EE527, Net-Centric Power-System Control
Units: 03
Term: Fall 2018; Day: Tu, Th; Time: 5:00-6:20 pm

Location: DEN, RTH115

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IT Help: Group to contact for technological services, if applicable.
Hours of Service:
Contact Info: Email, phone number (office, cell), Skype, etc.
Course Rationale

No sooner than the recent 2016 IEEE International Conference on Smart Grid Communications, some concern was still raised as to what the so-called “smart grid” really is. Historically, it was developed for economic reasons: competition in the electricity market to allow consumers to purchase their electricity at the cheapest price. This already had the unforeseeable effect of creating large transport of power across the country, overloading the lines with the potential for blackouts. Another significant attribute of the smart grid is its increasing reliance on renewables, which have the effect of injecting fluctuations in the grid, calling for stochastic analysis. “Smartness” of the grid probably stems from the massive amount of sensors that are currently deployed and the utilization of those measurements for control purposes. Unfortunately, everybody with ordinary skill in the control art understands that the more feedback loops are closed, the more the potential for problems such as instability. This is the “dark” aspect of sensors. On the positive side, the very accurate PMU sensors allows for monitoring the grid with unprecedented time resolution, making it possible via statistical signal processing to detect false data injection and to anticipate blackouts before they become catastrophic.

Power grid versus information grid topology
There has been a tremendous amount of activity on the topology of the information grid. Such concepts as Scale-Free networks, Small-World networks, betweenness centrality, etc. have dominated the Internet publication arena over the past 15 years. However, this line of research has shown signals that, on the one hand, it is running out of steam and, on the other hand, that it might not have captured the topological features of real power, communication, transportation, and other networks. This has created a still ongoing revolution in the field, trading the old concept of Scale-Free networks for negatively curved Gromov and Ollivier-Ricci hyperbolic grids, a revolution that is currently pervading the power grid. The universal acceptance of the concept of Gromov hyperbolic networks and Ollivier-Ricci hyperbolic networks stems from the fact that, in the information grid, it is closely related to congestion and queue overflow and, in the power grid, it is related to line overloading.

Power grid versus information grid security
Among the aspects making the power grid “smart” is the massive deployment of Phase Measurement Units (PMUs), which provide the sensing information that reflects the state of “health” of the grid. Unfortunately, sending the PMU’s across the grid via classical “secured” information technology for possible (centralized) control action makes the grid vulnerable to attacks, especially false data injection. In particular, in this course, we will focus on the recent stealthy deception attack, against which no protection has yet been found.

Course description: Four parts

Part 1 (“Power Network”)
The first part of the course will be taught from the “networking” point of view. It is heavily graph-oriented. It will proceed from basic electrodynamics (synchronous generator, transmission lines, loads, adaptation, active & reactive power, power flow equations), from where bus models will be formalized in the context of graph theory—in particular, “resistive networks” together with spectral graph theory (Laplacian operator). This formalization will be geared towards a better understanding of “congestion,” interpreted in the sense of line overload. A betweenness centrality concept able to anticipate congestion will be developed. From a more modern mathematical viewpoint, it will be shown that line overload occurs along negatively curved paths. The impact of fluctuations of renewables (e.g., wind farms) and pricing on congestion will also be addressed.

Part 2 (“Security”)
This part deals with defense mechanisms against (possibly “stealthy”) false data injection attacks of the State Estimator (SE). The approach relies on the machine learning technique of “graphical models.” A
graphical model of the bus phase angles is compared with the actual grid topology and, should a discrepancy be observed, the red flag is raised that some data tampering has happened.

**Part 3 (“Control”)**

Part 3 is centralized around the concept of reactive power flow and voltage stability. We will first review static voltage collapse together with static load modeling. Then we will unravel the hidden feedbacks in the power grid and proceed towards the less well understood concept of dynamic voltage collapse together with dynamic load modeling.

**Part 4 (“PMU Signal Analysis”)**

The last part of the course deals with statistical PMU signal analysis. It will be shown that PMU signals are fractal as a result of an aggregation of load effect. Most importantly, it will be shown that before a voltage collapse appears imminent, the AR(1) coefficient and Hurst exponents of frequency PMU signal both increase. The increase will be statistically confirmed using the Kendall tau and the Jonckheere-Terpstra rank correlation.

**Learning Objectives**

In summary, the “smart grid” is a multi-disciplinary venture and this course only claims to cover some of its aspects. Nevertheless, we will try to make this course of relevance to control, computer engineering, and power students. At the end of the semester, students will be able to get the symbiotic picture of the “smart” grid.

**Prerequisite(s):** Basic linear feedback control (EE482); good working knowledge of linear algebra (EE441); Linear System Theory (EE585) is not a “must,” but is desirable as a “recommended preparation.” Some familiarity with nonlinear systems (especially the describing function also referred to as equivalent linearization) would be helpful, but not required, as the basic nonlinear theory will be covered in a self-sufficient manner.

**Software, Matlab, etc.** Familiarity with Matlab will be assumed. In the course of the semester, MATPOWER will be reviewed and students will be required to become familiar with it and utilize it in homework assignments.

**Course Notes**

**Grading Type:** letter grade

The course is Web-Enhanced (Blackboard). Copies of lecture slides and other class information will be posted on Blackboard. Classroom utilization of Matlab and Mathpower will be used as multimedia/technology-enhanced learning strategies.

**Technological Proficiency and Hardware/Software Required**

Students will be assumed to be familiar with Matlab.

**Required Readings and Supplementary Materials**

It is difficult to find a textbook that covers all that has to be covered, especially since this class deals with a topic that has only very recently taken shape. Nevertheless a recommended text that comes close to the spirit of this class is

Furthermore, the instructor will provide a bundle of notes & papers that cover fairly well the topics of the class.

Additional (suggested) readings:

- J. A. Hall, Strategic environmental research and development program statement of need for FY08; Sustainable infrastructure (SI) new start; Scalable power grids that facilitate the use of renewable energy technologies, November 2006, *Department of Defense*, SON Number SISON-09-4, http://www.serdp.org/funding/.

Description and Assessment of Assignments
Students will be assigned a homework every other week. Homework will consist in solving “textbook” problems and will include a “research-oriented” problem to stimulate and probe students’ creativity. There will be one midterm and one final.

Grading Breakdown

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Points</th>
<th>% of Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>participation</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>homework</td>
<td></td>
<td>20%</td>
</tr>
<tr>
<td>midterm</td>
<td></td>
<td>35%</td>
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<tr>
<td>final or project (TBD)</td>
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<td>40%</td>
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TOTAL 0 1

Assignment Submission Policy
Homework to be submitted two weeks after assignment.

Additional Policies
Late assignments will be penalized (unless valid, e.g., medical, reason).
Attendance of the lectures is expected.
Matlab and Mathpower will be used in the classroom.
## Course Schedule: A Weekly Breakdown

<table>
<thead>
<tr>
<th>Week</th>
<th>Dates</th>
<th>Topics/Daily Activities</th>
<th>Readings and Homework</th>
<th>Deliverable/ Due Dates</th>
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</thead>
<tbody>
<tr>
<td><strong>Week 1</strong></td>
<td>Dates</td>
<td>The concept of network. Information network, sensor networks, telephone network, power grid, bus model, transportation network. The concepts of “flow” and “commodity;” multi-commodity flow, etc.</td>
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<tr>
<td><strong>Week 2</strong></td>
<td>Dates</td>
<td>Introduction to the power grid elements: generation, transmission, distribution. The deregulation issue and large-scale power transmission. The concept of “renewables” (wind farms, photovoltaic cells).</td>
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<td>Homework #1 assigned</td>
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<tr>
<td><strong>Week 3</strong></td>
<td>Dates</td>
<td>Review of some electrodynamics (depending on students’ background): Tellegen’s theorem; complex power, active power, and reactive power. Lagrange-Hamilton formulation of circuits. Variational interpretation of active and reactive power.</td>
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<tr>
<td><strong>Week 4</strong></td>
<td>Dates</td>
<td>Power flow equations. Solving nonlinear power flow equations using Newton-Raphson iteration.</td>
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<td>Homework #1 due, Homework #2 assigned</td>
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<tr>
<td><strong>Week 5</strong></td>
<td>Dates</td>
<td>Classical (non-topological) graph topology. Degree distribution, Scale-Free graphs, Small-World graph model of power grid. Adjacency matrix, graph Laplacian. Topographical versus</td>
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<tr>
<td>Week 6 Begins</td>
<td>State Estimators (SEs) and SCADA</td>
<td>Homework #2 due, Homework#3 assigned.</td>
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<tr>
<td>Week 7 Begins</td>
<td>Large scale synchronous Phasor Measurement Units (PMUs) deployment. Time stamp by Global Positioning System (GPS). Networked PMUs.</td>
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<tr>
<td>Week 8 Begins</td>
<td>Notion of structure learning, machine learning, L1 and regularizer.</td>
<td>Homework #3 due, No homework due because of midterm</td>
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</tr>
<tr>
<td>Week 9 Begins</td>
<td>Detection of false data injection by structure learning of grid graph using Conditional Covariance Test (CCT). Gaussian versus non Gaussian property of state estimator and PMU signals. Application of structure learning to detect stealthy deception attack.</td>
<td>Midterm</td>
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<td>Week 10 Begins</td>
<td>Battery buffer between household appliances and smart meter to protect privacy of consumers. Notion of mutual information between signals on both sides of battery buffer.</td>
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<td>Week 11 Begins</td>
<td>Static load models and static voltage collapse scenario ((P,V) diagram). Nonlinear, frequency-dependent load models in</td>
<td>Homework #4 assigned</td>
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### Week 12 Begins

| the sense of Berg, significance of the non-integer exponents of the frequency in Berg model, “dynamic” Hill model, comparison between Berg and Hill models, the static-dynamic gap, describing function (“equivalent gain”) load models. Modeling of tap changer. |

### Week 13 Begins

| Hidden control feedbacks in the power grid. Simple one-generator, one-line, one-load model; many-generator, many-line, many-load multivariable models. Callier-Desoer decomposition of the grid control graph in strongly connected components and application to load aggregation effect. Application of modern multivariable control theory to voltage collapse. Frequency disruptive and non-frequency disruptive voltage collapse. |

### Week 14 Begins

| Fractional dynamics model of grid dynamics |
| Homework #4 due, Homework#5 assigned. |

### FOURTH PART: STATISTICAL PMU SIGNAL ANALYSIS


### Week 15 Begins

| Inadequacy of the swing equation to reproduce |
| Last homework #5 due. |
| the statistic pof the PMU signals | Date: For the date and time of the final for this class, consult the USC Schedule of Classes at www.usc.edu/soc. |
Statement on Academic Conduct and Support Systems

Academic Conduct
Plagiarism – presenting someone else’s ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Section 11, Behavior Violating University Standards. [https://scampus.usc.edu/1100-behavior-violating-university-standards-and-appropriate-sanctions/] Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, [http://policy.usc.edu/scientific-misconduct/].

Discrimination, sexual assault, and harassment are not tolerated by the university. You are encouraged to report any incidents to the Office of Equity and Diversity [http://equity.usc.edu/] or to the Department of Public Safety [http://capsnet.usc.edu/department/department-public-safety/online-forms/contact-us]. This is important for the safety whole USC community. Another member of the university community – such as a friend, classmate, advisor, or faculty member – can help initiate the report, or can initiate the report on behalf of another person. The Center for Women and Men [http://www.usc.edu/student-affairs/cwm/] provides 24/7 confidential support, and the sexual assault resource center webpage [sarc@usc.edu] describes reporting options and other resources.

Support Systems
A number of USC’s schools provide support for students who need help with scholarly writing. Check with your advisor or program staff to find out more. Students whose primary language is not English should check with the American Language Institute [http://dornsife.usc.edu/ali], which sponsors courses and workshops specifically for international graduate students. The Office of Disability Services and Programs [http://sait.usc.edu/academicsupport/centerprograms/dsp/home_index.html] provides certification for students with disabilities and helps arrange the relevant accommodations. If an officially declared emergency makes travel to campus infeasible, USC Emergency Information [http://emergency.usc.edu/] will provide safety and other updates, including ways in which instruction will be continued by means of blackboard, teleconferencing, and other technology.