EE-466 Energy Storage Systems and Applications

Course Introduction

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Course program

- Fundamentals of energy storage and applications
- Overview of major energy storage technologies and their key attributes
- In-depth discussions of:
  - Batteries (models, battery management systems, and safety)
  - Pumped-storage hydropower
- Scheduling and operation of energy storage systems
- Lab: equivalent-circuit models of battery cells and state-of-charge (SoC) estimation

(Not in chronological order).

Expectations: what not to expect from this course

What not to expect:

- The course will not cover detailed technological design aspects of energy storage technologies.

- For example: you will not learn how to design a battery cell (electrochemistry), a pump-turbine (mechanical design and computational fluid dynamics), or a membrane for a proton-exchange membrane fuel cell (materials science).

Expectations: what to expect from this course

What to expect:

- The course focuses primarily on the applications and integration of energy storage technologies.
- You will learn mathematical models that capture, with reasonable accuracy, the properties of energy storage relevant for practical applications (e.g., in power systems).
- By the end of the course, you should be able to understand the main properties of energy storage technologies, outline algorithms for scheduling their operation, and gain insights into how to determine their design parameters (e.g., power rating and energy capacity).

Classes teaching materials

The course consists of ex-cathedra lectures, guest lectures and seminars from experts, and one online module (a recorded class).

The teaching material consists of:

- the slide pack of all classes (handed over in in digital form at the beginning of the class, or after the class for seminars)
- the additional resources suggested in the slides
- the development of the teacher at the blackboard and the in-class discussions.

If errors are spotted on the slides during the class, I will do my best to provide the corrected slides after the class on moodle.

Communication during the course

If I need to pass along important information (updates to the program, important news, updates on exam modalities), I will use the forum section on moodle.

Exercises

Exercise sessions are designed to apply the modeling and theoretical concepts covered in the course. They typically consist of coding exercises.

I will refer to MATLAB (which I recommend and which is available through the campus license linked to your email address), but the exercises can be adapted to other languages if you wish. No advanced programming concepts are required (e.g., no object-oriented programming or similar).

Laboratories – to be confirmed

In laboratory ($\neq$ exercise) sessions, you will play with real hardware (battery cells) and measurements.

Laboratory will start after the autumn break (week 4 of October or week 1 of November, to be defined later according to the course program development).

There are two laboratory sessions, followed by one presentation of your achievement (“laboratory presentation”).

Laboratories: Session 1

Identification of open-circuit-voltage (OCV) versus state-of-charge (SOC) curve of a battery. Duration: 4 hours.

20 groups of 2 if less than or equal to 40, or groups of 3 if more than 40.

Laboratories: Session 2

SOC estimation problem. 4 hours (one class session will be devoted to this) + independent work as necessary

You will

- review literature on SOC estimators
- implement a SOC estimator of your choice/your design
- be given with some time series that you can use to test and validate your model

Laboratories: Session 2 - Competition among SOC estimators

- You will implement your SOC estimator to estimate the battery SOC in real-time given with a one-use current and voltage time series.
- Results will be recorded and ranked.
- Each team will prepare a 5 min presentation illustrating the principle of their SOC estimator. The score of each team will be released after their own presentation. A ranking will be produced at the end of all presentations.

Exam modalities

Final mark = 50% Midterm exam + 50% Final semester written exam

Midterm exam (exact modalities to be defined soon):

- It will not be a written exam; instead, it will consist of a report or a presentation, prepared offline and—if applicable—presented in class, based on the course activities.
- Timing: expect the workload to be concentrated between November and early December, with a preparation period of 1–2 weeks.

Exact dates and modalities will be communicated soon (end of September max.).

Midterm exam: Example from the last academic year

Evaluation of the laboratory work:

- Originality of the developed method: 30%
- Modelling performance: 40%
- Presentation quality and delivery: 30%

Presentations should also specify the division of the work among team members. The mark for the laboratory work is the same for all group members (unless cases of severe disparity of workload among team members; this case will be discussed individually with me).

Timeline and course development

Course and class schedule

The formal schedule is 2 academic hours of lecture and 1 hour of academic exercise per week (1 academic hour = 45 minutes).

In practice, this division is not convenient. Please expect and plan for a single block (e.g., a full class, or laboratory) of 2.5 to 3 academic hours instead. As this may affect the overall workload (ECTS), we may conclude 1–2 weeks earlier once the program is finalized.

Class schedule (2h - 2h15 effective time):

- 13:15 - 14:30: Part I
- 14:30 - 14:45: 15-min pause
- 14:45 - 15:30 (or 45): Part II

Course calendar and special arrangements

All according to the official calendar (is-academia), except for the following dates:

- Thu, Sept 25: No physical class. Online lecture on "Optimal Scheduling of Energy Storage Systems"
- Thu, Oct 2: (Recommended, not mandatory) Visit to HES-SO labs and seminar in Sion on "Harnessing Hydropower's Energy Storage and Flexibility for the Energy Transition," with speakers from academia and industry
- Thu, Oct 16: Guest lecture by an industrial speaker (to be confirmed). Expected duration: 2h30
- Thu, Oct 23: Autumn break (no class)

The class end date will be determined based on the estimated effective workload and may be moved up by 1 or 2 weeks.

Thu, Oct 2 afternoon

Class replaced with a seminar at the Energypolis campus of Sion (rue de l'industrie 23, 1950 Sion), preceeded by a visit to the energy & energy storage infrastructure of HES-SO VS.

Tentative program (to be confirmed further):

- 15:15 - 16:15: Visit to the battery system and CO2 network for space heating.
- 16:40 - 18:40: Seminar with title "Harnessing Hydropower's Energy Storage and Flexibility for the Energy Transition", with industrial and academic speakers (Alpiq, KWO, HES-SO, UPC)

A registration link will follow for organizational purposes. Travel arrangements are to made on your own. A recording of the seminar might be available for those who can't join.

Introduction

Storage: high-level definition and examples

Plenary discussion

Simple energy storage model

The power-to-energy relation in continuous time is

$$\dot{E}(t) = P(t)$$

Discretizing it by applying the difference quotient definition on an finite time interval with duration Δ_T yields:

$$\frac{E(t + \Delta_T) - E(t)}{\Delta_T} = P(t).$$

Rearranging:

$$E(t + \Delta_T) = E(t) + P(t)\Delta_T. \tag{1}$$

Simple energy storage model (cont'd)

Calculating (1) at $t = 0$ yields:

$$E(\Delta_T) = E(0) + P(0)\Delta_T.$$

At $t = \Delta_T$:

$$E(\Delta_T + \Delta_T) = E(\Delta_T) + P(\Delta_T)\Delta T.$$

Replacing the first equation above into the second gives:

$$E(\Delta_T + \Delta_T) = E(0) + P(0)\Delta T + P(\Delta_T)\Delta T.$$

Simple energy storage model (cont'd)

At $t = k\Delta_T$ (with k being a non-negative integer variable):

$$E\left((k+1)\Delta_T\right) = E(0) + \sum_{\tau=0}^{k} P(\tau\Delta_T)\Delta_T.$$

With a slight abuse of notation (since t was a real variable and already used for the time), redefining t as being the index of the time interval, the expression above becomes:

$$E\left(t+1\right) = E(0) + \sum_{\tau=0}^{t} P(\tau)\Delta_T.$$

Simple energy storage model (cont'd)

The expression

$$E\,(t+1) = E(0) + \Delta_T \sum_{\tau=0}^{t} P(\tau)$$

can be used to compute the **state-of-energy** (SOE) of an (ideal) energy storage resource at a time interval $t+1$ as a function of the discrete-time charging (positive)/discharging (negative) power $P(t)$ and an initial known energy status $E(0)$. In continuous-time, $P(t)$ is assumed to be constant in the interval Δ_T (piecewise constant).

A well-interpretable unit for Δ_T is "hour", so that if P is in kW, E is in kWh.

Above, a positive $P(t)$ denotes charging power because it increases the SOE; for a grid-connected energy storage asset, this corresponds from taking power from the power grid. A negative $P(t)$ denotes discharging power, the system injects power into the grid. (passive sign convention, if active convention is wished, one can adapt the definition above by changing the sign of the power)

Simple energy storage model: state of charge (SOC)

Say $\bar{E}$ is the "energy capacity" (the maximum value of energy you can store in an energy storage asset) of an energy storage resource, a state-of-charge model (we will see a more accurate one for batteries) can be derived by dividing the state-of-energy $E(t)$ by the energy capacity $\bar{E}$.

With this definition in place, the SOC evolution in discrete time can be computed as:

$$\mathrm{SOC}\,(t+1) = SOC(0) + \frac{\Delta_T}{\bar{E}} \sum_{\tau=0}^{t} P(\tau).$$

Simple energy storage model: including (energetic) efficiency

Energy storage resources are “energetically” non-ideal, meaning that the conversion from power to stored energy and back happens with losses. The model seen above does not account for this.

To model losses, one can augment the model above by rescaling the charging/discharging power $P(t)$ by, say, an efficiency factor $\eta < 1$ to account that not all the power makes it to the SOE due to losses in the process. Note the following:

- for positive (charging) power $P(t)$, applying the efficiency as $\eta P(t)$ makes sense to reflect that only a fraction of the input power contributes to increasing the SOC;
- however, for negative (discharging) power $P(t)$, rescaling the power as $\eta P(t)$ would yield a reduction in SOC that is smaller than in the unit-efficiency case. This is not reasonable, since a lower efficiency should correspond to a deeper discharge for the same $P(t)$, not the opposite. Therefore, the discharging power should be rescaled by the inverse of η ...

Simple energy storage model: including energetic efficiency (cont'd)

The SOC model with efficiency reads as follows:

$$\mathrm{SOC}\,(t+1) = SOC(0) + \frac{\Delta_T}{\bar{E}} \sum_{\tau=0}^{t} \left(\eta\,[P(\tau)]^{+} - \frac{1}{\eta}[P(\tau)]^{-} \right).$$

where the notation $[x]^{+}$ and $[x]^{-}$ denotes the positive and negative part of the argument x respectively. They are defined as the following non-negative functions:

$$[x]^{+} = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases} \qquad [x]^{-} = \begin{cases} 0 & \text{if } x > 0 \\ -x & \text{otherwise} \end{cases}$$

With $\eta = 1$, this model reduces to the model with ideal efficiency.

Exercise 1

- In Matlab, develop a code to compute the state of charge over time of an energy storage system with a charging/discharging efficiency of 0.75 and energy capacity of 100 kWh. Consider a sampling period of 60 seconds. Test it for a discrete-time power profile sampled from a Gaussian distribution (1000 samples) with 0 mean and a variance of 20.

- Compare the results against the same power profile applied to an ideal energy storage system ($\eta = 1$). What can you conclude from comparing the trajectories of the two state-of-charge time series? Use either a plot (visual comparison) or another metric you feel it is pertinent.

Exercise 2

Assume an energy storage system with a capacity of $\bar{E}$ (kWh) and charging/discharging efficiency of η. Say that such a system has to deliver, in the next actuation period, a power value (piecewise constant in the actuation interval) of known magnitude but unknown direction, denoted by $+p$ or $-p$ (kW). Calculate the initial state of charge such that, after the actuation, the system has symmetric margins from the physical state of charge limits (i.e., 0% and 100%).

(Examples of "symmetric" margins are 10% - 90%, 20% - 80%, etc.)