson, M., "Application of Parametric System Identification to Power System Dynamic Stability with Statistical Bounds," *Ph.D. Dissertation*, University of Wyoming, Fall 2004.

17. Zhou, N. and J.W. Pierre, "Electromechanical Mode Estimation of Power Systems from Injected Probing Signals Using a Subspace Method," *Proceedings of North American Power Symposium (NAPS)*, August 2004.

18. Legowski, I. and J.W. Pierre, "An Initial Study of the Computational Burden of Identifying Electromechanical Modes from Ambient Power System Measurements," *Proceedings of North American Power Symposium (NAPS),* August 2004.

19. Wies, R.W., J.W. Pierre, and D.J. Trudnowski, "Use of Least-Mean Squares (LMS) Adaptive Filtering Technique for Estimating Low-Frequency Electromechanical Modes in Power Systems," *Proceedings of the IEEE Power Engineering Society General Meeting*, June 2004.