# New Course:

# EE527, Net-Centric Power System Control

E. Jonckheere

**Note:** This is a new course and the research on this rapidly evolving subject is in full swing. This is a tentative syllabus; it might still evolve during this summer, but the final one should not be too far from this one. Feel free to contact me at jonckhee@usc.edu is there are questions.

**July 06 update:** The syllabus has been updated to be more explicit about the control part. Also, some prospective students inquired as to how they could prepare themselves for the class. The updated "textbooks" part could be of help. However, I added a "bibliography" section of relevant papers that should be easy to download from the internet. These papers could be excellent preparatory readings.

## *Synopsis*

This new course is the University of Southern California response to the "smart grid" government-initiated program. The *Southern California Edison* and the *Los Angeles Department of Water and Power* were also instrumental in setting up this course, as both organizations perceived the need for a "crash program" to train a new breed of power engineers able to cope with the energy problems the country is likely to face in a not so distant future.

This program came at a time when there is more and more concern about the information grid vulnerability to attacks and its potential impact on the power grid, as the power grid and the information grid are more and more intertwined.

This program is also concomitant with a revival of control in the wake of *Networked Control* and *Network Control*. The two concepts should not be confused: *Networked Control* refers to large-scale distributed control systems borrowing the information infrastructure to transmit sensing/actuating signals through unreliable channels. *Network Control* refers to the control of networks to have them work properly, for example, control of the network to avoid congestion, Random Early Detection (RED).

This new course is, therefore, designed at the crossroad between the power grid and the information network. It will be taught in a way that should be of interest to the power grid, the computer networking, and the control communities. This symbiotic approach can certainly be justified on the ground that software vulnerabilities have been shown to have the potential to create blackouts, but next to this, there is the more compelling reason that congestion control techniques initially developed for information grid are in fact applicable to the line overload in the power grid.

This course will, therefore, be taught from the "networking" point of view. It will proceed from graph topology, and then will develop a concept of "traffic" applicable to both the power and information grids. Both grids are driven by consumers' demands, which can be formulated in terms of the "traffic" that has to flow from "sources" (power generating stations, transmitters, resp.) to "destinations" (distributions, receivers, resp.) without creating "congestion" (line overload, packet drops, resp.). Control comes into the picture to secure the proper flow and to avoid "congestion."

## *Technical digression*

It might appear as a bit of a surprise that line overload and computer communication congestion can be treated under a unifying theme. The gist of it is a very recent research observation: It turns out that the traditional power flow equations of the bus model can be decoupled into active power flow equations and reactive power flow equations. Both the active and the reactive equations can be interpreted as relationships between currents and voltages in a resistive grid. Going to the effective resistance defines a metric, which behaves pretty much like the metrics of the information grid. This explains how resistive grid methods have recently been utilized in sensor networks[1].

## *Format*

### Instructor

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We will try to organize discussion sessions with the TA, but this is still subject to Chair's approval.

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[1] Edmond A. Jonckheere, Mingji Lou, Prabir, Barooah and Joao P. Hespanha, "Effective resistance of Gromov-hyperbolic graphs: Application to asymptotic sensor network problems," *IEEE Conference on Decision and Control,* New Orleans, LA, December 2007, Session WePI20, Agents, Networks, and Autonomous Systems, paper WePI20.12, pp. 1453-1458.

## Prerequisites

We will try to make the course as self-contained as possible. No power prerequisites will be required, although basic electrical engineering background (resistors, capacitors, inductors, impedance, Kirchoff's laws, etc.) will be assumed. No networking prerequisites will be required either, although knowledge of the basic concepts (routing, link utilization, Transmission Control Protocol, etc.) would be useful. The student will be assumed to have the very basic control background (differential equations, closed-loop stability, etc.)

## Textbooks

Unfortunately, there is no textbook that puts under the same cover the wide variety of material that will be covered in this class. However, the following books might be useful, especially to those who would like to get up to speed on power systems:

- J. Arrillaga and C. P Arnold, *Computer Analysis of Power Systems.* John Wiley & Sons, 1994, ISBN 0 471 92760 0.
- M. D. Ilic and S. X. Liu, *Hierarchical Power Systems Control: Its Value in a Changing Electric Power Industry, ser. Advances in Industrial Control.* London, U.K.: Springer-Verlag, 1996.
- M. D. Ilic and J. Zaborszky, *Dynamics and Control of Large Electric Power Systems.* New York: Wiley Interscience, May 2000.
- D. Siljak, Decentralzied *Control of* Complex *Systems.* NewYork: Academic, 1991.
- Romeo Ortega, Antonio Loria, Per Johan Nicklasson, and Hebertt Sira-Ramirez, *Passivity Based Control of Euler-Lagrange Systems*, Springer, New York, 1998, ISBN: 1-85233-016-3.

To compensate for this lack of formal textbook, the instructor will put plenty of relevant papers on the blackboard.

## Exams & Midterms & etc.

The course will be "project oriented," in the sense that students will have to turn in a midterm project (tentatively, 30%) and a final project (tentatively, 70%). The projects will be to the students' choice, but subject to instructor's approval. The final project could be a spinoff of the midterm project, but it need not be. The final letter grade will be assigned based on the quality of the projects.

## *Time table*

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| August 2010 | The concept of network. Information network, sensor networks, telephone network, power grid, transportation network, percolation network, quantum networks. The concepts of "flow" and "commodity;" multi-commodity flow, etc. |
| September 2010 | Classical graph topology. Degree distribution, Scale-Free graphs, Small-World graph model of power grid; expander graphs, super concentrators, adjacency matrix, graph Laplacian. |

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| September 2010 | Introduction to the power grid elements: generation, transmission, distribution. Structure of an electric power system. The deregulation issue and large-scale power transmission. |
| September 2010 | Power flow equations. Conservation of power, Kirchhoff and Tellegen's theorems. Phasor and complex variables. Complex power, active power, reactive power. Auxiliary resistive grids, effective resistance. |
| | Vulnerability and resiliency of networks from classical topological viewpoint and its application to power grid. Cascading and blackout in networks from classical topological viewpoint and its application to power grid. Study of American 2003 and Italian 2003 blackouts. |
| October 2010 | Riemannian geometry of graphs. Approximation of a graph by a Riemannian manifold. Graph curvature, concept of Gromov hyperbolic graphs. Curvature of resistive networks. Concept of graph inertia. |
| October 2010 | Congestion in information grid and line overload in power grid. Line overload in power grid will be shown to be more likely to happen if the grid is Gromov hyperbolic. Overloaded lines will be identified as those of low graph inertia. The connection with Distributed Denial of Service (DDoS) attacks will be established. |
| November 2010 | Review of control. Feedback and feedforward control. Closed-loop stability, Nyquist plot, Callier-Desoer criterion for stability of interconnected systems. |
| | Synchronization in dynamic networks and its relation to the stability of power grid. Small perturbation theory. |
| | Frequency and voltage control in power grids. AGC (Automatic Generation Control). AVC (Automatic Voltage Control). EGC (Energy Management System). SCADA (Supervisory Control and Data Acquisition). Process modeling for load frequency and voltage control. Decentralized control of excitation systems and turbine governors. Droop control and modern joint control of active and reactive generation. Control time scales (short-term control loop, mid-term control loop, long-term control loop) |
| December 2010 | Future green power grid and smart power transmission. Integration of large farms of renewable power generation. Smart grid foundations. Dynamic demand control. Smart power scheduling and transmission system. FACTS (Flexible AC Transmission System). Adaptive power generation and distribution based on fast data communication in a smart power grid. |

## *Bibliography*

The following papers, easily downloadable from the Internet, should give prospective students a very good indication as to what the course will be all about. In fact, the following papers will be discussed in the course:

- P. Crucitti, V. Latora, and M. Marchiori, “A topological analysis of the Italian electric power grid,” *Physica A*, volume 338, pages 92-97, 2004.
- 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, http://dx.doi.org/10.1109/CNSR.2007.66, IEEE Computer Society, Washington, DC, USA.
- Name of 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, pp. 202-221, June 2007, DOI 10.1007/s11518-007-5044-8.
- 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, January 14-16, 2004.
- G. Korniss, M.B. Hastings, K.E. Bassler, M.J. Berryman, B. Kozma, and D. Abbott, “Scaling in Small-World resistor networks,” *Physics Letters A*, volume 350, number 5-6, pp. 324-330, February 2006. Available at arXiv:cond-mat/or08056 v1 Aug 2005.
- Bei Gou, Yunzhi Cheng, and Weibiao Wu, “A new topology error detection approach for power system state estimation,” *Power and Energy Society General Meeting---Conversion and Delivery of Electrical Energy in the 21st Century*, July 2008, Pittsburgh, PA, pp. 1-7.
- L. Milli, G. Steeno, F. Dobraca, and D. French, “A robust estimation method for topology error identification,” *IEEE Transactions on Power Systems*, volume 14, number 4, pp. 1469-1476, November, 1999.
- Paul Hines and Seth Blumsack, “A Centrality Measure for Electrical Networks,” *HICSS '08: Proceedings of the Proceedings of the 41st Annual Hawaii International Conference on System Sciences*, 2008, page 185, ISBN 0-7695-3075-8, doi http://dx.doi.org/10.1109/HICSS.2008.5, IEEE Computer Society, Washington, DC, USA.
- Ulrik Brandes and Daniel Fleischer, “Centrality Measures Based on Current Flow,” *Proc. 22nd Symp. Theoretical Aspects of Computer Sciences*, Lecture Notes in Computer Science, Springer Berlin / Heidelberg, volume 3404/2005, 2005, pp. 533-544.
- D. Trudnowski, M. Donnelly, and E. Lightner, “Power-System Frequency and Stability Control using Decentralized Intelligent Loads,” Power-System Frequency and Stability Control using Decentralized Intelligent Loads,” *Transmission and Distribution Conference and Exhibition*, Dallas, TX, May 2006, pp. 1453-1459.
- Edmond A. Jonckheere, Mingji Lou, Prabir Barooah, and Joao P. Hespanha, “Effective resistance of Gromov-hyperbolic graphs: Application to asymptotic sensor network problems,” *IEEE Conference on Decision and Control*, New

Orleans, LA, December 2007, Session WePI20, Agents, Networks, and
Autonomous Systems, paper WePI20.12, pp. 1453-1458.