Syllabus
ENG EC/ME/SE 543 Sustainable Power Systems: Planning, Operation, and Markets
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Preamble

Breakthroughs in centralized as well as distributed clean energy generation technologies, up to fourfold higher efficiency of heat pumps in conjunction with low enthalpy geothermal energy in providing space conditioning relative to direct fossil fuel burning, and the prospect of electrifying the transportation industry, will render electricity the dominant energy form in a sustainable environment future. Under this premise, the course considers key technical and economic characteristics of power systems and presents their interaction in the design and operation of markets that foster competition and economic efficiency while allowing for the safeguard of security and stability in today's complex power systems.

Course Overview

We review the key characteristics of Electric Power Transmission and Distribution (T&D) networks and the associated planning and operation requirements that ensure supply adequacy, system security and stability. Investment and operational costs of assets are discussed in a systems engineering context where long term as well as short term and real-time interaction of supply and demand is considered. Recent developments in the introduction of competitive wholesale markets at the High Voltage level, the associated rules that define market participation, market clearing and price formation are presented. Algorithms used to implement market rules are also discussed and analyzed in terms of their effectiveness in fostering cost reflective price signals and competitive conditions that encourage efficient distributed/not-centralized investment and operating decisions. In particular, the functions of interacting markets operating at different time scales, including long term, day-ahead, adjustment and real-time markets are analyzed and the incorporation of system security requirements into the market rules are explained.

The fundamental difference of Power markets relative to other markets is the absolute requirement of system wide energy balance in real-time. This is a difficult requirement to meet because of (*i*) limited control of how electricity flows over the Transmission and Distribution (T&D) network – it follows Kirchoff's law rather than an operator's routing directions – and (*ii*) significant uncertainty in the future availability of resources (T&D lines and generating capacity) and in forecasting the actual demand level and, to the extent that demand is exposed to dynamic clearing prices, in forecasting demand response. The combination of uncertainty (i.e. the ipmossibility of perfect forecasts) on one hand and the inability to tolerate even temporary energy imbalances on the other, nececitates not only the scheduling of generation to meet expected demand, but also contingency planing, namely (*i*) determination of the required quantities of capacity reserves that are sufficient to overcome practically all uncertainty realizations, and (*ii*) the actual procurement of these capacity reserves. While the procurement of capacity reserves and of energy can be achieved by market clearing procedures, to secure system stability we need to manage the utilization of the procured reserves through a combination of automated distributed control policies and commands determined and disseminated in practically real-time at a centralized facility/control center. The objective of centralized capacity reserve management is to secure system stability – i.e. avoid system black outs and unacceptable quality such as brown outs and surges – while minimizing market based procurement costs.

The handling of technical and economic considerations mentioned above becomes more interesting – and onerous – as (*i*) the adoption of intermittent clean energy generation increases, (*ii*) distributed generation (e.g., roof top PV) and distributed resources (e.g., storage, smart appliances, plug-in electric hybrid vehicles) become more prevalent, and (*iii*) the advent of the smart grid increases the opportunity to utilize new information and control options and to achieve higher efficiencies and value added. The material coverage outlined below aims at presenting salient power systems engineering, physics, economics, market design and regulation issues that are crucial to mastering the "domain knowledge" required to work successfully as a researcher or practitioner in specific aspects of Power Systems and Markets including technology, communication, control, economics, market design, management, finance, and, last but not least, policy and legal matters.

Course Prerequisites and Desirable Background

Students interested in taking the course should have College of Engineering senior or graduate status, or graduate status in another School or College with background in elementary calculus, introductory physics and introductory economics. In-depth expertise in some discipline, be it systems engineering and optimization, power systems, physics, economics, management, or law is an asset.

Homework, Term Papers, Examinations and Grading

Short homework assignments will be assigned, and a midterm examination will be administered on April 13, 2011. Each student will be required to complete a substantive term paper in his/her particular area of interest. The term paper's topic and abstract must be submitted to and approved by the instructor. The term paper will be due on the last day of the study period, May 9, 2011. Complete and exhaustive referencing and citation of published work, in print or on the web, must be VERY carefully addressed in the reports submitted. **Deficiencies in doing so may result in a <u>failing grade</u>**. The final grade will depend on homework, examination, and term paper performance with 20%, 40% and 40% weights, respectively.

Reading Material and References

Notes, published papers, and URLs will be distributed electronically through posting on the course's BU Blackboard web page.

Textbooks listed below may be helpful as references. Kirschen and Strbac's book is a required text and is available in the B.U. bookstore. Particularly useful references are marked by a *.

-Fundamentals of Power System Economics, **Daniel S. Kirschen and Goran Strbac, 2004. REQUIRED Textbook.**

-Power System Economics: Designing Markets for Electricity, Steven Stoft, Wiley-Interscience, 2002.

-Optimization Principles: Practical Applications to the Operation and Markets of the Electric Power Industry, Narayan S. Rau, Wiley-Interscience, 2003.

-Power System Operations and Electricity Markets, F. I. Denny and D. E. Dismukes, Wiley-Interscience 2002

-Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management by M. Shahidehpour, H. Yamin, and Zuyi Li Wiley-Interscience, 2002.

-Electric Power Planning for Regulated and Deregulated Markets, Arthur Mazer, 2007.

-Power Generation, Operation and Control, A. J. Wood and B. F. Wollenberg, John Wiley, 1996.

-Power Systems Analysis and Design, J. D. Glover, M. S. Sarma and T. J. Overbye, 2007.

-Elements of Power Analysis, by William D. Stevenson, McGraw Hill.

-Electricity Economics: Regulation and Deregulation, Geoffrey Rothwell, Tomás Gómez Wiley-Interscience, 2003.

-Power System Engineering: Planning, Design, and Oper. of Power Sys. and Equip., J. Schlabbach and K-H Rofalski, 2008.

-*Economic Market Design and Planning for Electric Power Systems, J. Momoh and L. Mili Wiley-Interscience, 2009.

-*Introduction to Electrical Power Systems, M. E. El-Hawary Wiley-Interscience 2008.

-Spot Pricing of Electricity, F. Schweppe, M. Caramanis, R Tabors, R Bohn, Kluwer, 1988.

-Optimization of Power System Operation, Jizhong Zhu, Wiley-Interscience, 2009.

-*Electric Power System Basics for the Nonelectrical Professional, Steven W. Blume, Wiley-Interscience, 2007.

-Sustainable Energy - without the hot air. Copyright David JC MacKay 2009. This electronic copy is provided, free, for personal use only. See www.withouthotair.com.

Tentative List of Material Coverage

Lectures 1-3 (Overview)

-Greenhouse Gas emissions and fossil fuels.

-Energy Conversion Efficiency and Quality/Available Work.

-Clean Energy Technologies.

-Electric Power System Idiosyncrasy: Instantaneous Energy Balance Requirements.

-Market Operation Basics and Existing Wholesale Markets

Lectures 4-14 (Power System Fundamentals)

-DC Power/Voltage, Transmission and Losses

-AC voltage generation, DC power flow, Losses, Transformers
-Location of Generation and Loads and T&D load flow (Kirchoff's law).
-Uncertainties impose T&D and Generation Capacity Reserve requirements.
-Long term planning and Reserve Requirements.
-Instantaneous energy balance constraint and requirements of different Reserves (Frequency, Regulation, Operating) for system security and stability.

<u>Lectures 15-18 (Whole Sale Markets)</u>

-Liberalization of Electricity Markets: Can markets emulate Centralized Control Functions?
-Market Rules and Regulation Recognize Competitive and Monopolistic Components of Power Systems.
-Unbundling of T&D costs from Generation Asset costs.
-Creation of Wholesale Markets. Locational (Nodal-Zonal) Marginal Pricing.
-Today's Status: Retail Markets remain regulated. Temporal and Spatial costs averaged and Socialized.
-Day-ahead and Real-time Wholesale Markets.
-Electricity as a Commodity: Futures Options at Power Exchanges, Transmission line Capacity financial/physical auctions.
-Mandated Price Caps for Risk Reduction and the Missing Money Problem.
-Long Term Capacity Markets in US Wholesale Power Markets (NE ISO, NY ISO, PJM…).
-Cascaded Markets, Hedging and Clearing: Day-ahead, Adjustment, and Real-time Markets.
-Quality of Supply/Reliability and Ancillary services providing capacity at different time scales/dynamics (Frequency control, regulation service, operating reserves).
-Co-Optimization of Energy and Capacity Reserves.
-Market Design and Monitoring: avoidance of market manipulation and market power.
-Competitive Pricing on networks of Energy and Reserve Capacity provided by the same asset.

<u>Lectures 19-25 (Opening Markets to the Demand Side and Introduction of Retail Markets, Synergies, Policy and Regulatory Reform for Sustainable Energy Future).</u>

-Extensive integration of intermittent renewable generation, distributed generation, and distributed resources will introduce a major paradigm shift requiring major changes in the way new participants buy and sell energy and reserves.
-Load Side Management: Demand Side Participation in Energy and Reserve markets.
-Potential benefits in reducing congestion at the Generation and T&D asset level.
-Markets are today seriously incomplete at the distribution/retail level.
-The Advent of the smart grid promises to enable Retail Markets.
-Distribution/Retail Level Costs and requirements: Local Voltage support, Feeder capacity, Transformer capacity, Losses.
-Retail market participants: Residential, commercial, small industrial.
-Significance of different loads and Distributed Resources: Lights, resistive/inductive/capacitive loads, smart appliances, capacity versus energy loads, roof-top PV, Electric Vehicles, cogeneration, storage.
-Buildings and micro grids: Sub metering, communication, control, user preferences and Energy Service Companies.

-Role of retail markets/smart grid in integrating distributed generation, resources, and energy loads (PHEVs) with limited incremental investment in distribution assets.
-Synergies of centralized intermittent clean generation (wind, PV, and the like) and distributed resources (wind, PV, storage, flexible loads and the like).
-Systems Engineering solutions remove adoption barriers for clean energy and environmentally friendly technologies.
-Requisite Policy and Regulatory Reform.
-CO_2 Emissions Pricing.
-New Business models and Contract Design enable "many-way company collaboration" and cost reflective rates.