

Syllabus

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

Spring 2023, M-W 4:30-6:15pm, CDS B62

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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 (see CDS), and the prospect of electrifying the transportation industry, will render electricity the dominant energy form in an environmentally sustainable 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:

- Environmental Sustainability
- Economic Sustainability (competition and economic efficiency) while allowing for
- Sustainable Security of Supply, i.e., assurance of secure and stable Supply of Energy in today's complex power systems that operate under ever increasing uncertainty.

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 under control that is either centralized or – as is increasingly the case since the late 1990s – market based. Investment and operational costs and benefits of producers and consumers are evaluated relative to location and time and their interactions are modeled in a Systems Engineering framework allowing coordination and optimal choice of actions ranging from long term to short term and real-time.

Recent developments in the introduction of **competitive Wholesale Markets at the High Voltage Transportation 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 -- as opposed to **centralized** -- investment and operational 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 into the market rules of system security and uncertainty driven reserves are explained.

The **fundamental difference of Power markets** relative to other markets is the absolute requirement of **system wide supply-demand 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. Uncertainty enters at multiple time scales (years, months, days, minutes, seconds, and real-time/milliseconds) and is associated with multiple sources (availability of T&D lines, generating capacity, wind and the like) and in forecasting the exogenous actual demand level or the response of demand to dynamic price signals.

The **combination of uncertainty** (i.e. the impossibility of perfect foresight) on one hand and the **inability to tolerate even temporary energy imbalances** on the other, necessitates not only the scheduling of generation to meet expected demand, but also **contingency planning**, 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 by a centralized facility/control center**. The objective of capacity reserve management (**physical layer**) is to secure system stability – i.e. avoidance of system black outs and unacceptable quality such as brown outs and voltage surges – while minimizing market-based procurement costs (**cyber or performance layer**). This constitutes a Cyber-Physical System that can be understood only in terms of a systems framework!

The handling of technical and economic considerations of the cyber physical system 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 Regulatory

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, namely the requisite expertise in technology, communications, 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/group presentations, Examinations and Grading

Short homework questions will be assigned, and a midterm examination will be administered in mid-April. Students will be required to complete a substantive project in their particular area of interest, and are encouraged to work on them individually or in small groups. Project topics and abstracts must be submitted by individuals or small collaborating groups in writing to the instructor no later than a week after the in-class examination. A written project will be due *on the last day of the study period*, and before the final exams period starts. Complete and exhaustive referencing and citation of published work, in print or on the web, must be addressed carefully in the reports submitted. **Failure to do so may result in a failing grade.** Resorting to open AI sources is not allowed. Projects must be presented on zoom or in class over a time slot proportional in length to the size of the group. The final grade will depend on homework/in class participation, examination, and term paper performance with 20%, 40% and 40% weights, respectively.

IMPORTANT DATES FOR SPRING 2023

- **Wednesday April 12, 2023, 4:30pm-6:15pm, Midterm Examination. Please make sure to be available!**
- **Wednesday April 19, 2023, 12 midnight.** Project title and abstract along with group participant names (no more than 5) must be submitted by email. Format of file name “**Abstract543ShortTitle.pdf**” Names of participants clearly stated inside.
- **Last day of Study Period in May 2023.** Projects due in electronic form. Format of file name “**Project543ShortTitle.pdf**”

Reading Material and References

Notes, published papers, and URLs will be distributed electronically by email to registered students.

Textbooks listed below may be helpful as references. Textbooks listed below may be helpful as references. Kirschen and Strbac, Stoft, and El-Sharkawi are recommended reference texts about power markets. Other useful references are marked by *.

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

RECOMMENDED Reference Textbook 1.

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

-The Economics of Electricity Markets, Darryl R. Biggar and Mohammad Hesamzadeh, 2019, Wiley

-Electric Energy: An Introduction, M. A. El-Sharkawi, Third Edition, CRC Press, Taylor and Francis Group, 2013 RECOMMENDED Reference Textbook 3

-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 Operation of Power Systems and Equipment, 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 4-20 (Power System Fundamentals and Power Markets)

A. Short Term Issues: Day(s), hours, minutes, seconds, real time.

- DC Power/Voltage, Transmission and Losses
- Introduction to Whole Sale Power Markets. Locational Marginal Cost Prices (LMP)
- AC voltage generation and Real Time Supply/Demand Balance relation to Frequency Control
- Real and Reactive Power, Line Losses, Transformers, Converters and Power Electronics
- Linearized AC power flow (DC power flow approximation)
- Instantaneous energy balance constraint and requirements of different Reserves (Frequency, Regulation, Operating) for system security and stability.
- Extended Locational Marginal Cost (LMP) Whole Sale Power Markets where energy and reserve offering is co-optimized with Energy offered and demanded.
- Uncertainties impose T&D and Generation Capacity Reserve requirements. Generation Reserve Requirements and Transmission Contingency Planning.

B. Long term planning issues

- Annual Loss of Load Probability
- 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...).
- Financial Transmission Rights

Lectures 21-27 if time allows (Renewable Generation, Flexible Storage-Like Loads, Distribution Market Extension, Optional)

- 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.
- Wholesale Markets. Locational (Nodal-Zonal) Marginal Pricing.
- Extension to Retail/Distribution network connected market participants
- Today's Status: Retail Markets remain regulated. Temporal and Spatial costs averaged and socialized.
- 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.
- Opening Markets to the Demand Side and Introduction of Retail Markets: Synergies, Policy and Regulatory Reform for Sustainable Energy Future.
- 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.
- Significance of different loads and Distributed Resources: Traditional Loads (Lights), storage-Like Flexible Loads (smart appliances, capacity versus energy loads), Roof-Top PV and accompanying power electronics (inverters), Electric Vehicles and accompanying power electronics (charger), Cogeneration, Distributed 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.
- CO₂ Emissions Pricing.