USC Viterbi School of Engineering

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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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 it increasing reliance on renewables, which have the effect of injecting fluctuations in the grid, calling for stochastic analysis. "Smartness" of the grid probably stems for 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 blackout 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, 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 on-going 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

- Romeo Ortega, Antonio Loria, Per Johan Nicklasson, and Hebertt Sira-Ramirez, Passivity Based Control of Euler-Lagrange Systems, Springer, 1998. ISBN: 1-85233-016-3. (This is a very good book on physically motivated Lagrangian control, especially relevant to Weeks 11-14.)

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

Additional (suggested) readings:

- Areeyata Sripetch and Poompat Saengudomlert, Topology Design of Optical Networks Based on Existing Power Grids, *CNSR '07: Proceedings of the Fifth Annual Conference on Communication Networks and Services Research*, 2007, ISBN 0-7695-2835-X, pages 35—40, DOI: http://dx.doi.org/10.1109/CNSR.2007.66, IEEE Computer Society, Washington, DC, USA.
- 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/.
- Author withheld, Generating random topology power grids, https://wiki.iti.uiuc.edu/pub/Main/ZhifangWang/Hicss41_RandTopo_Wang_v2.pdf.
- David L. Pepyne, "Topology and cascading line outages in power grids," *Journal of Systems Science and Systems Engineering,* volume 16, number 2, June 2007, pages 202-221, DOI 10.1007/s11518-007-5044-8.
- Eric J. Lerner, "What's wrong with the electric grid?" *The Industrial Physicist,* volume 9, Pages 8-13, October-November 2003.
- P. Crucitti and V. Latora and M. Marchiori, "A topological analysis of the Italian electric power grid," *Physica A,* volume 338, pages 92-97, 2004.
- P. Kuchment, "Graph models of wave propagation in thin structures," *Waves in Random Media,* Volume 12, 2002, Number 4, pages R1-R24.
- G. L. Doorman and T. Holtedahl and H. S. Woldstad, "Large scale power exchange in the greater Mekong subregion," *International Conference on Electric Supply Industry in Transition: Issues and Prospects for Asia,* Thailand, 2004, January 14-16.
- E.A. Jonckheere, "Lagrangian theory of large scale systems," (invited paper), *European Conference on Circuit Theory and Design,* The Hague, the Netherlands, August 25-28, 1981, pp. 626-629.
- H. Sedghi and E. Jonckheere, ``On the conditional mutual information in the Gaussian–Markov structured Grids,'' *Information and Control in Networks,* G. Como, B. Bernhardsson, and A. Rantzer, Editors, *Lecture Notes in Control and Information Sciences,* Springer International Publishing, Vol. 450, pp. 277-297, 2014. (ISBN 978-3-319-02149-2, URL http://dx.doi.org/10.1007/978-3-319-02150-8_9. DOI 10.1007/978-3-319-02150-8_9, available at http://eudoxus2.usc.edu .
- H. Sedghi and E. Jonckheere, ``Statistical structure learning to ensure data integrity in smart grid,'' *IEEE Transaction on Smart Grid,* Volume 6, Number 4, pp. 1924-1933, 2015.
- R. Banirazi and E. Jonckheere, ``Geometry of power flow in negatively curved power grids: Toward a smart transmission system,'' *49th IEEE Conference on Decision and Control (CDC),* Atlanta, GA, December 15-17, 2010, pp. 6259-6264.
- H. Sedghi and E. Jonckheere, ``Statistical structure learning of smart grid for detection of false data injection,'' *IEEE power and Energy Society General Meeting,* Vancouver, BC, Canada, July 21-July 25, 2013, pp. 1-5.
- P. Bogdan, E. Jonckheere, and S. Schirmer, ``Multi-fractal geometry of finite networks of spins,'' *Chaos, Solitions & Fractals,* submitted, Sept. 2016.
- E. Grippo and E. Jonckheere, ``Effective resistance criterion for negative curvature: application to congestion control,'' *IEEE Multi-Conference on Systems and Control,* Buenos Aires, Argentina, September 19-22, 2016.
- L. Shalalfeh and E. Jonckheere, ``Load aggregation effect in the power grid," *IEEE Conference on Decision and Control,* Las Vegas, NV, December 2016, to appear.
- L. Shalalfeh, P. Bogdan and E. Jonckheere, ``Kendall's tau of frequency Hurst exponent as blackout proximity margin," IEEE International Conference on Smart Grid Communications, November 06-09, 2016, Sydney, Australia, to appear.
- L. Shalalfeh and E. Jonckheere, ``The Existence of a Voltage Collapse Solution in the Static-Dynamic Gap,'' *2016 American Control Conference,* Boston, USA, July 6-8, 2016, pp. 4126-4131.

- L. Shalalfeh, P. Bogdan, and E. Jonckheere, ``Evidence of long-range dependence in power grid," *Power and Energy Society General Meeting (PESGM),* Boston, USA, July 17-21, 2016.

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

Assignment	**Points**	**% of Grade**
participation		5%
homework		20%
midterm		35%
final or project (TBD)		40%
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

	Topics/Daily Activities	Readings and Homework	Deliverable/ Due Dates
	FIRST PART: GRAPH THEORY OF TRANSMISSION NETWORK		
Week 1 Dates	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.		
Week 2 Dates	Introduction to the power grid elements: generation, transmission, distribution. The deregulation issue and large-scale power transmission. The concept of "renewables" (wind farms, photo-voltaic cells).		Homework #1 assigned
Week 3 Dates	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.		
Week 4 Dates	Power flow equations. Solving nonlinear power flow equations using Newton-Raphson iteration.		Homework #1 due, Homework#2 assigned.
Week 5 Dates	Classical (non-topological) graph topology. Degree distribution, Scale-Free graphs, Small-World graph model of power grid. Adjacency matrix, graph Laplacian. Topographical versus		

	electrical connectivity. Linear DC power flow models. Virtual resistive grids. Resistive networks, Laplacian, effective resistance. Concept of graph betweenness centrality and its relation to “stress points.”		
	SECOND PART: STATE ESTIMATOR, CYBER SECURITY, AND PRIVACY		
Week 6 Begins	State Estimators (SEs) and SCADA		Homework #2 due, Homework#3 assigned.
Week 7 Begins	Large scale synchronous Phasor Measurement Units (PMUs) deployment. Time stamp by Global Positioning System (GPS). Networked PMUs.		
Week 8 Begins	Notion of structure learning, machine learning, L1 and regularizer.		Homework #3 due, No homework assigned because of midterm
Week 9 Begins	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.		Midterm
Week 10 Begins	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.		
	THIRD PART: VOLTAGE STABILITY		
Week 11 Begins	Static load models and static voltage collapse scenario ((P,V) diagram). Nonlinear, frequency-dependent load models in		Homework #4 assigned

	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 12 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 13 Begins	Fractional dynamics model of grid dynamics		Homework #4 due, Homework#5 assigned.
	FOURTH PART: STATISTICAL PMU SIGNAL ANALYSIS		
Week 14 Begins	Real-time fractal analysis of PMU signals. Detrended Fluctuation Analysis. Auto-Regressive Fractionally Integrated Moving Average Models (ARFIMA). AR(1) coefficient and Hurst exponent. Kendall tau and Jonckheere-Terpstra statistical confirmation of increase of AR(1) and Kendall tau in anticipation of forthcoming blackout.		
Week 15 Begins	Inadequacy of the swing equation to reproduce		Last homework # 5 due.

	the statistic pof the PMU signals		
FINAL			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.htmlprovides 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.