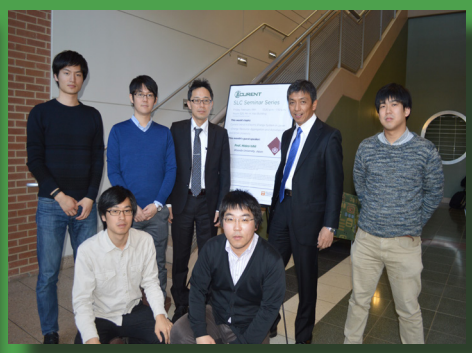
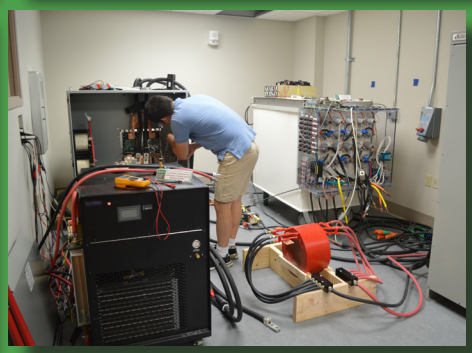
Spring 2016 Newsletter
Issue 5

CURENT

CENTER FOR ULTRA-WIDE-AREA RESILIENT
ELECTRIC ENERGY TRANSMISSION NETWORKS





a National Science Foundation &
Department of Energy
Engineering Research Center

Welcome from the Director

Dr. Kevin Tomsovic

Dear CURENT colleagues and supporters,

Welcome once again to our newsletter. In it, we'll tell you about CURENT research, education and industry happenings.

In this issue, we highlight some recent research results in dynamic state estimators for large-scale power systems by Dr. Ali Abur, Dr. Hanoch Lev-Ari and Pengxiang Ren (PhD student); wide-area measurement systems from our deputy director Dr. Yilu Liu; characterizing nonlinear power system oscillations from Dr. Kai Sun; and missing data recovery of PMU measurements by Dr. Joe Chow and Dr. Meng Wang. These updates are from research currently going on at our center.

Our industry members have grown by over ten percent since last August. We now have 33 members with several more indicating a desire to join. We launched our member web portal in January. Please browse our website and let us know what you think. We also are continuing our monthly industry seminars, which provide our students with invaluable information from seasoned professionals and are usually webcast for industry as well. Several companies are taking full advantage of our students and we presently have eight students on corporate internships. We are interested in what we can do to provide industry with timely information, so please let us know what we can do to be more effective.

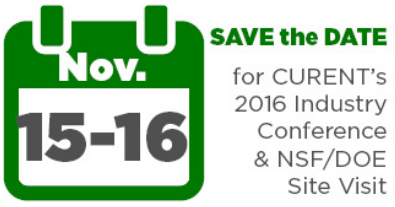
Our 5th Annual Industry Meeting and Site Visit is set for Nov. 15th-17th. This meeting allows for the annual NSF and DOE evaluation of the Center. It also lets us to share research highlights, show off our laboratories and let people see all the work being done here. We value your participation and look forward to showing you the value of the Center's work.

It's hard to believe we've been at this for five years, but as this fifth year progresses, I can reflect on the how far we've come. We have a strong, established program. We have several mature research projects. We hope we are a value-added partner to industry. All these things would not have been possible without your support and participation in our Center. For this, we thank you.

Please let us know if you have any ideas about how we can provide more value to your organization. Your feedback and comments are crucial to us.

Sincerely,

Kevin Tomsovic



SAVE the DATE
for CURENT's 2016 Industry Conference & NSF/DOE Site Visit

Mark your calendars.
Our 2016 site visit is coming up in November at the Crown Plaza in downtown Knoxville, TN. We hope to see you then.

Contents:

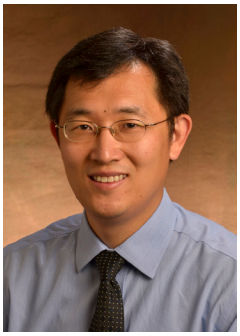
achievements

Dr. Yilu Liu was elected as a member of the National Academy of Engineering (NAE). Liu, who serves as a professor of electrical engineering and computer science, becomes the fifth member of the UTK College of Engineering so honored. Dr. Liu is also a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and deputy director of CURENT.

Above: Dr. Liu

According to NAE President C. D. Mote Jr., academy membership honors those who have made outstanding contributions to "engineering research, practice, or education ... the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education." Election to the NAE is among the highest professional distinctions accorded to an engineer.

Dr. Kai Sun was chosen by the NSF for a CAREER award for his work entitled "Integrated Research and Education in Nonlinear Modal Decoupling and Control for Resilient Interconnected Power Systems." Dr. Sun's research focuses on finding new ways to understand and prevent power system instability and improving the accuracy of results over methods traditionally used.



Above: Dr. Sun

CAREER awards are given by the NSF to help nurture the careers and research of young faculty they feel hold promise in their given fields.

welcome

Meet our Industry Outreach Director - Lisa Beard

Above: Lisa Beard

Lisa Beard joined us in September 2015. She assists in the leadership of CURENT, identifying funding opportunities and working with industry member companies and various College of Engineering faculty to promote education, research and support member relationships. Her focus is on maintaining strong relationships with existing industry members; identifying, engaging and recruiting new company members; and developing long-range sustainability plans for the Center.

Prior to her engagement with CURENT, she worked for Quanta Technology as a Principal Advisor helping utilities launch strategic initiatives in large-scale, smart grid investments projects related to synchrophasors. Before that, Lisa worked as a Program Manager for the Tennessee Valley supporting integration and implementation of wide-area, power system monitoring and control using synchrophasors. She holds a B.S. degree in Microbiology from the University of Georgia, a M.S. in Environmental Management from the University of Texas and a M.S. in Civil Engineering from the University of Tennessee.

In her spare time, Lisa loves relaxing at her dock on Norris Reservoir and watching the bald eagles fly overhead, and spending time with family and friends.

Meet our Industry Technovator - Bill Giewont

Above: Bill Giewont

Bill Giewont joined us as Industry Technovator in January 2016. He will assist CURENT with technology transfer and commercialization activities.

Bill has worked over 37 years in research and product development of control and power electronics for power converters ranging from 120-4160V and 1KW up to 6MW. For the last 10 years, he has held the positions of Chief Engineer of MV Drives, Technical Director of MV R&D and is currently the Director of Technology and Innovation North America for Danfoss Drives. His responsibilities include principle investigator on a Solar ADEPT ARPA-e project which showcases 20A 10kV SiC MOSFETs and heading the development of disruptive power device packaging concepts at Danfoss Silicon Power exclusively for Danfoss Drives.
Bill received his Bachelor of Science degree in electrical engineering from Penn State University.

Missing data recovery of large volumes of PMU data by exploiting low-dimensional structures

by Dr. Joe Chow (chowj@rpi.edu) and Dr. Meng Wang (wangm7@rpi.edu)

Data losses happen due to either device malfunction or communication errors. The recovery of missing PMU (Phasor Measurement Unit) data is an important preprocessing step for other monitoring and control tasks such as state estimation and disturbance detection. We propose new online and offline data recovery methods by collectively processing measurements from multiple PMUs simultaneously. We verify the effectiveness of our proposed methods on PMU data from New York ISO (NYISO) and New York Power Authority (NYPA). We can accurately recover the missing data of 53 PMUs in historical NYISO datasets, some of which contain 10-15% data loss.

The central idea of our proposed methods for data recovery is to exploit the low-dimensional structures of spatial-temporal PMU data blocks. Because PMU measurements are sampled at synchronized time instants, and the measurements of nearby PMUs are correlated through the power system topology, the high dimensional PMU data exhibits a coherence property. If measurements of multiple PMU channels are represented by a matrix with each row representing the measurements of one channel across time, then the matrix only contains a small number of significant singular values.

Leveraging the aforementioned approximate low-rank property of PMU data, we connect the problem of missing PMU data recovery with recent advances in low-rank matrix completion method. The low-rank property of data blocks has been studied in other applications, and various low-rank matrix completion algorithms have been proposed. We proposed an online algorithm that can fill in the missing PMU measurements for real-time applications and tested our methods on historical PMU data from NYISO. The computational time for the 5-minute snapshot with 30 samples/second of PMU voltage magnitude data (9000 by 53 matrix) is only about 6 seconds using our developed online algorithm for PMU data processing OLAP algorithm (Intel i7-4770 with 12 GB RAM). Figure 1 compares the recovery performance of multiple recovery methods, including our developed OLAP algorithm and existing methods such as singular value thresholding (SVT) and information cascading matrix completion (ICMC). All three methods have similar performance on this dataset and can correctly recover the missing points with negligible error.

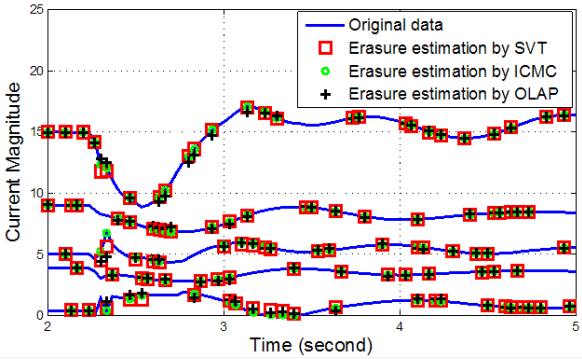


Figure 1: Missing PMU Data Recovery by different recovery methods

Figure 2 shows the recovery performance on historical PMU data in New York State. All the missing points are recovered with negligible error.

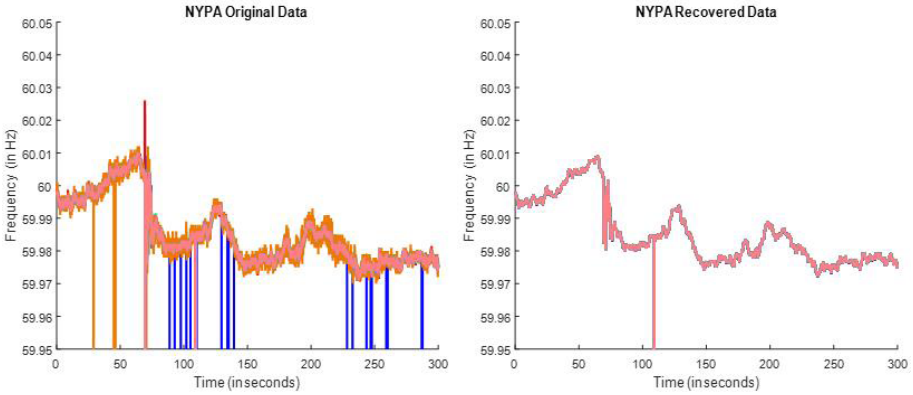


Figure 2: Missing data recovery of historical PMU data in New York State

Missing data recovery (continued)

All algorithms are currently implemented in MATLAB. Future work includes implementing the online OLAP algorithm in Open PDC to allow for its use in tandem with a number of other real-time applications, such as phasor state estimation and data visualization (Figure 3).

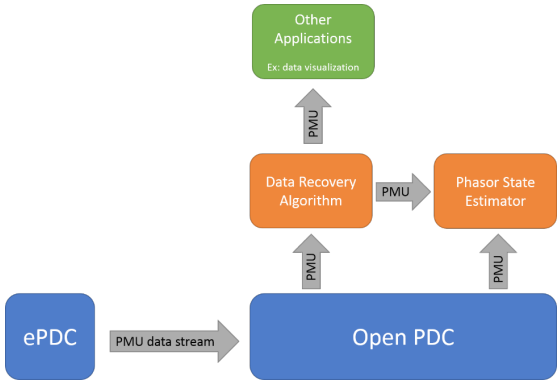


Figure 3: Real-time implementation of the Data Recovery Algorithm

Measurement-based Adaptive Wide-Area Damping Controller Considering Time Delays

by Dr. Yilu Liu (liu@utk.edu)

Wide-area measurement systems enable the wide-area damping controller (WADC) to use remote signals to enhance the small signal stability of large scale interconnected power systems. System operating condition variations and signal transmission time delays are the major factors that decrease the damping effect and even threaten the system stability. At CURENT, we developed a novel measurement-based adaptive WADC scheme using oscillation mode prediction and system identification techniques. These techniques adjust the parameters of WADC as well as the time delay compensation in an online environment. To achieve fast online implementation, the high-order multi-input multi-output (MIMO) model identified from wide-area measurements is deformed into a low-order single-input single-output (SISO) model according to the residue of MIMO model. The SISO model can accurately represent the power system dynamics in the form of a transfer function, capturing the dominant oscillatory behaviors in the frequency range of interest. The effectiveness of the proposed measurement-based adaptive WADC has been demonstrated in a two-area, four-machine system on the Hardware Testbed (HTB) under various disturbance scenarios.

Figure 1 illustrates the flow chart of measurement-based adaptive WADC scheme considering communication delays. Figure 2 shows the effectiveness of the SISO model in representing the system small-signal dynamics. Figure 3 shows the superior damping control performance of proposed adaptive WADC controller compared to the conventional fixed-parameter WADC method.

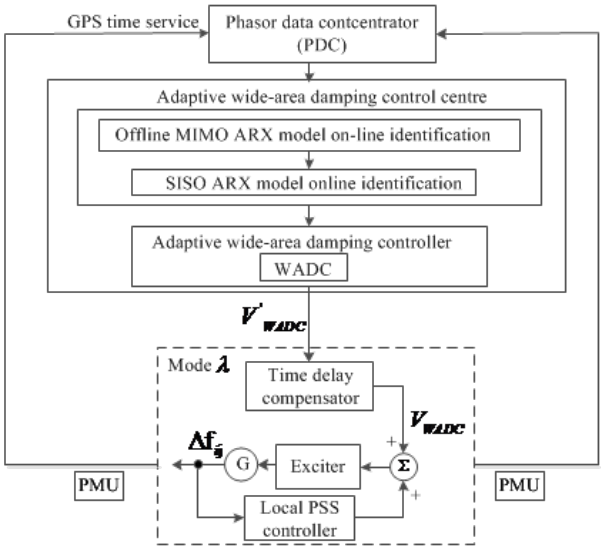


Figure 1: Measurement-based adaptive WADC scheme considering communication delay

Measurement-based Adaptive Wide-Area Damping Controller (continued)

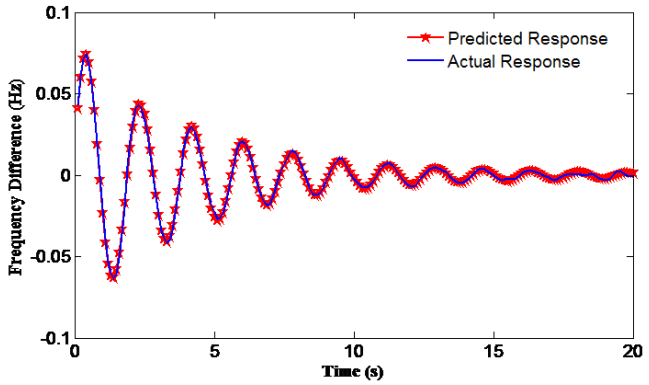


Figure 2: SISO model for damping control

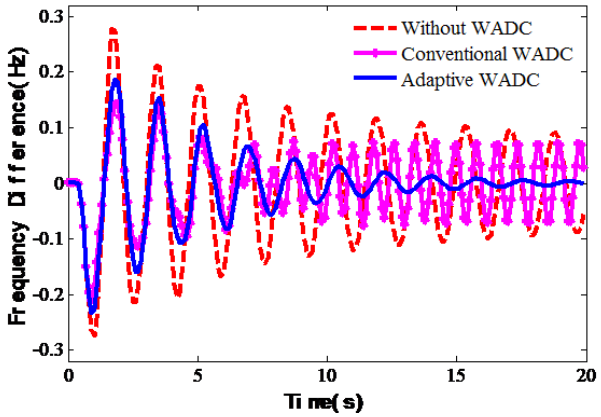


Figure 3: Damping control performance comparison

Frequency-amplitude curve – a new analytical tool for characterization of nonlinear oscillations in power systems

by Dr. Kai Sun (kaisun@utk.edu)

Inter-area oscillations have been threatening system operations and stability since the beginning of interconnecting power systems over weak tie lines in the 1960s. An inter-connected power system is essentially a nonlinear oscillator network, so its electromechanical oscillations (EOs) have inherent nonlinearities and are different from oscillations with a linear system. Power system oscillations have been analyzed in the past several decades. However, most methods do not take the nonlinearities with a power system into account and only use a linearized system model to study oscillations from a small-signal stability point of view. The measurement-based methods, such as the Prony method and Hilbert-Huang Transformation, either assume an EO to be harmonic with its constant frequency, damping and phasing during a specific time period or purely rely on signal processing without considering the nonlinear nature with a power system. As a result, if the modal frequency fluctuates during the measurement window, an existing measurement-based method detects two or more separate modes.

Based on our previous studies, a power system EO mode can change its frequency all over the swings, which can be captured by a phase-locked loop based method applied to the measurements. This effort has focused on analytical studies addressing the nonlinear mechanism of an EO mode. Both model-based and measurement-based approaches have been developed to study nonlinearities of EOs mainly due to the networking of generator swing equations. First, the oscillation frequency of an undamped Single-Machine-Infinite-Bus (SMIB) system is analytically formulated to discover the frequency-energy dependency with a single EO mode under disturbances around a given stable system equilibrium. Accordingly, a new tool named frequency-amplitude (F-A) curve, as a comparative concept of the power-voltage (P-V) curve for voltage stability analysis, is proposed to characterize EOs regarding a specific mode. We also discovered the existence of such an F-A curve for each of the dominant EO modes with a multi-machine power system. A measurement-based method is proposed to estimate the F-A curve for any EO mode of interest and accordingly calculate an associated angular stability margin index. Such a measurement-based method is valuable for online angular stability monitoring regarding any EO mode of interest and for taking preventive control actions if the F-A curve shows a transition of the mode to an instability mode. From the tests on the CURENT WECC large-scale testbed (LTB) system, it is found that the modeling of more details of generators (e.g. increasing the orders of models and adding excitation systems) does not impact the shapes of formulated F-A curves. Figure 1 below gives the F-A curve about the only EO model of an SMIB system. The curve shows the nonlinearity of the mode due to its frequency-energy dependency. The function of the F-A curve can be analytically solved by means of elliptic integrals about the swing equation. Figure 2 shows the same post-disturbance trajectory of the IEEE 9-bus system drawn respectively in the phase plane and the F-A plane: in the phase plane, the trajectory is tangled while in the F-A plane, we may clearly see the stability margins of four segments TW1-TW3 on the trajectory. The F-A curves estimated for selected EO modes of the WECC system are shown in Figure 3. Each star on an F-A curve is the real-time location of the actual system state seen from that EO mode, whose distance to the nose-point tells the real-time angular stability margin.

Frequency-amplitude curve (continued)

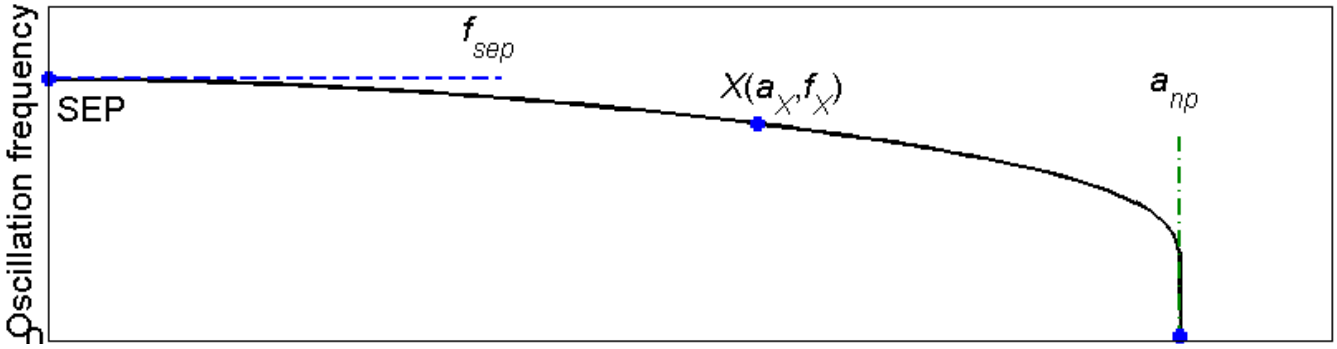


Figure 1: F-A curve about a SMIB system

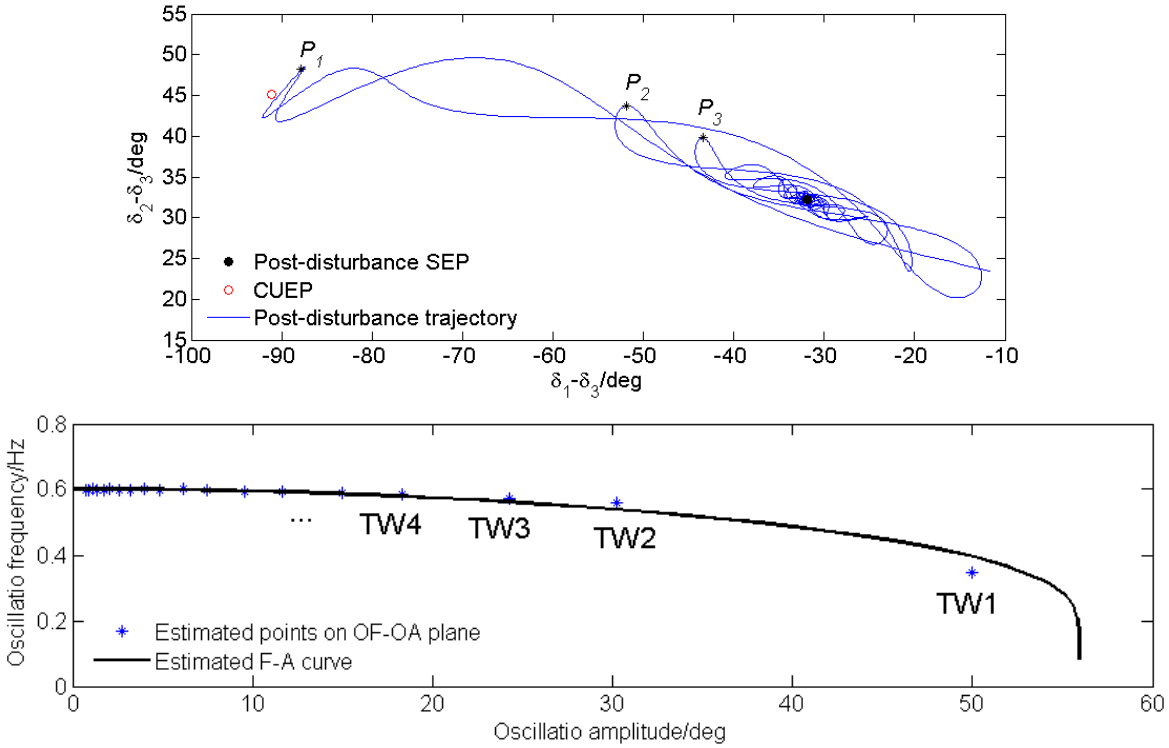


Figure 2: Visualization of the same post-disturbance trajectory in the phase plane and the F-A plane

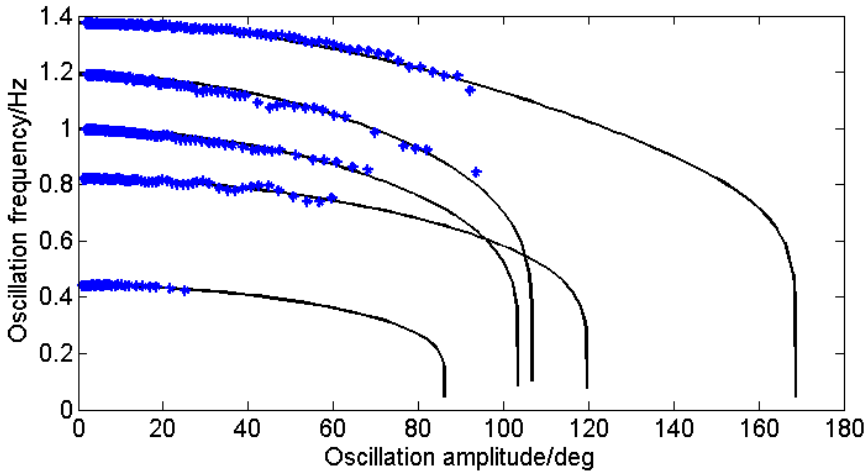


Figure 3: F-A curves estimated for selected EO modes of the WECC system

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Robust Continuous-Discrete Extended Kalman Filter for Estimating Machine States with Model Parameter Uncertainties

by Pengxiang Ren (PhD Student), Dr. Hanoch Lev-Ari (levari@coe.neu.edu) and Dr. Ali Abur (abur@coe.neu.edu)

An accurate knowledge of rotating machine states, (e.g., generator states such as rotor speed, rotor angle and transient voltages, as well as exciter field voltage), is important for dynamic state estimation in large-scale power systems. The performance of dynamic state estimators, such as the (extended) Kalman Filter deteriorates in the presence of moderate model parameter uncertainties. In practice, parameters of rotating machines are known only with limited accuracy, and their values may vary with time. Several methods have been proposed in the literature to mitigate the effect of model uncertainties on overall performance, such as the H∞ approach, the set-valued estimation approach, and the guaranteed-cost paradigm. However, most of these methods are designed for state estimation in linear systems, whereas the (two-axis) generator model we consider is highly nonlinear.

A Robust Extended Kalman Filter (REKF) is developed for estimating machine states in the presence of model parameter uncertainties. Our robust filter is derived as a solution to a minimum-maximum (worst-case) optimization problem: it minimizes a squared residual norm over the entire range of (bounded) possible model parameter errors. The resulting REKF, which consists of modified time- and measurement-update steps, outperforms the standard Extended Kalman Filter (EKF) in the presence of moderate parameters inaccuracies.

The following figures provide generator state estimation results in the presence of uncertainties in the damping constant (D) (Figure 1) and the reactance (Xd) (Figure 2), comparing the proposed REKF algorithm with the ordinary EKF.

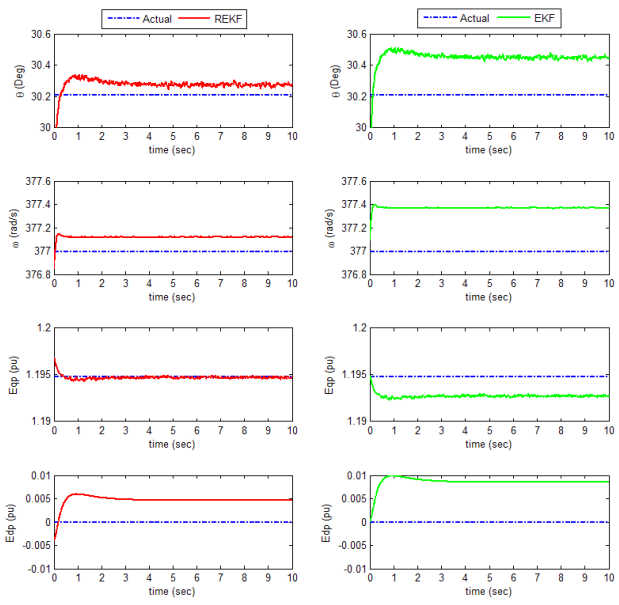

Figure 1: SE with uncertain Damping Constant

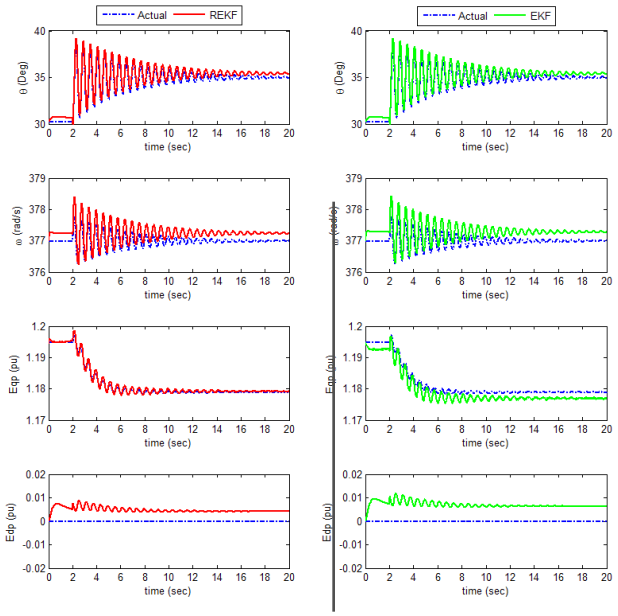

Figure 2: SE with uncertain Reactance with transient

SAVE the DATE

Nov. 15-16

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Education Programs and Goals

To make the K-12 education program more sustainable, CURENT is looking at creating a donation account where individuals can donate money to K-12 education programs. Funds for all K-12 events currently are supplied by NSF and DOE funds, but to make the programs last long term additional support will be needed. Some of the programs provided by CURENT in the Min H. Kao Building are:

- Adventures in STEM Girls Camp – a one week day camp for middle school girls that are interested in learning about electricity, mathematics, biology, and careers. More information about the camp can be found at http://curent.utk.edu/camp
- Young Scholars Program (YSP) – a four week research program for local high school students that introduces them to the topics important to power engineering. Each student has a faculty or graduate student mentor that mentors the student through a research project. The program includes field trips, technical seminars, lab work, professional development and social events. More information about the program can be found at http://curent.utk.edu/ysp
- Research Experience for Teachers – a four week curriculum development program for local high school teachers that explores electricity concepts and tools that can be used to enhance students' science and engineering learning experiences. More information about the program can be found at http://curent.utk.edu/ret
- K-12 Outreach – Classroom visits, lab demonstrations, field trips, materials supply, and family engineering nights are some of our common activities that we work on. Each event is custom designed based upon the needs of the school. For more information, contact Mr. Erin Wills (ewills1@utk.edu).

congratulations

Graduate student Can Huang received the 2015 Chinese Government Award for Outstanding Self-financed Students Abroad. The award was established to encourage research excellence and to recognize the achievement among Chinese students abroad. It is granted across all fields of study and was presented to only 500 out of 460,000 Chinese oversea students all over the world. The final winners were selected by a review committee organized by China's Ministry of Education. Out of the winning students, Can is the only student majoring in Power Systems Engineering.

Dr. Daniel Constinett's research team from the UTK College of Engineering and CURENT were selected as one of 18 finalists for the Google Little Box Challenge. Sponsored by Google and the IEEE Power Electronics Society, the global challenge seeks to improve upon the current design and size of inverters, which play a key role in everything from solar power to electric vehicles. Dr. Costinett and his team—which included Drs. Leon Tolbert, Fred Wang, and Zheyu Zhang and graduate students Chongwen Zhao, Brad Trento, Ling Jiang, and Bo Liu, and collaborators from CURENT member company EPRI— worked to develop the smallest, most efficient two-kilowatt inverter possible. The resulting device was about the size of a deck of index cards, a 20-fold reduction compared to the current commercial state-of-the-art. Our research team was selected as a finalist from among hundreds of applicants worldwide. The team is honored to be among the finalists.

Dr. Chien-fei Chen received an award in September 2015 from the NSF CRISP (Critical Resilient Interdependent Infrastructure Systems and Processes) Program. The interdisciplinary proposal is entitled, "Revolution through Evolution: A Controls Approach to Improve How Society Interacts with Electricity," with the efforts of the lead principal investigator, Dr. Andrea Mammoli from the University of New Mexico and other collaborators from Michigan Technological University and Texas Tech University.

internships

Recent internships for CURENT students:

Taylor Woodward - Duke Energy
Summer Church - Eaton Corporaton
Siqi Wang - NEC Lab
Yidan Lu and Haoyu Yuan - Peak Reliability
Micah Till - Dominion Virginia Power
Yonggli Zhu, Wenyun Ju and May Mahmoudi - GE
Dallas Hamlin - ORNL
Taylor Short - Southern Company

"I strongly encourage my students to obtain internships so they can learn the exciting new technologies in the electric power industry and apply the skills they obtain at school to solve real-world problems. When they then return to school, the intern experience helps them be better prepared to understand new theories and methods."

- Dr. Fran Li

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Above: Students Jared Baxter and Taylor Short help with Family Engineering Night

Family Engineering Night

The Fall 2015 Family Engineering Nights went very well. In total over 700 students attended three events. The schools represented very different school systems. Lake City Elementary School is a small rural school in Anderson County. Green Magnet Elementary is an urban school located close to downtown Knoxville. Sequoyah Elementary School is a small suburban school located close to the University of Tennessee Campus. These three schools have been organizing engineering events for over three years. Sequoyah Elementary has the longest sequence of events and has gradually taken over more of the event planning. This year Sequoyah teachers designed their own activities, while CURENT supplied materials and graduate students.

The Spring 2016 Family Engineering Nights concentrated on Middle Schools in February and several elementary schools will be doing their first engineering night toward the end of the semester in April and May. Schools planning on doing engineering nights in the fall of 2016 include Vine Middle Magnet School, Whittle Springs Middle School, Gresham Middle School, Norwood Elementary School, and South Knox Elementary.

congratulations

Graduate students Chongwen Zhao and Saeed Anwar both won "Best Presentation" awards within their respective sessions at the IEEE Applied Power Electronics Conference (APEC) in March 2016. Saeed's presentation was titled "Integrated DC-DC Converter Design for Electric Vehicle Powertrains" and Chongwen's poster was titled "A Single-Phase Dual Frequency Inverter Based on Multi-Frequency Selective Harmonic Elimination."

Graduate student Lingwei Zhan received national recognition as he was named the North American SynchroPhasor Initiative (NASPI) Outstanding Student of the Year in October 2015.

Undergraduate student Jessica Boles took 3rd place in the Perfect Pitch competition at the ERC meeting in Washington, D.C. in October 2015. Her pitch was "Wireless Charging for Drones via Transmission Lines." During the contest, she presented her idea to congressional staffers, NFS director Dr. France Cordova and ERC program director Dr. Keith Roper.

Above: Jessica Boles delivers her "Perfect Pitch"

Above L to R: Saeed Anwar, Lingi Jiang and Chongwen Zhao at APEC

recent graduates

UTK:

Yutain Cui, Ph.D.
Qinran Hu, Ph.D.
Yin Lei, Ph.D.
Xue Li, Ph.D.
Yue Tong, Ph.D.
Weimin Zhang, Ph.D.

RPI:

Nickolas Barry, M.S.
Andrew Kindle, Ph.D.
Genevieve de Mijolla, M.S.
Felipe Wilches, Ph.D.

NEU:

Guangyu Feng, M.S.
Pengxiang Ren, M.S.

Annual Site Visit

CURENT's 4th Annual Site Visit was held on October 6 – 8, 2015. The previous site visits had been held in the spring so this was a departure from the usual timing. However, both the industry day and the site visit were very successful and it has been determined that future site visits will be held in the fall as well. Overall, the site visit attracted approximately 60 industry attendees and approximately 200 students. These were good numbers considering that there were several other big industry events going on during this same week.

The site visit kicked off with an informal Industry mixer on Monday evening, Oct. 5th. Approximately 30 industry attendees met with each other and faculty to catch up and to discuss mutual topics of interest.

Our annual Industry Day had a representation of over 125 industry representatives, students and faculty members. A stellar group of presenters kicked off the planning session including Michael McCarty, Principal Power Systems Engineer at Solar City; David Wade, Chief Operating Officer at EPB; Hongming Zhang, EMS Network Applications Manager at Peak Reliability; Manu Parashar, Corporate Power System Engineer at Alstom Grid; Jessica Bian, Technical Staff at FERC; David Roop, Director of Electric Transmission at Dominion Virginia Power; and Thomas Coleman, Director of Reliability Assessments at NERC. Their expertise provided invaluable information to those in attendance. The afternoon presentations were divided into two concurrent sessions – Power System Modeling and Estimation and Power Electronics – during which graduate students updated the audience on the latest CURENT research.

The Annual NSF Site Visit began the next day and focused on updating the center's technological progress to the site visit team. Dr. Kevin Tomsovic gave an overview of CURENT and its mission. This was followed by overviews of the thrusts given by the thrust leaders. The Monitoring and Modeling Thrust overview was given by Dr. Yilu Liu and Dr. Ali Abur; the Control and Actuation Thrust overview was given by Dr. Joe Chow and Dr. Fred Wang; and the CURENT Engineered Systems Overview was given by Dr. Leon Tolbert. After lunch, Brad Trento gave the Innovation and Industry Collaboration Program overview. A tour of the research labs and a poster session followed at the Min H. Kao Building where Dr. Chein–fei Chen also gave a talk on the Education and Outreach Program.

The 2016 site visit dates have been announced and are Nov. 15 & 16. The site visit will be held at the Crown Plaza in downtown Knoxville, TN. See curent.utk.edu for further details. Thank you to everyone who participated in making our Annual Industry Day and the NSF Site Visit a success.

Above: Site visit attendees visit the Visualization Lab

Above: Site visit attendees and students discuss research posters during the lab tours

Upcoming Events

2016 IEEE PES General Meeting
July 17-21 in Boston, MA

CURENT Industry Strategy Meeting (following the IEEE PES General Meeting)
July 21 at Northeastern University in Boston, MA

2016 CURENT Industry Day and Annual Site Visit
Nov. 15-16 in Knoxville, TN

CURENT would like to thank all our Industry Partners, the NSF (National Science Foundation) and the DOE (Department of Energy) for all their support.

ABB

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EPRI ELECTRIC POWER RESEARCH INSTITUTE

OPAL-RT TECHNOLOGIES

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