Wide-Area Control & Associated Cyber-Physical Challenges for Next Generation Smart Power Systems using the Synchrophasor Technology

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My current research spans the fundamental areas of mathematical modeling, dynamic data analysis and nonlinear control of large-scale electric power networks using cutting-edge measurement and instrumentation technologies such as Wide-area Phasor Measurement Systems (WAMS). Since the past four years I have been involved with several system and control theoretic research problems for the US power grid, especially for the US west-coast power system (WECC), using the WAMS technology, and lately with various fundamental problems on integration of conventional power grids with renewable energy sources such as wind energy. In the Electrical & Computer Engineering department of Texas Tech I direct the *Phasor Lab*, where graduate and undergraduate students are currently performing high-quality, multi-disciplinary applied research in power and energy systems. The main themes of current interest to us are :

1. Development of concrete mathematical frameworks to address challenging and pertinent problems on WAMS-based modeling, control and optimization of geographically distributed interconnected power systems, especially from a *network* point of view.
2. Data analyses, pattern recognition and visualization of power system dynamics involving both large and small-scale generation networks.
3. Cyber-physical interpretations of power system operations through a successful integration of WAMS-based sensing and FACTS-based actuation technologies with underlying problems in computation, topological dynamics, communication constraints, etc.
4. Modeling, integration and control of alternative energy sources with experimental validations and hardware testbeds.

Our efforts are geared to provide a much-needed, timely infusion of dynamic system-theoretic ideas for advancing technical research on smart grids. We have recently been donated a package of digital relays by Schweitzer Engineering Laboratories, Inc. (SEL) serving the functionalities of a Phasor Measurement Unit (PMU), as shown in the adjoining figure. Two modules of compacRIO real-time power controllers from National Instruments with a GPS-clock and associated Labview interface, and a Frequency Disturbance Recorder (FDR), gifted by the Power IT lab of Virginia Tech, are also housed in this space.

These modules are currently taking electrical measurements from the wall outlet, performing data analysis and displaying the results through a visualization software. We are measuring massive volumes of real-time voltage and current phasor data and developing algorithms to illustrate how they can be meaningfully interpreted to understand complicated, nonlinear dynamic behavior of a power grid following both small and large disturbances. This knowledge can further be utilized for actuating proper wide-area control mechanisms to ensure better performance and security of the system, both locally and globally.

A brief list of topics that are currently being investigated in PhasorLab is as follows.

1. **WAMS-based System Identification and Performance Monitoring of Large Power Systems** :

   One often hears power system operators mentioning how 'Northern Washington' oscillates against 'Southern California' in response to various disturbance events. The main question here is whether one can analytically construct dynamic electro-mechanical models for these conceptual, aggregated generators representing Washington and California, which in reality are some hypothetical combinations of thousands of actual generators. The goal of this project is to develop a unified framework of analytical procedures by which such *equivalent* electro-mechanical power system models can be identified, not by the traditional approach of modeling each individual component in the network, but by using PMU data available from a limited number of points in the network. The developed aggregated models are used for formulating performance metrics that provide an in-depth visibility of the *wide-area* dynamics of the grid, and help power system operators in assessing the possible vulnerabilities of their systems with respect to neighboring interconnections. Concepts of nonlinear circuit theory, fundamental physics, signal processing and graph theory are being used for such measurement-based model reduction.

2. **Understanding Disturbance Propagation from PMU Data Patterns :**

   In order to initiate foundational thoughts on controlling and robustifying a power grid from external disturbances in a smart way, we first need to understand how the dynamic effects of large nonlinear disturbances disseminate or 'spread' spatially through the network, and how the stability or instability inherent in such disturbance modes can be efficiently captured from oscillation patterns in voltages and currents measured by PMUs at different points in the network. Using ideas from network theory and pattern recognition theory we are developing analytical models of disturbance-spread in a power system network for any network graph/topology, and also quantitatively defining the strength and immunity of the grid depending on which a disturbance may die out quickly or become catastrophic and wide-spread.

3. **Cyber-Physical Challenges in WAMS Research :**

   A significant challenge behind the afore-mentioned methods on model aggregation and disturbance identification is the implementation of these algorithms in real-time. Assuming that each aggregated cluster in the network is equipped with its own localized processing computer (technically referred to as a Phasor Data Concentrator or PDC) each area-specific PDC must build its own area-model using local PMU measurements, and then exchange information about this model with other PDCs to derive the global interconnection structure between the clusters. Next, based on this development, appropriate *global* control actions need to be designed for interarea damping, which will pose further challenges in control-allocation as in reality these control actions must be actuated through individual *local* controllers distributed arbitrarily across the network. Significant research needs to be done to define these problems in clear mathematical terms.

4. **Modeling and Integration of Renewable Energy Sources :**

   A new area of our current research is to identify equivalent dynamic models of renewable energy sources, mainly wind power systems, from PMU measurements collected from terminal high-voltage buses. Our aim is to understand how the cumulative action of the dynamic components of the wind power unit together with typical operational uncertainties such as blade noise, high-frequency converter chattering, and discontinuous service of the wind turbine, when integrated with a conventional power grid, may corrupt its modal oscillation patterns and dynamic visibility.

By virtue of our involvement with the Power Systems Research Consortium (PSRC) and the North American Synchrophasor Initiative (NASPI) since the past three years, we have had the opportunity to collaborate with a wide network of power system researchers, both from academia and industry. PhasorLab currently receives real-time PMU data from actual power system disturbance events from several substations in the WECC through a non-disclosure agreement with Southern California Edison. We are currently in talks with American Electric Power and Oncor Electric Delivery, two of the most accomplished Texas-based power utility companies, for sharing power system data from their substations in East Texas as well as the future wind-based power stations in Panhandle Texas with the goal of developing an in-house Texas smart power data network. We are also collaborating with the Wind Engineering and Science Research Center (WISE) of Texas Tech for our wind energy projects.