ECE 145: Modern Electric Power Systems

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Class Room: TBD
Class Hours: M/W 12:45-2:00pm
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Houston, Texas, during the 2021 freeze in the ERCOT grid. *Source: NASA Earth Observatory.*

Course Description

This course begins with a solid foundation in classical power system engineering, covering the basic operation and control of electric grids. It then explores the grid's transformation into a data-rich, power electronically interfaced system. It introduces modern AI-driven approaches for forecasting, renewable integration, and smart grid operations. Through hands-on learning with simulation software, realistic data sets, and case studies, students will bridge engineering fundamentals with data science applications. The course equips students with tools to understand, model, and design sustainable and intelligent power systems in the age of AI.

In this course, we will embark on a journey through the most intricate machine ever built by humans: the electric power grid. We will begin with generators, transformers, transmission lines, and the *power flow equations*—the fundamental laws that govern how electricity moves through a network. Despite more than a century of study, these non-linear equations still present captivating engineering challenges; to this day, just counting the total number of solutions is still an unsolved mystery. We will then follow the grid into the present day, as solar, wind, batteries, and electric vehicles connect to it through power electronics, and learn to harness scientific computing, optimization, and machine learning to model, operate, and design the grids that will power our world.

This course was formerly numbered Engineering Sciences 145 (ES 145).

Learning Objectives

By the end of this class, you will be well-prepared to **model, analyze, and operate electric power systems** with both classical engineering tools and modern data science methods. These skills are crucial for integrating renewable energy, meeting the rapid growth of demand from electrification and data centers, and making the grid resilient to extremes. Moreover, we will explore surprising connections between power systems and broader fields like graph theory, optimization, and statistical learning.

Upon successful completion of this course, students should be able to:

- *Analyze* single-phase and three-phase AC circuits, including unbalanced circuits and faults, and *model* generators, transformers, lines, and loads in per unit.
- *Construct* matrix-based network models, such as the bus admittance matrix, which is a weighted graph Laplacian.
- *Solve* the power flow equations numerically, and *recognize* when approximations such as DC power flow are appropriate.
- *Explain* how grid frequency and voltage are controlled, and how inverter-based resources change the dynamics of the grid.
- *Analyze* the power electronic converters that connect solar, wind, batteries, and data centers to the grid, and the harmonics they create.

- *Design* computational tools for economic dispatch and optimal power flow, and *interpret* the locational marginal prices they produce.
- *Predict* grid operating conditions with statistical and machine learning models, and *reconstruct* the power flow equations from measurement data.
- *Demonstrate* how to manage and visualize large data sets of real grid measurements.
- *Assess* the societal and ethical dimensions of how we design and operate the grid, such as fairness in pricing, energy burden, resilience, and the electricity demand of AI.

Resources

- **Our course notes:** Will be made periodically available on Canvas.
- **Main textbooks (available for free online):**
  - Steven H. Low, "Power System Analysis: Analytical tools and structural properties", Caltech, 2026. Link.
  - James L. Kirtley, "6.061 Introduction to Electric Power Systems", MIT OpenCourseWare, 2011. Link.
- **Recommended textbook for power electronics:**
  - Robert W. Erickson and Dragan Maksimović, "Fundamentals of Power Electronics", Springer, 3rd edition, 2020. Link.
- **Additional resources:** These are books I have found useful over the years. They are *not* required; we will go over anything we need together. For those that are not free online, search HOLLIS.
  - Alexandra von Meier, "Electric Power Systems: A Conceptual Introduction", Wiley-IEEE Press, 2006.
  - J. Duncan Glover, Mulukutla S. Sarma, Thomas J. Overbye, and Adam B. Birchfield, "Power System Analysis and Design", Cengage, 7th edition, 2023.
  - Le Xie, Yang Weng, and Ram Rajagopal, "Data Science and Applications for Modern Power Systems", Springer, 2023.
  - Daniel K. Molzahn and Ian A. Hiskens, "A Survey of Relaxations and Approximations of the Power Flow Equations", Foundations and Trends in Electric Energy Systems, 2019. Link.
  - Stephen Boyd and Lieven Vandenberghe, "Convex Optimization", Cambridge University Press, 2004. Link.
- **Software and data:**
  - Steinmetz.jl, our course's open source Julia package and starter code (link **TBD**).
  - `tellegen.dev`, an interactive optimal power flow map that runs in your web browser.
  - The PGLib-OPF benchmark library of power system test cases.
  - The U.S. Energy Information Administration's Hourly Electric Grid Monitor (EIA-930) for real load and generation data.
  - The National Solar Radiation Database (NSRDB) for solar irradiance data.

Prerequisites/Corequisites

Familiarity with the core elements of these courses will be assumed and central to this class:

- Linear algebra: Math 21b or equivalent.
- Electricity and magnetism: Physical Sciences 12b, Physics 15b, or Applied Physics 50b.

A solid understanding of electrical circuits (ECE 50/ES 50 or a similar class) is also recommended. The following skills are helpful for ensuring success in this course, but are *not* prerequisites:

- Probability theory and statistical inference (e.g., Stat 110).
- Programming in any language (e.g., CS 32 or CS 50).
- Linear and convex optimization.
- Signals, linear systems, and controls.

Course Structure

The schedule of topics, readings, due dates, and weekly learning goals is posted separately on Canvas, and may change. There is no class and no new material during Reading Period (04/29 to 05/05). An optional, free, ungraded visit to the Blackstone Steam Plant is planned for Friday 02/12 (to be confirmed); participants sign a waiver, and a short reading is the alternative.

Homework 0: Your grid

Along with the first problem set, you will complete Homework 0: look up the grid that powers a place you care about, plot a week of its real electricity demand, set up the course software, and answer a short background survey and a few practice

problems. It is not graded for correctness; please answer honestly, because it helps me tailor the course to you.

Problem sets

There will be a problem set assigned approximately every 1-2 weeks. Problem sets are intended to assess both basic knowledge of the course material and to encourage a deeper understanding, so it is likely that some additional research will be required beyond coming to class. Each problem set comes with Julia starter code from Steinmetz.jl, but you may complete the computational problems in any language you like. Each problem in a problem set will be graded from 0-2 for understanding and completion. Credit will be assigned as follows:

- Solution was complete and correct: 2/2
- Solution was almost completely correct with a minor technical error 1.5/2
- Solution showed solid grasp of the problem, and was partially correct: 1/2
- Solution was partially attempted but was incomplete: 0.5/2
- Solution could not be understood or was not attempted: 0/2

The minimum of your problem set scores will not be considered in your final grade.

Each problem set follows the same rhythm: *predict*, *derive* by hand, *build* in code, *verify* against the laws of physics, try to *break* it, and *explain* in your own words. Each part says whether AI systems are permitted, and each submission ends with a short AI disclosure log. **Every point in this course can be earned without using AI systems**, and disclosed AI use where it is permitted is never penalized. Two class sessions include simulation labs, whose work is part of HW2 and HW6.

Participation puzzles

Beginning the second week of class, *participation puzzles* may occasionally appear in class. During a puzzle, a challenging, counter-intuitive problem will be presented in a fun or “game-ified" manner. The puzzle will be followed by a period of group discussion and peer feedback, and then reviewing the solution together. Puzzles will be graded on a binary scale, where full credit is earned for any submission. Per the name, you will always receive full credit for participating. The goal of the puzzles is to promote outside-the-box thinking, promote a community atmosphere, and encourage in-person attendance. I expect all students to receive full points in this section.

Midterm exam

There will be one written midterm exam, held in class on Monday 03/08 and covering the material through Wednesday 03/03, including locational marginal prices. It is closed book: no notes and no calculators. On your midterm revision and your final project report, you will sign the affirmation “I attest to the honesty of my academic work and affirm that it conforms to the standards of the Harvard College Honor Code."

The midterm exam may be revised; this opportunity is intended to encourage a growth mindset and to serve as a redemption opportunity for those who wish to improve their final grade. If you choose to revise your midterm exam, you must submit a 1 page reflection statement. A revision earns back half of the points you missed. Revisions must be your own work, with no collaboration and no AI systems.

Final project

In the final project, you will apply the tools from this course to a problem you care about, working individually or in teams of up to three on a real data set or a realistic test case. Examples include forecasting load for a real balancing authority, finding how much rooftop solar a feeder can host, or reconstructing an extreme weather event. I am happy to help you find a project. The milestones are an interest statement, a progress report, an in-person presentation on Monday 04/26, and a final report.

Assignments

Credit will be awarded for the work you do according to the following distribution:

- **0%**: Self-assessment (HW0: your grid, setup, and background survey)
- **10%**: Participation puzzles
- **20%**: Problem sets (x6, percentages evenly distributed)
  - HW1: AC power, three-phase systems, symmetrical components, and the per-unit system
  - HW2: Network matrices, the power flow equations, and contingencies
  - HW3: Generators, frequency control, faults, and transient stability
  - HW4: Economic dispatch, optimal power flow, and electricity markets
  - HW5: Power electronics and distribution systems
  - HW6: Grid data and machine learning

- **40%**: Final class project
  - **0%**: Project proposal/interest statement
  - **10%**: Progress report
  - **20%**: Final report
  - **10%**: In-person project presentation
- **30%**: Midterm exam + revisions

Credit will be recorded on Canvas. Please post a private note on Ed if anything on Canvas is incorrect. Your grade will be calculated based on the following credit thresholds:

$$\begin{aligned} &\text{A} \geq 93\%, \quad \text{A}- \geq 90\%, \quad \text{B}+ \geq 87\%, \quad \text{B} \geq 83\%, \quad \text{B}- \geq 80\%, \quad \text{C}+ \geq 77\%, \\ &\text{C} \geq 73\%, \quad \text{C}- \geq 70\%, \quad \text{D}+ \geq 67\%, \quad \text{D} \geq 63\%, \quad \text{D}- \geq 60\%, \quad \text{E} < 60\%. \end{aligned}$$

Final grades will follow all applicable FAS policies. You can take the course pass/fail with my permission. Because of limited staff time, students taking the course pass/fail may receive less detailed feedback on assignments.

Required materials

This is a computational and theoretical course, so the only required materials are a pen, a notebook, and a computer. We will run simulations in Julia with **Steinmetz.jl**, built on PowerIO.jl and JuMP. Julia is recommended but *not* required: you may use another language, such as Python with the `powerio` package, as long as your submissions follow each assignment's format. Julia can be more resource-intensive than Python; if your computer is not powerful enough, the SEAS Computing in Engineering Education program has a limited number of laptops to loan for the semester.

Course Expectations and Guidelines

Support for student health and well-being

I would like to ask that you please be kind to yourself. Your physical and mental health matter. I affirm my support for your well-being and I am thrilled that you have joined us to learn something new together this semester. If you are struggling, your Resident Dean is a great first point of contact. Other resources include Counseling and Mental Health Services (CAMHS) (CAMHS Cares, available 24/7: `(617) 495-2042`), the Academic Resource Center, the Ombuds Office, the Harvard Chaplains, and the Dean of Students Office. In an emergency, call the Harvard University Police Department at `(617) 495-1212`, or 911.

Office Hours

Walk-ins are welcome when my door is open.

Communication

Please ask technical questions on Ed Discussion, linked from Canvas (signup: **TBD**), so that everyone can see and add to the answers. For logistics, post a private note on Ed. Announcements go out through Canvas, and you are responsible for them, so I recommend turning on Canvas notifications. If I need to contact you personally, I will use your Harvard email address.

Attendance and participation

Lecture attendance is expected unless you have a compelling reason not to do so, but you are fully trusted and your time is respected. Excused absences include, but are *not limited to* religious or cultural observations, physical or mental health matters, job search obligations, or housing instability.

Religious observance. In accordance with Massachusetts General Laws Chapter 151C, Section 2B, any student who is unable to attend class, take an exam, or meet an assignment deadline because of religious observance will be excused, and will be given an opportunity to make up the missed work without penalty. Please let me know about any such conflicts as early in the term as possible so that we can plan together. If an observance conflicts with your project presentation, you may present on another date without penalty. Major observances are marked on the schedule.

Late Work Guidelines

- **Problem sets and the progress report:** You have two free *slip days*. Each one lets you turn in one assignment up to 24 hours late with no penalty. After your slip days are used, you may turn in any assignment up to 48 hours late with a 15% penalty. Assignments more than 48 hours late will not be accepted.
- **Midterm:** If you are sick or cannot attend the midterm, you may take a makeup exam, which may differ from the original.
- **Project:** The final report is due on our course's Final Deadline Group date set by the FAS, **TBD**. Extensions for illness or other serious reasons are possible until the end of the Final Examination Period (05/15); after that, only the Administrative Board can grant them.

Collaboration and group work

Students are *strongly* encouraged to discuss and collaborate on problem sets with one another. However, each student must individually produce and turn in their own solutions written in their own words, with code they wrote themselves. Please list everyone you collaborated with at the top of each submission. Collaboration of any kind is *not* permitted on the midterm exam. On the final project, collaboration within your team is expected, and any help from outside your team must be acknowledged. Cases where solutions appear to be identical or nearly identical will be immediately referred to the Harvard College Honor Council.

Use of Artificial Intelligence

Certain assignments in this course will permit or even encourage the use of artificial intelligence (AI) systems. By "AI systems," I mean any technology that is based upon or utilizes any form of foundation model (FM). The default for the course is that any such use is disallowed unless otherwise stated explicitly in the assignment. Any use of AI systems must be appropriately acknowledged and cited. Certain assignments may require students to provide such acknowledgements in an AI disclosure format. It is each student's responsibility to assess the validity and applicability of any AI output that is submitted; you bear the final responsibility for properly validating and citing the content of your work. Violations of this policy will be considered academic misconduct. Given the pace of improvement in the capabilities of AI systems, I reserve the right to revise this policy at any time. If such revisions occur, I will endeavor to do so in collaboration with those enrolled in the course, and to provide timely notice. Any revision will apply only to work that has not yet been assigned. I draw your attention to the fact that different classes at Harvard could implement different AI policies, and it is the student's responsibility to conform to expectations for each course.

Academic Integrity and Honesty

At Harvard, we believe that it is important to strive for an atmosphere of mutual respect, acknowledgement, and responsibility between faculty members and the student body. The Harvard College Honor Code articulates the basic expectations that we share:

> Members of the Harvard College community commit themselves to producing academic work of integrity – that is, work that adheres to the scholarly and intellectual standards of accurate attribution of sources, appropriate collection and use of data, and transparent acknowledgement of the contribution of others to their ideas, discoveries, interpretations, and conclusions. Cheating on exams or problem sets, plagiarizing or misrepresenting the ideas or language of someone else as one's own, falsifying data, or any other instance of academic dishonesty violates the standards of our community, as well as the standards of the wider world of learning and affairs.

See the Harvard College Student Handbook for more details. In the end, simple respect for knowledge, hard work, and cordial interactions will help build the environment we seek. Therefore, I encourage you to remain committed to the ideals of the Honor Code while in this class.

Accommodations for Students with Disabilities

Harvard University values inclusive excellence and providing equal educational opportunities for all students. Our goal is to remove barriers for disabled students related to inaccessible elements of instruction or design in this course. If reasonable accommodations are necessary to provide access, please contact the Disability Access Office (DAO) at `(617) 496-8707` or `dao@fas.harvard.edu`. Accommodations do not alter fundamental requirements of the course and are not retroactive. Students should request accommodations as early as possible, since they may take time to implement. Students should notify DAO at any time during the semester if adjustments to their communicated accommodation plan are needed. In addition, if you are a student with **visible or invisible** challenges, please know that you can reach out to me to discuss your learning needs, so that I can best serve you.

Recording of class sessions

Unauthorized audio or video recording of class sessions is not permitted. Lectures will not be recorded by default; if you need a recording because of an accommodation or a religious observance, please contact me so that we can arrange one. Audio recording approved by the Disability Access Office is always permitted.

Sexual and gender-based harassment

Harvard is committed to an educational environment free from discrimination and harassment. If you or someone you know has experienced sexual or gender-based harassment, confidential support is available from the SHARE Team at `(617) 496-5636` (24/7 hotline: `(617) 495-9100`). The Office for Community Support, Non-Discrimination, Rights, and Responsibilities (CSNDR) can explain your options, and the College Title IX team can be reached at `collegetitleix@fas.harvard.edu`. All course staff are Responsible Employees: if you tell one of us about sexual or gender-based harassment, we must share it with a Title IX Resource Coordinator. SHARE is confidential.