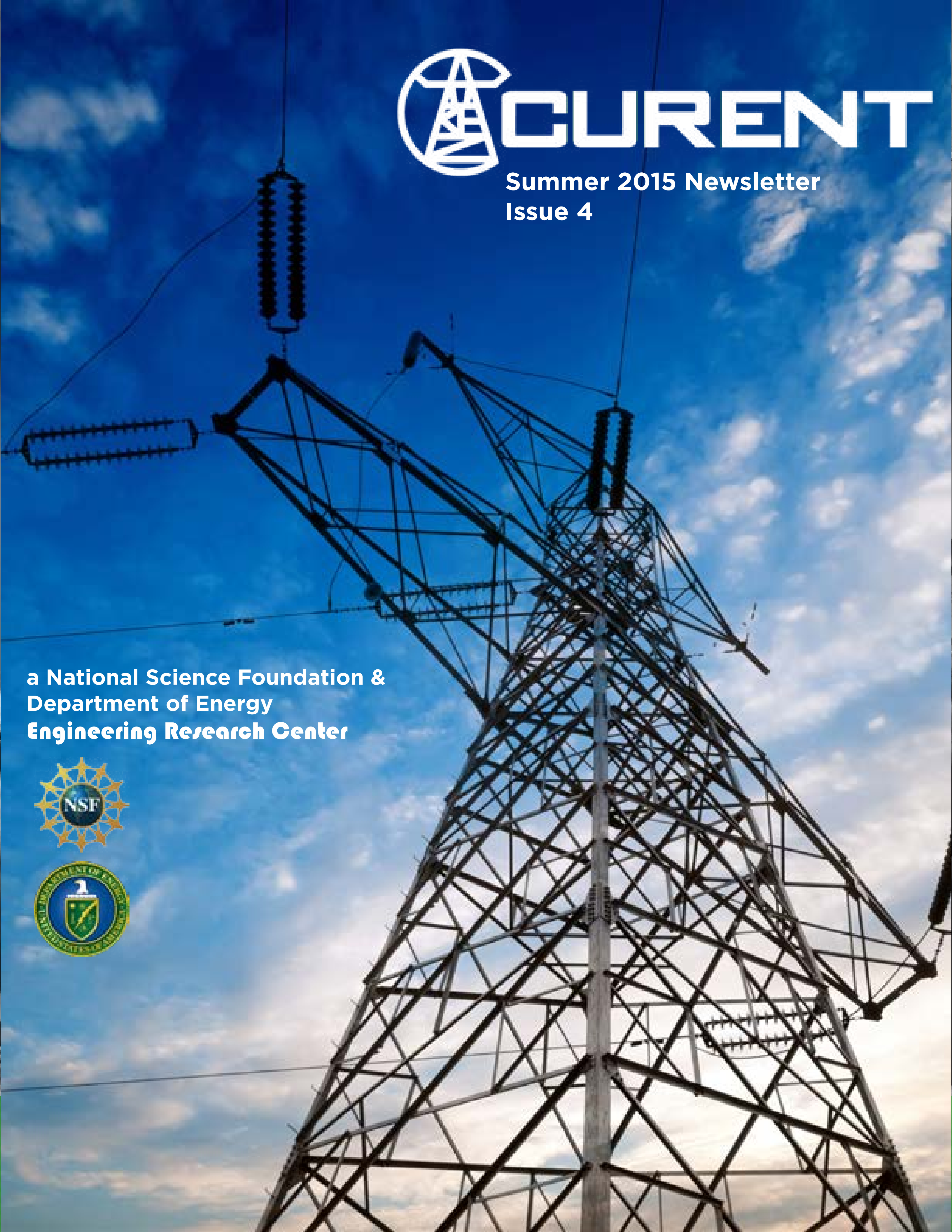
CURENT

Summer 2015 Newsletter
Issue 4



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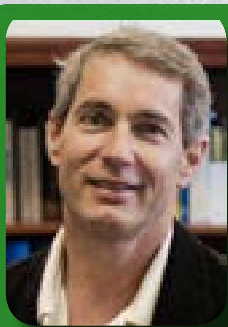


from the

Director

Dr. Kevin Tomsovic

Dear CURENT colleagues and supporters,

The CURENT Newsletter is one way we update you about our recent accomplishments and upcoming events.

In this issue, we highlight some recent research results in data security from Dr. Stella Sun and linear state estimators from Dr. Ali Abur. We also include work in the area of data analytics for synchrophasor's data by Dr. Meng Wang and Dr. Joe Chow. This work stems from our DOE project ***Data Architecture and Analytics***. This important endeavor touches on many of the ongoing research projects at CURENT and we have included a section about this effort in the newsletter.

We continue to increase our involvement with our industry partners. Since the beginning of 2015, our industry members have provided over 20 of our students with internships. We also offer industry seminars once a month to our members students. These seminars give our students a chance to learn from experienced industry professionals. We also plan to continue with our monthly project reviews and co-sponsorships of industry meetings and research conferences. Please let us know what we can do to make these reviews more effective.

Our annual Industry Meeting and Site Visit is set for Oct. 6th through 8th. The annual meeting will highlight our accomplishments as well as provide the forum for the annual NSF and DOE evaluation of the Center. Your participation is critical to us showing the value of the Center work. This meeting is also a good time for you to see all the work of the Center. We hope to have as many people from your organization as possible.

As CURENT wraps up its fourth year, I want to take a moment to thank all of you for your support and participation in our center. We have now firmly established our programs and are hopefully moving into a phase where we can have even more impact on the industry. Thank you for all you've done to support the Center.

Please feel to let us know if there are ways that we can provide more value to your organization. Your feedback and comments are important to us.

Sincerely,

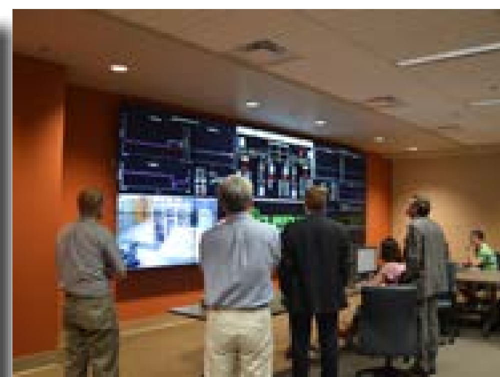
Kevin Tomsovic

in this issue

Research Highlights

Education & Student News

Industry Highlights



Meet our new Administrative Director - Pam Arrowood

Pam Arrowood is the newest member of the CURENT staff and serves as our AD (Administrative Director). She has many years of experience in transactional accounting, financial reporting and financial management. She is a proven leader and mentor. Pam comes to CURENT from a corporate science and technology background and her skillset has already made her an invaluable member of CURENT. When Pam is not crunching numbers or managing projects, she enjoys spending time with family, visiting the Great Smoky Mountains National Park and being outdoors in the beautiful lake and mountain areas of East Tennessee.

Northeastern

THE UNIVERSITY OF TENNESSEE KNOXVILLE

A Low-Rank Matrix Approach for the Analysis of Large Amounts of Power System Synchrophasor Data

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

With the installation of many new multi-channel phasor measurement units (PMUs), utilities and power grid operators are collecting an unprecedented amount of high-sampling-rate measurements of bus frequency, bus voltage phasor, and line current phasor with accurate time stamps. The data owners are interested in efficient algorithms to process and extract as much information as possible from such data for real-time and off-line analysis. Traditional data analysis methods typically analyze one channel of PMU data at a time and then combine the results from the individual analysis to arrive at some conclusions. We proposed a spatial-temporal framework for efficient processing of blocks of PMU data. A key property of these PMU data matrices is that they are low rank. Using this low-rank property, various data management issues such as data compression, missing data recovery, data substitution detection, and disturbance triggering and location can be processed using singular-value based algorithms and convex programming.

Fig. 1 illustrates data management through processing spatial-temporal blocks of PMU data. Figs. 2-4 illustrate the low-rank property of PMU data blocks from PMU data obtained from six multi-channel PMUs deployed in the Central New York (NY) Power System (Fig. 2). Six PMUs measure thirty-seven bus voltage and line current phasors in total. Fig. 3 shows the current magnitudes of PMU measurements in twenty seconds at a rate of thirty samples per second. Fig. 4 shows the singular values of the data matrix. Despite its high dimensionality (37 by 600), the number of significant singular values is very small. Therefore, the data matrix can be approximated by a low-rank matrix.

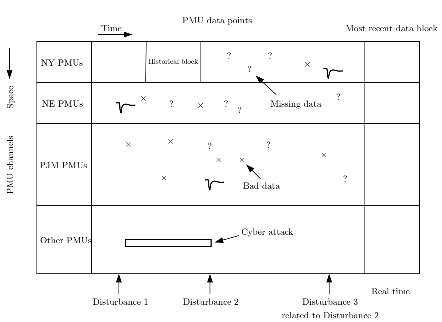


Fig. 1 - Spatial-temporal PMU data blocks for multiple tasks

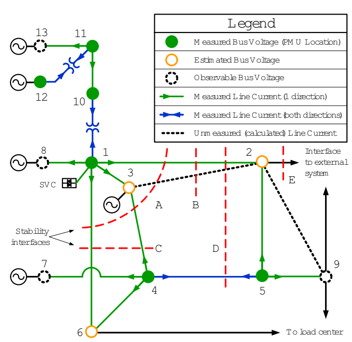


Fig. 2 - Locations of Six PMUs in the Central NY Power System

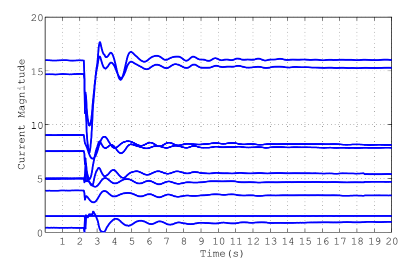


Fig. 3 - Current magnitudes of PMU data (9 current phasors out of 37 phasors) in 20 seconds

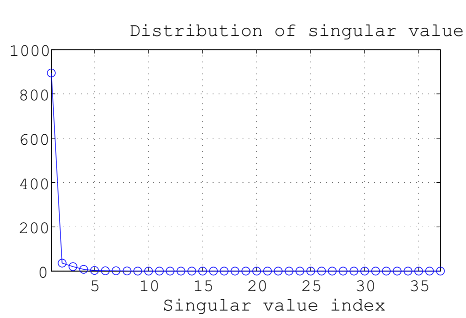


Fig. 4 - Singular values of a 600 × 37 PMU data matrix

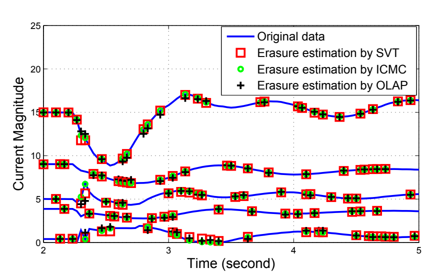


Fig. 5 - Missing data recovery by different recovery methods

We exploited this low-rank property of PMU data matrix for multiple data management tasks. Take missing data recovery as an example. Data losses can happen in an unpredictable way during the communication between PMUs and the phasor data concentrator at the central operator. Losing measurements makes the system unobservable and degrades the performance of the state estimator. We formulated the missing data recovery problem as a low-rank matrix completion problem and developed computationally efficient data recovery methods. Fig. 5 compares the recovery performance of multiple recovery methods. For the dataset shown in Figs. 2~4, even when 30% of the measurements are lost at random locations, our methods can accurately recovery the missing points. Using MATLAB running on a desktop with Intel i7-4770 @ 3.40GHz and 12 GB DDR3 RAM, our developed online data recovery method took less than 1 millisecond to fill in the missing points in each sampling instant. Hitachi America is interested in implementing our methods in their prototype of new remedial action scheme (RAS) for Bonneville Power Administration (BPA).

Fun Fact -

Did you know that data loss and computer downtime can cost enterprises $1.7 trillion per year or the equivalent of nearly 50% of Germany's GDP?

faculty spotlight

Professor Meng Wang is e the newest CURENT faculty member. She says, "CURENT is a unique organization that brings people of diverse backgrounds and expertise together. The intellectual communication within CURRENT happens very naturally and smoothly and I really enjoy the synergy of our research. It is exciting and fun to be a team member here."

Prof. Wang is also an assistant professor in the Department of Electrical, Computer and Systems Engineering at Rensselaer Polytechnic Institute (RPI). She obtained her B.S. and M.S in Electrical Engineering from Tsinghua University in 2005 and 2007, respectively, and earned her PhD degree in Electrical and Computer Engineering from Cornell University in August 2012. She was a postdoc research scholar at Duke University before she joined RPI in Spring, 2013.

When asked how she came to the field of power systems in academia, Prof. Wang stated, "I like math and physics and wanted to explore fundamental science. I also like to know how things work and want to do something to contribute to everyday life. Electrical Engineering is a field that combines these two objectives perfectly. I can work on problems that have clear practical applications, while I still have the freedom to explore fundamental theoretical developments beyond applications. For example, one project that our group is currently working on is the data management and information extraction of large amounts of synchrophasor measurements in power systems. It is an important question in power system monitoring and operation. The techniques we develop exploit low-dimensional models of signals in high-dimensional space. These techniques are generic and thus can be applied to other fields like image processing, social network analysis, etc. This type of exploration makes academia a natural choice for me. I very much enjoy the freedom of research. Another big bonus of academia life is that I get to work with many brilliant students, both undergraduate and graduate students. I am happy to share my experiences and to learn with them."

Prof. Wang's current research focuses on high-dimensional data analysis and its application in power system monitoring. Her boarder research interests include signal processing, optimization and networked systems.

Welcome, Professor Wang!

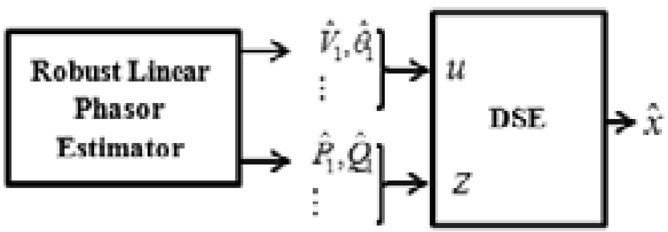
research highlights

Linear Phasor Estimator Assisted Dynamic State Estimation

by Dr. Ali Abur (abur@coe.neu.edu)

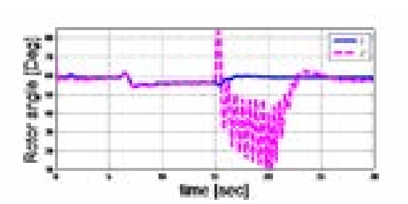
Real-time network and machine models are necessary for the dynamic security analysis of the power systems. In order to procure these models, dynamic estimators can be used in the system for tracking the state variables and parameters associated with these models in real-time. Numerous researchers have so far proposed power system dynamic state estimation algorithms in the literature. The effects of load dynamics and unpredicted topology changes in the system on the dynamic state estimation are typically neglected by these studies due to their short duration of interest for dynamic state estimation (DSE) results. On the other hand, if DSE is to run continuously, these need to be incorporated in the model. Furthermore it is necessary to maintain robustness of DSE in the presence of bad data.

In order to address these issues, a two-stage dynamic state estimator is proposed. Distinguishing features of the proposed estimator is its utilization of a robust linear phasor estimator for the phasor bus voltages; a partitioned zone-based approach to estimation, an unscented Kalman filter (UKF) based dynamic estimation for machine dynamic variables and a procedure for predicting the state variables of a generator for a few time steps ahead to reduce errors due to delays.

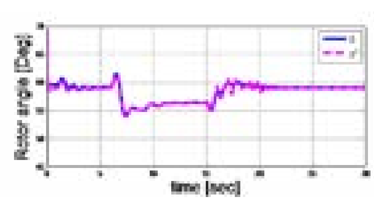


Block diagram of the proposed approach

The proposed estimator is implemented on a medium-size utility system with 140 buses and 48 generators including two-axis generators and IEEE-Type1 exciters. As an example the following figures show the robustness of this approach for estimation of rotor angle of one the generators under bad data.



Actual and estimated by using estimated measurements



Actual and estimated by using direct measurements

achievements

Dr. Fran Li received the 2015 College of Engineering Professional Promise in Research Award, which recognizes tenured or tenure-track faculty members at the assistant or associate professor rank who have received national and/or international recognition in their fields and show professional promise in their research. In the past five years, Dr. Li has published more than 40 journal papers and 50 conference papers and holds a US patent. He is an Editor of IEEE Transactions on Sustainable Energy, an Editor of IEEE Power and Energy Society Letters, a Guest Editor of IEEE Transactions on Smart Grid, the Vice Chair of IEEE PES Power System Planning and Implementation (PSPI) committee, and a registered Professional Engineer (P.E.) in the state of North Carolina.

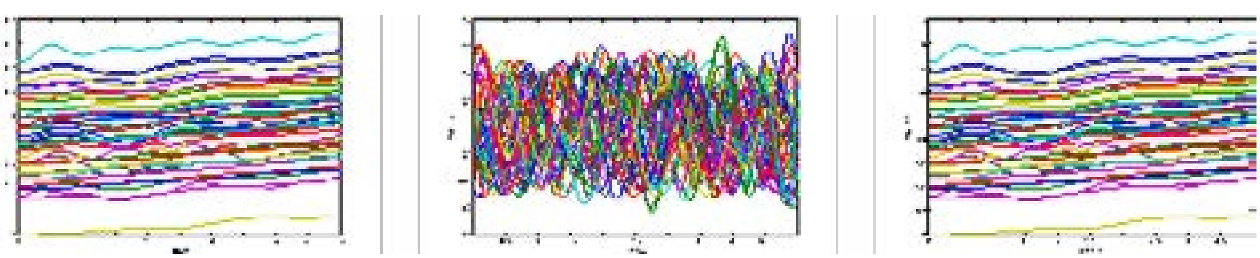
Secure Outsourcing of Power System Data Analysis and Computation for Efficient Operations of The Grid

by Dr. Kai Sun (kaisun@utk.edu) and Dr. Jinyuan Stella Sun (jysun@utk.edu)

At present, the control center of a power utility company or transmission operator is the unique location to gather and analyze raw measurement data from the grid and to perform computation essential to grid operations, e.g., state estimation, contingency analysis, oscillation mode analysis, and time-domain power system simulation. With the growing penetration of intermittent renewable resources and responsive loads, the grid for real-time monitoring and control will significantly expand in three dimensions: the complexity of the system model, the volume of online data, and the length of the required simulation period. Computational burdens will be exponentially increased if all analysis and computation are handled at control center.

At CURENT, we developed a viable solution leveraging the cloud to provide computational resources needed by utilities in a secure manner, i.e., outsourcing fully protected data from one or multiple utility companies while allowing the cloud to perform big data analysis and computation over such protected data. This technology, if deployed at a utility company, will greatly improve the company's online data analysis and computing capabilities for grid operations without incurring high cost or data security breaches. Specifically, we developed novel outsourcing algorithms for two representative types of power system computation involving algebraic equations and differential-algebraic equations: Cross-utility data analysis and computation, two examples of which include real-time multi-company inter-area oscillation analysis and multi-company collaborative state estimation and powerflow-based contingency analysis; and Real-time time-domain power system simulation.

Fig. 1 shows the experimental results for power system time-domain simulation where computationally expensive differential equations are outsourced. We implemented the injective mapping-based outsourcing technique with Power System Toolbox on the NPCC 48-machine, 140-bus power system model. Fig. 2 shows the results for inter-area oscillation analysis where synchrophasor data is needed from multiple PMU clusters owned by different utilities and is securely outsourced for spectral estimation. We implemented the homomorphic encryption-based outsourcing technique with Java's BigInteger library and Paillier cryptosystem. The spectrograms of the encrypted and recovered data with meaningful oscillation modes are shown in Fig. 2.



(a) Original machine angles b) Disguised machine angles (c) Recovered machine angles

Fig. 1: Injective mapping-based outsourcing technique for power system time-domain simulation.

a) Encrypted spectrogram of the cluster angle (b) Recovered spectrogram of the cluster angle

Fig. 2: Homomorphic encryption-based outsourcing technique for spectral estimation in oscillation analysis.

Compared with the traditional time-domain simulation that is conducted locally, the outsourcing approach could achieve an order of magnitude speedup. The computational overhead incurred by the outsourcing approach was only about 2% which was absorbed by the total runtime saving due to the faster processing of the cloud. The outsourcing approach can accurately and reliably produce correct computation results, as if it were operating on the original data. Our implementation only requires new software development.
In the future, we will enhance the security of the injective mapping-based solution with garbled circuits which guarantee provable security but will increase the computational complexity. We also plan to extend the inter-area oscillation analysis by developing a secure Prony analysis which considers damping and mode shape.

Detection, Recognition, and Localization of Multiple Cyber/Physical Attacks through Event Unmixing

Probably the best way to summarize the uniqueness of CURENT's cybersecurity research is that it focuses on "Measurement-based Cyber Physical Security". The goal of measurement-based cyber-physical security (CPS) is two-fold, to maintain the fidelity (i.e., security and quality) of the measurement in order to facilitate the subsequent data analyses, and to use the measurement data to identify the sources of security breaches. Most existing research activities focus on "cyber" security and "physical" security has been largely neglected. Physical attacks are more easily orchestrated and launched (does not take a college degree), leading to a more vulnerable power grid system. We solve the security issue by taking advantage of the intercorrelation between the physical law and behavior of physical devices as well as features of information flow, adding another dimension to the security research.

Cyber and physical attacks are intertwined components of power grid security, where the physical element could be aimed at destabilizing the system and inflicting some lasting damage, and the cyber element could focus on blinding the operator to the true nature of the problem, inhibiting defensive responses. Regardless of the sources of attack, the net effect is always reflected in the measurement data as changes to the voltage, current, and frequency. Therefore, accurate detection and in-depth understanding of this change is essential to the power grid security.

This project focuses on the study of multiple coordinated attacks. The objective is to detect, recognize, and localize attacks from multiple sources through sound mathematical techniques using data provided from the ultra-wide-area monitoring network (e.g., FNET/Grideye). With more in-depth understanding of the attacks, the outcome of this research can serve power electronics actuators with more accurate situation awareness, turning a large volume of real-time data into actionable information, improving the effectiveness of response, and contributing to the construction of a resilient power grid.

When multiple coordinated attacks occur in cascading fashion, the measurement taken at the sensor, e.g., the frequency disturbance recorder (FDR), would more than likely be a "mixture". Existing approaches can only detect the initial event.
In this research, we propose a new conceptual framework in the study of multiple attack analysis, referred to as "event unmixing", where we consider the real-world events (e.g., attacks) sensed at each FDR as a linear mixture of a limited number of constituent root events, including generator trip, load shedding and line trip. This concept is a key enabler for analysis of events to go beyond what are immediately detectable in a system, providing high-resolution data understanding at a finer scale.

achievements

Dr. Kevin Tomsovic received the 2015 College of Engineering Research Achievement Award, which recognizes tenured faculty members with more than 10 years in tenure line who have received national and/or international recognition in their field, who stimulate research and creative achievement, and who also emphasize that faculty research is integral to the mission of the College of Engineering.

We proposed the nonnegative sparse event unmixing (NSEU) algorithm where we interpret the event formation process from a linear mixing perspective and simultaneously detect the type of physical attacks and the starting time of the attacks in one unmixing procedure. However, due to the high intra-class difference and the high inter-class similarity, as well as system nonlinearity, NSEU would not perform well for large systems. We discovered that although for the same event, very different signal profiles are collected at different buses, there exists a stable grouping characteristics in the grid, where within the same group, the behavior of the acquired signals are similar. This grouping feature remains the same for different types of events. Based on this discovery, we have developed the cluster-based NSEU (c-NSEU) that would achieve high accuracy event for large and complex systems.

Future research includes how to perform multiple attack analysis across different control areas and how to do it in a real-time fashion where the window size is largely reduced.

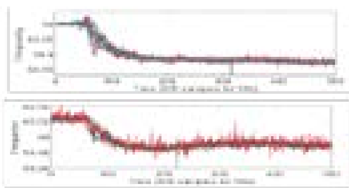


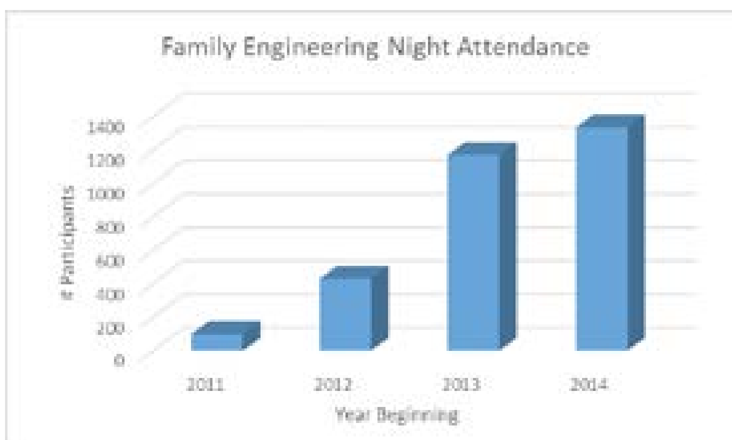
Fig. 1: Difficulty in event unmixing – Comparison on frequency readout from FDRs for single event with one generator trip (GT) (top) and multiple events with two GTs and three line trips (LTs) (bottom).

Fig. 2: The multiple event analysis results are obtained based on the large scale testbed developed at the CURENT center, where the Eastern Interconnection is modeled using 140 buses. We observe c-NSEU yields much improved detection and recognition accuracy while maintaining a very low false alarm rate as compared to NSEU.

education highlights

Family Engineering Night

At the end of the 2013, we were quite proud of the improvements we had made to the outreach programs. Our early grades program had expanded from a few hundred family members experiencing the enjoyment and creativity of engineering to over a 1,000 people experiencing our fundamental engineering activities. With high expectations for 2014-2105 school year, improvements were made to existing activities and new activities were added into our portfolio. Total attendance for the past year was over 1,300 parents and students, but what was more impressive is that we exceeded the previous year's total with one fewer event. The average attendance of our events now exceeds 200 people.



Starting in the fall of 2014, CURENT has worked with local middle school teachers to develop an "Energy in a Box" curriculum. The concept is to develop complete lessons that emphasize renewable energy and provide the plans, materials, and other helpful resources in a transportable container. The first version of the box contains permanent magnets, electromagnets, wind turbines, solar panels, generators, sterling engines, different light technologies, and electricity meters. Testing of the box may occur in Knox County School as early as the fall semester.

Statistics and Parent Quotes

Total parents and students reached: 3,000 Total feedback from parents and students: 1,200

"Love the hands-on child directed learning that was not only developmentally appropriate for many ages, but was fun and involved parents, too! FANTASTIC!"
"This is one of our favorite events. Thank you!"
"This event is a family favorite and has fostered a love for science and problem-solving in my daughter."
"We will try a few @ home"

Student built solar “cars”

Girl’s camp

Girls Camp and MITES

Over the summer of 2015, CURENT organized two weeklong middle school events. We created curriculum for the MITES8 (Middle School Introduction to Engineering Systems for Eighth Graders) program and organized the 3rd Annual Girls-Only STEM Camp. Both camps explored the concepts of how the power grid operates by using hands-on activities. The final project had the students creating a small power grid that included houses with multiple LED lights, transmission lines spanning the width of the room, and wind turbines that provided the power to operate the system. This project was created, as well as other activities explored, over the course of approximately 14 classroom hours. The programs also included discussions with engineers to learn about their careers, field trips to the American Museum of Science and Energy, and building tours of the Power Systems and Power Electronics Labs.

Girls Camp: 25% satisfied + 75% very satisfied = A successful summer camp

What did you like most?

“I enjoyed interviewing people. Doing this helped me to realize how hard, confusing and fun engineering and science can be!”

“I loved doing more hands on activities without instructions because it gives us more room for creativity.”

“Doing the solar car, wind turbine, and circuits. Because we got hands on experience, no help.”

“I gained knowledge on how the electric grid works in how the different forms of energy can help create mechanical energy into electrical energy”

“I’ve learned how other energy is made, how energy is transported and created”

congratulations

Three papers by CURENT students and faculty have named for best conference paper awards at the 2015 IEEE PES General Meeting held on July 26-30 in Denver, CO. The paper titles and authors are listed below. Congratulations to all the authors!

Paper #1: Universal Grid Analyzer Design and Development Authors: Lingwei Zhan, UTK; Jianyang Zhao, UTK; Shengyou Gao, Tsinghua University; Jerel Culliss, UTK; Yong Liu, UTK; and Yilu Liu, UTK

Paper #2: Measurement Accuracy Limitation Analysis on Synchrophasors Authors: Jiecheng Zhao, UTK; Lingwei Zhan, UTK; Yilu Liu, UTK; Hairong Qi, UTK; Jose R. Garcia, ORNL; and Paul D. Ewing; ORNL

Paper #3: A GPS-free Power Grid Monitoring System over Mobile Platforms Authors: Haoyang Lu, UTK; Lingwei Zhan, UTK; Yilu Liu, UTK; and Wei Gao, UTK

Summary of the Next Generation Grid Data Architecture and Control Workshop

The Next Generation Grid Data Architecture and Control Workshop was co-sponsored by CURENT and NRECA (National Rural Electric Cooperative Association) on behalf of the U.S. Department of Energy (DOE) Office of Energy Delivery and Energy Reliability and the National Science Foundation (NSF) on November 17 and 18, 2014, at facilities provided by the NRECA in Arlington, Virginia. The purpose of the workshop was to assemble experts on information management and the electric grid domain to define objectives and identify research gaps in the data architecture necessary to support advanced grid modeling and analytics. The workshop had over 75 participants representing vendors, utilities, national laboratories, research institutes, academia and other stakeholders.

The workshop discussion highlighted two disparate architectural approaches - application centric vs. data centric architectural and suggests a research roadmap that addresses these two main alternatives. It was determined that further research is needed on how these two approaches can be aligned and iterated to converge toward an overall solution.

High-level workshop discussion themes were used to develop a roadmap for future research that are summarized as follows:

1. Produce a top-down, application-oriented data architecture and taxonomy at a high level that can serve as a reference standard (not mandated, but one that emerges as an implementable consensus).
2. Build a well-defined bottom-up set of use cases for innovative data exploitation that drives the data architecture and analytics requirements and that:
   - Includes consumption and distribution of information among multiple data sources and sinks including data hosted in the cloud
   - Includes specific examples of high data rate and high data variety information sources and sinks
   - Accommodates methods to improve data quality
   - Challenge the research community to develop affordable, new analytics and applications
   - Addresses the challenges of sharing data among utilities and system operators
3. Based on an alignment of the top-down and bottom-up approaches, create a data service framework from open source components that addresses use-case requirements.
4. Select a technique successfully used within other industries (e.g., the healthcare or the financial sector) that can be applied to the management of utility metadata.
5. Conduct demonstrations within the electric industry across diverse application domains for implementation of the metadata management solution and data service framework.

Our 2015 site visit is coming up in October. Mark your calendars. We hope to see you then.

internships

Recent internships for CURENT students:

Micah Till - ABB
Yutian Cui - ABB
Xin Fang - Dominion
Jared Baxter - ORNL
Micah Till - Dominion
Haoyu Yuan - ABB
Linquan Bai - ABB
Jidong Chai - PJM
Jessica Boles - ORNL
Benjamin Dean - Southern Co.
Guangyu Feng - Mitsubishi
Ailin Asadinejad - MISO
Bin Wang - ISO New England
Wei Li - Royal Institute of Technology
Jason Guo - Dominion
Jidong Chai - China Southern EPRI
Hesen Liu - Dominion
Yu Xia - ISO New England
Xiaohu Zhang - ORNL
Genevieve De Mijolla - ISO New York
Bin Wang - ISO New England
Christoph Lackner - ISO-New England
Ashlund Nicholas - Rockwell Collins
Saptarshi Bhattacharya - IBM Reseach
Stephanie Steren-Ruta - Southern Co.
Weimin Zhang - Tesla Motor Co.
Qinran Hu - ORNL

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