Mini-course at MTNS 2014, Groningen, The Netherlands

Role of Graph Theory in Modeling, Analysis and Control of Electric Power Systems

Aranya Chakrabortty and Thomas R. Nudell

North Carolina State University, Raleigh, NC, USA
Emails: achakra2@ncsu.edu, trnudell@ncsu.edu
Website: http://people.engr.ncsu.edu/achakra2

Motivation & Objectives

In this 21^{st} century, electric power engineering is gradually going green and smart. Triggered by several recent catastrophes such as the major blackout in the Northeastern USA in 2003 and Hurricane Katrina in New Orleans in 2005 together with the Energy Act of 2007, the term *smart grid* has become almost ubiquitous across the world not only as a political concept but also as an entirely new technology that requires tremendous amount of inter-disciplinary research. As a part of this enterprise, for example, power engineers are investigating efficient and intelligent ways of energy distribution and load management, computer scientists are researching cyber-security issues for reliable communication of information across the grid, the signals community is looking into advancing instrumentation facilities for detailed grid monitoring, wind engineers are studying renewable energy integration while business administrators are reframing power system market policies to adapt to these new changes in the system.

However, majority of the so called smart grid *'control'* problems so far have either been addressed very incrementally, or have been defined in a broad and intuitive way without rigorous mathematical formulation, thereby impeding control theorists to relate face-to-face with this technology. Motivated by this gap in understanding, we propose to organize this mini-course (125 minutes) in MTNS 2014 to inform and educate our control audience, especially young students and scientists, about the tremendous potential of control theory in modern power system research. Our discussion will be particularly geared towards one of the most critical aspect of power system modeling and control, namely - graph theory. Graphs and networks play an ubiquitous role in power system dynamics. Starting from simple electro-mechanical oscillation models of interconnected synchronous generators and loads to more complex nonlinear mechanisms of bifurcation, voltage collapse and cascading failure, almost every aspect of how a power system reacts to external disturbances depends on the characteristics of its underlying network graph. Therefore, a perennial question of interest to power system operators is how this network graph may be designed during *planning*, or manipulated during *operation* in order to guarantee stability, robustness and quality-of-service following large disturbances. These questions are, in fact, becoming more and more critical with every passing day due to increasing load demand and resulting transmission expansion, injection of new loads such as plug-in hybrid vehicles and smart buildings, and penetration of intermittent renewable energy resources such as wind and solar power, etc., all of which have significant impact on the network topology, and therefore on the system dynamics. Added to this is the recent outburst of sensing and actuation technologies in both utility-scale and residential power systems that brings up numerous graph-theoretic questions on network identifiability, controllability and observability. Integration of conventional grids with large-scale communication networks for wide-area protection and control too motivates the need for developing multi-agent, distributed control designs using tools from network optimization.

Motivated by these examples, our goal in this mini-course is to educate control engineers about advanced models and control laws for power systems, to formulate problems on making these controllers *smart* (or, self-automated), and to point out how graph theory can play an instrumental role in solving these problems. The total duration of the tutorial will be 125 minutes. It will consist of 3 talks of respective lengths 50 minutes, 50 minutes, and 25 minutes. Details of these talks are given as follows.

Time schedule

Talk	Duration	Title	Speaker
Talk 1	50 minutes (25 min + 25 min)	Role of Graph Theory in Modeling and Identification of Power System Networks	Aranya Chakrabortty
Talk 2	50 minutes (25 min + 25 min)	Wide-Area Monitoring and Cyber-Security of Power Grids	Thomas Nudell
Talk 3	25 minutes	Wide-Area Control of Power Systems	Aranya Chakrabortty

Description of Talks

- **Talk 1: Role of Graph Theory in Power System Modeling & Identification** - This 50-minute talk will cover the following topics:

  1. Power system models - review of basic electro-mechanical and electro-magnetic dynamic models of synchronous generators, swing equations with asymmetric Laplacian structure, differential-algebraic models for power balance, load models, structure-preserving network models, Kron reduction.
  2. Model reduction - advanced ideas of clustering, coherency, and aggregation of power system network graphs, model reduction via singular perturbation and its graph-theoretic interpretation, dynamic equivalent models.
  3. Oscillation analysis and identification- detailed derivation of complex eigenvalues from swing equations using graph Laplacian, separation of eigenvalues due to clustering and coherency, definitions of local and inter-area oscillations.
  4. Graph-theoretic interpretations of identifiability - a brief discussion on how network topology affects identifiability of power system models, associated sensor placement algorithms that guarantee uniqueness of identification.
  5. Ending discussion on how conventional modeling techniques will change with large-scale wind penetration.

- **Talk 2: Wide-Area Monitoring & Cyber-Security of Power Systems** - This 50-minute talk will cover the following topics:

  1. Transient stability monitoring - definition of transient stability, derivation of Lyapunov energy functions for evaluating transient stability, dependence on network graphs.
  2. Localization of disturbances and malicious attacks - brief introduction to nodal domains of graphs using Laplacian eigenvalues and eigenvectors, preliminary applications of nodal domains in multi-agent consensus networks, extension to synchronization models in power systems, use of nodal domains for attack localization, detection of malicious oscillations in generator circuits due to controller failures.

- **Talk 3: Wide-Area Control of Power Systems:** - This 25-min talk will cover the following topics:

1. Power flow control and synchronization - adaptive control of linear Power System Stabilizers (PSS) for power oscillation damping and synchronization of grid frequency following small-signal disturbances, example of lead-lag PSS design for a single-machine infinite bus power system model using root-locus techniques
2. New control technologies - brief overview of new technologies such as HVDC (High Voltage DC), FACTS (Flexible AC Transmission Systems) and WAMS (Wide-area Measurement Systems)
3. Impact of network delays - overview of stability conditions for PSS/FACTS control with communication delays, interaction between graph topologies of physical and cyber networks, interaction between continuous-time dynamics of power system and discrete-time dynamics of communication network, arbitrated network control conditions using Linear Matrix Inequality (LMI), game theory for wide-area control.

All the talks will be made interactive to promote participation from the audience. Matlab demos, visualization charts, graphics and videos will be shown as much as possible to illustrate theoretical concepts. A detailed handout listing references to online study materials for further reading, links to prototype IEEE models of power systems, and to open-source power system software codes will be provided to the attendees at the end of the course.

Our target audience for this course are faculty members, postdoctoral researchers, masters and doctoral students, and industry practitioners who want to learn about the recent advancements in the field of power system dynamics and control. The session will provide a much-needed thrust to power system education for control engineers, especially for new graduate students who are looking for fresh research problems to work on. We will encourage graduate students in the audience to interact with the speakers after their talks, thereby promoting the chances of collaborative research as well as industrial internships. In between the talks, students will also be informed briefly about new strides in energy research currently being undertaken by organizations such as the Future Renewable Electrical Energy Delivery and Management (FREEDM) sponsored by the US National Science Foundation (NSF), and encouraged to join similar other energy forums going on currently in the US and Europe, especially in the Netherlands. The overall effort, therefore, will be an excellent opportunity to promote next-generation smart grid research in the networks and controls community.