USC Viterbi
School of Engineering

Course ID and Title:
EE527, Net-Centric Power-System Control

Units: 04
Primary Audience: MS and PhD students
Term: Spring 2021
Days: Tue & Thu
Time: 4:30-6:20 pm
Location: OHE 100D (DEN) & ONLINE

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IT Help: Distance Education Network (DEN)
Hours of Service:
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Course Description

Course Rationale

"Smart grid" might be defined as the merging the "old" power grid with the explosive information technology of the 21st century. 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, calling for the power grid to be thought of as a *network*—in the sense of modern information technology. 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. Another problem created by substitution of Photo Voltaic Cells (PVCs) for old CO2 generating turbo-machines is the decrease of inertia in the grid and the resulting more problematic frequency stability, calling for a new frequency stability control science. On the distribution side, such new "loads" as electric vehicle and even all-electric aircraft that need to be recharged cause new scheduling challenges. "Smartness" of the grid probably stems for the massive amount of sensors, e.g., PMUs, and their utilization for controlling the grid in a semiautonomous way for optimal performance. The unprecedented accuracy of PMU data allows for detection of subtle "abnormalities" in the signal that could indicate such nuisance as tendency towards voltage collapse. Unfortunately, the network availability of a massive amount of grid data comes with a price, not unlike the privacy/security issues that have come with the Internet. SCADA power measurement data and PMU voltage, frequency, and phase data can be compromised by deliberately injecting false data at the measurement devices with malicious intent. This calls for machine learning techniques to detect and mitigate such attacks. Privacy issues related to household smart meters also call for information theoretic protection techniques.

Course description: Four parts

Part 1 (Power Network Analysis)
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, classical loads and such new loads as electric vehicles and all electric aircraft). From there, bus models will be formalized in the context of graph theory—in particular, "resistive networks" where the more palatable DC current is a substitute for power flow. This in turn would allow graph topology to be analyzed using spectral graph theory (Laplacian operator). This formalization will be geared towards a better understanding of "congestion," interpreted in the sense of line overload and storage element deployment. 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. Here "negatively curved paths" could be interpreted in the sense of Gromov curvature; however, it will be shown that the Ollivier-Ricci concept of curvature is better appropriate to analyze traffic in the power grid. Closely related concepts of "graph entropy" will also be shown to be relevant. The impact of fluctuations of renewables (e.g., wind farms) and pricing on congestion will also be addressed.

Part 2 (Machine Learning SCADA Data Authentication)
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 warning that some data tampering has happened. In addition, we will develop the so-called L1 approach, along with the concept of regularizer, as another approach with the same goal as graphical models. The related optimization techniques will be developed.

Part 3 (Frequency Stability Control)
Part 3 is centralized around the concept of frequency & voltage stability. We will first review static voltage collapse together with static load modeling and then develop dynamical models based on the well-known swing equations, revised to be in line with smart grid technology and its problematic frequency stability. We will unravel the hidden feedbacks in the power grid as an indication that anomalies propagate through the whole grid.

Part 4 (PMU "Big Data" Statistical Decision)
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 a load aggregation effect. Most importantly, it will be shown that before a voltage collapse, the Hurst exponents, as revealed by Detrended Fluctuation Analysis (DFA), increases. Moreover the AR(1) coefficient, even of a simple ARMA model, increases as well but in a less statistically significant way. ARFIMA (Auto Regressive Fractionally Integrate Moving Average) model of the voltage, frequency and phase angle of PMU signals will be covered in some details. The increase of Hurst exponent or AR(1) will be statistically confirmed using the Kendall tau and the Jonckheere-Terpstra rank correlation. Finally, the increase of the Hurst exponent will be put in the time-sensitive context of Change Point Detection, that is, a compromise between detection delay and False Alarm Rate. The mathematics behind the Change Point Detection—the Dirichlet-Newman escape problem—and its extension to the nonGaussian set-up, will also be covered in some details. The background material of Ito calculus will also be covered.

Learning Objectives

To paraphrase the 4 parts of the course, the learning objectives are the following:

- To have the students think smart grid as a *network*—with *power* its specific *commodity.*
- To provide students with the basic concepts of electrodynamics, e.g., Kron machine, with special emphasis on such modern devices as PVC cells, wind farms, and other potentially emerging technologies.
- To develop a machine learning platform to detect false data injection and other malicious attacks on the grid.
- To provide the students with non-Gaussian signal analysis applied to PMU data, in particular voltage collapse early warning.
- To develop a modern control theory approach to frequency stability.

Prerequisite(s):

- EE482 (Linear Control Systems),
- EE510 (Linear Algebra for Engineering).

Recommended preparation:

- EE503 (Probability for Electrical and Computer Engineers)

Co-Requisite(s): N/A

Concurrent Enrollment: N/A

Recommended Preparation: EE585 (Linear System Theory), EE593 (Robust Multivariable Control)

Course Notes

Grading Type: letter grade

The course is Web-Enhanced **(DEN (preferred) or Blackboard)**.

Copies of lecture slides and other class information will be posted on DEN or 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. Some familiarity with Mathpower is desirable but not required.

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 topics that have 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 Week 3.)

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/.

- 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.
- 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://ee.usc.edu/~jonckhee .
- 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, Solitons & Fractals,* vol. 103, pp. 622-631, Oct. 2017.
- 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, pp. 129-136.
- L. Shalalfeh and E. Jonckheere, ``Load aggregation effect in the power grid,” *IEEE Conference on Decision and Control,* Las Vegas, NV, December 2016, pp. 5793-5798.
- 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.
- 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.
- L. Shalalfeh and P. Bogdan and E. Jonckheere, “Modeling of PMU data using ARFIMA models,” *Clemson University Power System Conference,* Charleston, SC, Sept. 2018.
- J. Sia and E. Jonckheere and L. Shalalfeh and P. Bogdan, “PMU Change Point Detection of imminent voltage collapse and stealthy attacks,” *IEEE CDC,* Miami Beach, FL, Dec. 2018, pp. 6812-6817.

Description and Assessment of Assignments

Students will be assigned 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.

A “textbook” problem is a problem that only requires application of some formulas, for example, computation of the betweenness centrality of some IEEE bus models.

A “research-oriented” problem is a problem, the solution of which is not immediate from the lectures, but should be accessible to the students upon some thinking. Typically, one such research-oriented assignment would be the reading of a paper from the specialized literature and have the students connect it with the class material.

Grading Breakdown

Assignment	Points	% of Grade
participation		5%
homework		20%
midterm		35%
final or project (TBD)		40%
TOTAL	0	1

Grading Scale (Example)

Course final grades will be determined using the following scale (subject to “curving.”)

A	90-100
A-	80-90
B+	75-80
B	70-75
B-	65-70
C+	63-65
C	60-63
C-	58-60
D+	55-58
D	53-55
D-	50-53
F	50 and below

Assignment Rubrics

N/A

Assignment Submission Policy

Homework assigned on Tuesday (or first day of class of the week), to be submitted two weeks after assignment, same day of the week.

Late assignments will be penalized (10%), unless valid reason, e.g., medical problem, family or other emergency

Grading Timeline
Graded homework will be returned within one week

Additional Policies
Attendance of the lectures is expected.
Matlab and Mathpower will be used in the classroom.
Cell phone beeping or texting will not be tolerated during classes.

Course Schedule: A Weekly Breakdown

	Topics/Daily Activities	Readings and Homework	Deliverable/ Due Dates
Week 1	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. Introduction to competition and pricing in electricity market.	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.	
Week 2	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 (PVC)). Turbulence problem in wind farms. Quantum theory of PVC and comparison with photosynthesis. (Why is photosynthesis still so much efficient compared with PVC?) Special "loads," e.g., electric vehicles and all electric aircraft (e.g., Eviation) and their impact on grid dynamics.	Eric J. Lerner, "What's wrong with the electric grid?" The Industrial Physicist, volume 9, Pages 8-13, October-November 2003. 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/.	
Week 3	Review of some electrodynamics (depending on students' background): Tellegen's theorem; complex power, active power, and reactive power. Lagrange-Hamilton formulation of circuits. Hamilton's principle and its calculus of variation	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. E.A. Jonckheere, "Lagrangian theory of large scale systems," (invited paper), European Conference on Circuit Theory	Homework #1 assigned

	exposed with some rigor to side step the weak versus strong variation trap. Variational interpretation of active and reactive power. Foundation of rotary electric machines: electrodynamics of current tubes moving relative to matter. Some elements of restricted relativity. Magnetic diode example.	and Design, The Hague, the Netherlands, August 25-28, 1981, pp. 626-629	
Week 4	Power flow equations. Solving nonlinear power flow equations using Newton-Raphson iteration.		
Week 5	Classical (non-topological) graph topology. Degree distribution, Scale-Free graphs, Small-World graph model of power grid. Adjacency matrix, graph Laplacian. Linear DC power flow models. Virtual resistive grids. Resistive networks, Laplacian, effective resistance. Concept of graph betweenness centrality and its relation to “stress points” in the grid. Concept of thermal rating of lines. Concepts of graph curvature (Gromov, Ollivier-Ricci) and related entropy concepts for power traffic analysis.	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. 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.  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, pp. 129-136.	Homework #1 due, Homework#2 assigned.
Week 6	State Estimators (SEs) and SCADA		
Week 7	Phasor Measurement Units (PMUs) deployment. Time stamping by Global Positioning System (GPS). Networked PMUs.		
Week 8	Notion of structure	H. Sedghi and E. Jonckheere,	Homework #2 due

	learning and graphical models using Conditional Covariance test (CCT). Machine learning, L1 theory and regularizers, and related computational solutions.	``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.	
Week 9	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.	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://ee.usc.edu/~jonckhee	Midterm week
Week 10	Application of structure learning to detect stealthy deception attack.	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.	
Week 11	Static load models and static voltage collapse scenario ((P,V) diagram). Nonlinear, frequency-dependent load models in 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. Revision o the swing equations. Proof of inadequacy of swing equation by ergodic theory concepts (Krylov-Bogoliubov theorem).	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.	Homework #3 assigned

Week 12	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.	L. Shalalfeh and E. Jonckheere, ``Load aggregation effect in the power grid," IEEE Conference on Decision and Control, Las Vegas, NV, December 2016, pp. 5793-5798.	
Week 13	Fractional dynamics model of grid dynamics. Riemann and Caputo concepts of fractional differentiation.		Homework #3 due, Homework#4 assigned.
Week 14	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.	L. Shalalfeh and P. Bogdan and E. Jonckheere, "Modeling of PMU data using ARFIMA models," Clemson University Power System Conference, Charleston, SC, Sept. 2018. 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.	
Week 15	Change Point Detection. Introduction to Dirichlet-Newman problem of escape of process from bounded set at first time boundary crossing. Foundations of Ito calculus. Extension to nonGaussian environment.	J. Sia and E. Jonckheere and L. Shalalfeh and P. Bogdan, "PMU Change Point Detection of imminent voltage collapse and stealthy attacks," *IEEE CDC*, Miami Beach, FL, Dec. 2018, pp. 6812-6817.	Last homework #4 due.
FINAL			Date: For the date and time of

			the final for this class, consult the USC *Schedule of Classes* at classes.usc.edu.

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 Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. 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.

Support Systems:

Student Counseling Services (SCS) – (213) 740-7711 – 24/7 on call
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention. engemannshc.usc.edu/counseling

National Suicide Prevention Lifeline – 1 (800) 273-8255
Provides free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week. www.suicidepreventionlifeline.org

Relationship and Sexual Violence Prevention Services (RSVP) – (213) 740-4900 – 24/7 on call
Free and confidential therapy services, workshops, and training for situations related to gender-based harm. engemannshc.usc.edu/rsvp

Sexual Assault Resource Center
For more information about how to get help or help a survivor, rights, reporting options, and additional resources, visit the website: sarc.usc.edu

Office of Equity and Diversity (OED)/Title IX Compliance – (213) 740-5086
Works with faculty, staff, visitors, applicants, and students around issues of protected class. equity.usc.edu

Bias Assessment Response and Support
Incidents of bias, hate crimes and microaggressions need to be reported allowing for appropriate investigation and response. studentaffairs.usc.edu/bias-assessment-response-support

The Office of Disability Services and Programs
Provides certification for students with disabilities and helps arrange relevant accommodations. dsp.usc.edu

Student Support and Advocacy – (213) 821-4710
Assists students and families in resolving complex issues adversely affecting their success as a student EX: personal, financial, and academic. studentaffairs.usc.edu/ssa

Diversity at USC
Information on events, programs and training, the Diversity Task Force (including representatives for each school), chronology, participation, and various resources for students. diversity.usc.edu

USC Emergency Information
Provides safety and other updates, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible. emergency.usc.edu

USC Department of Public Safety – UPC: (213) 740-4321 – HSC: (323) 442-1000 – 24-hour emergency or to report a crime.
Provides overall safety to USC community. dps.usc.edu