ASCR Project Final Report

Advanced Kalman Filter for
Real-Time Responsiveness in Complex Systems

PI: Gregory Welch (UNC-Chapel Hill)

10 June 2014

DOE Award#: DE-SC0002271
UNC Award#: A10-0335-002
Project Start: September 15, 2009
Project End: September 14, 2013
Call Name & Number: Multiscale Mathematics and Optimization for Complex Systems, LAB 08-13
Total Funding Received at UNC: $320,502
Total Spending at UNC: $320,502
External Partners: This research project is a joint effort involving The Pacific Northwest National Lab and the University of North Carolina at Chapel Hill. Each organization will receive funding separately.

Statement of Work/Abstract

Complex engineering systems pose fundamental challenges in real-time operations and control because they are highly dynamic systems consisting of a large number of elements with severe nonlinearities and discontinuities. Today's tools for real-time complex system operations are mostly based on steady state models, unable to capture the dynamic nature and too slow to prevent system failures. We developed advanced Kalman filtering techniques and the formulation of dynamic state estimation using Kalman filtering techniques to capture complex system dynamics in aiding real-time operations and control. In this work, we looked at complex system issues including severe nonlinearity of system equations, discontinuities caused by system controls and network switches, sparse measurements in space and time, and real-time requirements of power grid operations. We sought to bridge the disciplinary boundaries between Computer Science and Power Systems Engineering, by introducing methods that leverage both existing and new techniques. While our methods were developed in the context of electrical power systems, they should generalize to other large-scale scientific and engineering applications.

To improve the state estimation accuracy and real-time responsiveness of large-scale power systems, the team at University of North Carolina at Chapel Hill (UNC-CH) developed various methods featuring on/off-line uncertainty analysis in three distinct but interrelated research topics, with applications in power systems.

1. Grid Sensor Placement

We presented an approach that combines off-line uncertainty analysis and network topology analysis, to estimate the steady-state performance of candidate sensor placement design for discrete-space systems. Based on this framework, we restated the optimal PMU placement problem, applied our method on different system configurations, and visualized the results quantitatively. Taking one step further, we tied it in with dynamic state estimation to provide example solutions to the industry.

The benefits of our approach include: (1) it can be performed efficiently without even running the actual estimation procedure; (2) it is generalized for any PMU placement design, regardless of achieving full observability.

While we have initially chosen to work with PMU measurements only, the future work could extend the measurement set to include conventional RTU measurements. Moreover, this method is not restricted to PMU placement problems—it can be employed in different discrete-space system sensor placement optimization frameworks.

Conference Papers

- J. Zhang, G. Welch and G. Bishop, "*Observability and Estimation Uncertainty Analysis for PMU Placement Alternatives*". 2010 North American Power Symposium (NAPS 2010), Arlington, TX, USA.
- J. Zhang, G. Welch, G. Bishop and Z. Huang, "*Optimal PMU Placement Evaluation for Power System Dynamic State Estimation*". IEEE PES Conference on Innovative Smart Grid Technologies Europe (ISGT 2010), Chalmers Lindholmen, Göteborg, Sweden.

Presentations

- J. Zhang, "*Observability and Estimation Uncertainty Analysis for PMU Placement Alternatives*" at North American Power Symposium, Arlington, TX, 2010.
- J. Zhang, "*Optimal PMU Placement Evaluation for Power System Dynamic State Estimation*" at IEEE PES Conference on Innovative Smart Grid Technologies Europe, Chalmers Lindholmen, Göteborg, Sweden, 2010.

Posters

- J. Zhang, G. Welch, G. Bishop, and Z. Huang. "*Adaptive Kalman Filtering for Robust Power System State Tracking*," poster presented at the DOE Applied Mathematics Program meeting, October 17–18 2011.

2. Filter Computation Adaptation

We presented Lower Dimensional Measurement-space (LoDiM) state estimation method, a Kalman-filter-based state estimation algorithm with a measurement selection procedure that can adapt to limited computational resources. Compared to the traditional batch approach of KF/EKF

methods, which handles the entire measurement-space, the LoDiM only needs to deal with a lower-dimensional measurement-space during each estimation cycle—the measurement selection procedure guides the LoDiM to dynamically choose a “most critical” (most effectively reduce the largest estimation uncertainty component) measurement subset. A smaller measurement-space incorporates less information each cycle, and hence leads to reduced computation time and increased reporting rate, which is favorable in various state tracking applications.
Specifically for power system dynamic state estimation problems, where the measurement-spaces are exceptionally large, we have proposed the Reduced Measurement-space Dynamic State Estimation (ReMeDySE) method derived from the LoDiM. Together with high frequency and accuracy PMU data, the ReMeDySE can facilitate dynamic state estimation in large-scale power systems.

When some emergency tasks are competing for computational resources with the estimation process, our method allows the estimation to continue with a reduced computational load, and release some resources for the tasks, without sacrificing the reporting rate. Then when the tasks are completed, the estimation process can reclaim the resources, so that the filter computation can go back up as desired. We can optimally adapt our algorithm to the available computation budget by analyzing the trade-offs.

Although the LoDiM approach is presented in the context of the Kalman filter, the associated measurement selection procedure is not filter-specific, i.e. it can be used with other state estimation methods such as particle and unscented filters. Selecting certain subspaces inherently delays the selection of the entire (remaining) measurement-space, which could potentially delay the observance of an important state change. One possible solution is to investigate the addition of measurement prioritization based on factors such as unexpected (deviating from prediction) state changes throughout the entire state space. For example, one can adjust the uncertainty parameters as discussed in our next topic, to affect priorities for parts of the state space, causing measurement selection to prioritize certain areas.

With all the matrix arithmetic operations, it is possible to further parallelize and optimize the algorithm by taking advantage of modern computational hardware such as the GPUs. Moreover, we can combine our approach with hierarchical/distributed estimation methods, making it particularly attractive in large-scale real-time state estimation, for wide-area power systems and beyond.

Conference Papers

- J. Zhang, G. Welch and G. Bishop, “*Power System State Estimation with Dynamic Optimal Measurement Selection*”. SSCI 2011 CIASG - 2011 IEEE Symposium on Computational Intelligence Applications in Smart Grid, Paris, France.
- J. Zhang, G. Welch, G. Bishop and Z. Huang “*Reduced Measurement-Space Dynamic State Estimation (REMEDYSE) for Power Systems*”. 2011 IEEE PowerTech, Trondheim, Norway.
- J. Zhang, G. Welch, G. Bishop, “*LoDiM: A Novel Power System State Estimation Method with Dynamic Measurement Selection*”. 2011 IEEE Power & Energy Society General Meeting, Detroit, MI, USA.

Presentations

- G. Welch, "*Power System State Estimation with Dynamic Optimal Measurement Selection*" at SSCI 2011 CIASG - 2011 IEEE Symposium on Computational Intelligence Applications in Smart Grid, Paris, France.
- G. Welch, "*Reduced Measurement-Space Dynamic State Estimation (REMEDYSE) for Power Systems*" at 2011 IEEE PowerTech, Trondheim, Norway.
- J. Zhang, "*LoDiM: A Novel Power System State Estimation Method with Dynamic Measurement Selection*" at IEEE Power & Energy Society General Meeting, Detroit, MI, 2011.

3. Adaptive and Robust Estimation

We presented a novel Adaptive Kalman Filter with Inflatable Noise Variances (AKF with InNoVa). With real-time phasor measurements, this algorithm enables convenient and on-line robust power system state estimation under various adverse conditions, given sufficient redundancy among measurements.

The AKF with InNoVa is designed to identify and reduce the impact of incorrect system modeling, as well as erroneous measurements. It is capable of doing so because besides the regular normalized innovation test, we also adopt a normalized residual test to help separating the process and measurement factors. With these tests, our algorithm efficiently adjusts the process and measurement noise parameters on-the-fly separately for more robust estimates. Specifically, the inflation of process noise covariance Q indicates fast changing state or even wrong model, making it practical for people to localize system anomalies, e.g. faults, load changes, electricity theft, etc.; while the inflation of measurement noise covariance R implies potentially bad measurements. At the same time, an exponential decay process is employed to enable automatic deflation of the parameters if the modeling/devices problems are resolved.

To produce real-time and robust estimation of more dynamic states besides traditional static states, we have combined the AKF with InNoVa with power system dynamic state estimation from our previous work. The result is a more comprehensive power system state estimation technique with a two-stage Kalman filter approach. The AKF with InNoVa in stage one deals with system modeling and measurement errors. It gives more accurate estimates on bus voltage phasors, which are also served as the input to the EKF in stage two, to generate more accurate estimates on generator rotor speed and angles. The output of both stages are essential for myriad time-critical applications. For example in contingency analysis, signatures in different types of contingency may be detected from the change in state estimates. In fact, nowadays in the age of social media, besides the "official" measurements from the industrial control systems, public information available on the internet is a new source of measurements that can help to confirm the contingency and hence alert the operators.

The AKF with InNoVa should not be limited to power system state estimation. Furthermore, with the advance of computational hardware technologies and optimization algorithms, our approach is subject to further modifications.

Journal Papers

- J. Zhang, G. Welch, G. Bishop and Z. Huang, "*A Two-stage Kalman Filter Approach for Robust and Real-time Power Systems State Estimation*", IEEE Transactions on Sustainable Energy, 2013

Posters

- J. Zhang, "*Adaptive Kalman Filtering for Robust Power System State Tracking*" at DOE Applied Mathematics Program Meeting, Washington, DC, 2011.

PNNL hosted the UNC-CH team for three visits: October of 2009, May of 2010, and May of 2011. The graduate student at UNC-CH, Jinghe Zhang, greatly benefited from the visits: she received technique support and insightful advice regarding the research progress from PNNL team, especially Dr. Zhenyu Huang, Dr. Ning Zhou, Dr. Pengwei Du and Dr. Ruisheng Diao. Dr. Jinghe Zhang successfully completed the oral defense of her doctoral dissertation entitled "Uncertainty-driven Adaptive Estimation with Applications in Power Systems" in May 2013, in the Department of Computer Science at the UNC-CH. Her dissertation covered the above mentioned three topics. Dr. Zhenyu Huang and Dr. Ning Zhou have served on her PhD Dissertation Committee, and provided many helpful feedbacks along the way.