# Energy Storage

# Course Introduction

Prof. Dr. Fabrizio Sossan (HES-SO Valais-Wallis)

fabrizio.sossan@hevs.ch

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This slide-pack is available on Moodle, which is progressively being updated.

# Timeline

2 hours per week of class + 1 hour per week of exercises.

Calendar issues to be discussed together:

- Thursday September, 26th. I am not available due to an overlapping event where I must present. Can we please shift to Friday September 27th 8-10?
- For 3 or 4 weeks of the course in the period end of October - December (detailed calendar to be released soon), I will need 4 hours instead of the usual 3 to allow for laboratories and extended classes. Silver lining is that the course will finish 2 weeks earlier than planned. Are you OK with this?
- Thursday October 10th: Guest lecture from industrial speaker (to be confirmed). Expected duration: 2h30 max.

# Topics

- Fundamentals of energy storage and applications
- Overview of main energy storage technologies:
  - **Batteries** (models, battery management system, and safety)
  - Pumped-storage hydropower
  - Power-to-gas
  - Flywheel and compressed-air energy storage
  - Demand Response
- Control and scheduling of energy storage
- Sizing energy storage systems
- Lab's: equivalent circuit models of battery cells and SOC estimations

(Not in chronological order).

# Expectations

What not to expect:

- the course is not about technologies, and it won't break down their theory details
- e.g., you will not be capable of designing a battery cell (electrochemistry), a water pump-turbine (mechanical design and computational fluid dynamic), or a membrane for a proton-exchange membrane fuel cell (material science).

What to expect:

- the course focuses primarily on integration and applications of energy storage technologies.
- the course will teach mathematical models that capture reasonably well the dynamics that are interesting for a practical (power system, typically) application;
- you might be capable of interpreting the main properties of energy storage technologies, sketching control algorithms for their scheduling and operations, and determine their design values (e.g., power rating and energy capacity).

# Classes and exercise

Classes are ex-cathedra. The teaching material consists of:

- the slide pack
- the additional resources suggested in the slides
- the development of the teacher at the blackboard and the in-class discussions.

Slides are handed over (in digital form, PDF) at the beginning of the class.

Exercise sessions are typically on Matlab and aimed at putting into practice the modeling notions seen in the class. Please install MATLAB.

# Laboratories

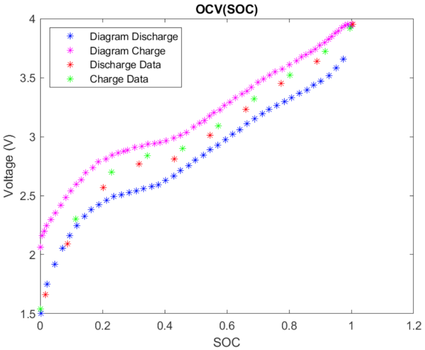
In laboratory ($\neq$ exercise) sessions, you will play with real hardware (battery cells) and measurements.

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: Laboratory 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: Laboratory 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: Laboratory 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.

# Lab summary and timeline

| Week(s) | Lab name | Activity |
|---|---|---|
| $\omega_0$ | 1 | OCV vs SOC identification |
| $\omega_0 + 1$ | 2 | Development of the SOC estimator. No class, independent work during the class time. |
| $[\omega_0 + 1, \omega_0 + 3]$ | 2 | The platform (web service) for the submission of the results is open. Weekly exercise sessions dedicated to delivering results and finalizing presentations. |
| $\omega_0 + 4$ | Laboratory presentation | Presentations from all teams, and publication of the competition results |

$\omega_0$ to be defined in 3-4 weeks according to class development.

# Exam modalities

Final mark = 50% Laboratory work + 50% Final semester written exam

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).

# Storage: high-level definition and examples

# Simple energy storage model

The power-to-energy relation in continuos time is $\dot{E}(t) = P(t)$. Discretizing it by applying the difference quotient definition on an finite time interval with duration $\Delta_T$ yields:

$$\frac{E(t+\Delta_T) - E(t)}{\Delta_T} = P(t), \quad \text{rearranging: } E(t+\Delta_T) = E(t) + P(t)\Delta_T.$$

Calculating the expression above for consecutive multiples of $\Delta_T$ reads as:

$$\begin{aligned} &E(\Delta_T) = E(0) + P(0)\Delta_T \\ &E(\Delta_T + \Delta_T) = \underbrace{E(\Delta_T)}_{\text{Calculated above}} + P(\Delta_T)\Delta T = E(0) + P(0)\Delta T + P(\Delta_T)\Delta T. \end{aligned}$$

By iterating, one gets:

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

Say now that $t$ is an index ($\{0, 1, 2, \dots\}$) for discrete-time intervals with duration $\Delta_T$ ([1]):

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

[1] Excuse the abuse of notation as $t$ referred to continuous time at this slide's beginning.

# Simple energy storage model: state of energy (SOE)

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 $\Delta_T$ (piecewise constant).

A well-interpretable and convenient unit of measurement for $\Delta_T$ is "hour", so that if $P$ is in kW, $E$ is in kWh.

Positive values of $P(t)$ denote charging power because they contribute to increasing the SOE; in the case of a grid-connected energy storage asset, the resource "absorbs" power from the grid. Negative values of $P(t)$ denote discharging power; the resource injects power into the grid.

# 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 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 result in a reduction of SOC that is smaller than the unitary-efficiency case. This effect is not reasonable because a lower efficiency should be reflected by deeper discharge values for the same $P(t)$, and not vice-versa. The discharging power should be rescaled by the inverse of $\eta$.

# Simple energy storage model: including 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:

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

Both are non-negative functions by construction.

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

# Exercises for today

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 0.5 and energy capacity of 100 kWh. Consider a sampling period of 600 seconds. Test it for a power profile sampled from a Gaussian distribution (1000 samples) with 0-kWh mean and 100-kWh standard deviation. Compare 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.
2. Assume an energy storage system with a capacity of $\bar{E}$ (kWh) and charging/discharging efficiency of $\eta$. 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.