Energy Storage Control with Aging Limitation

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(based on PowerTech 2015 article)

Outline of the presentation

1. Introduction to aging control

2. ESS control with aging limitation

3. Control evaluation on a simulation

4. Conclusion

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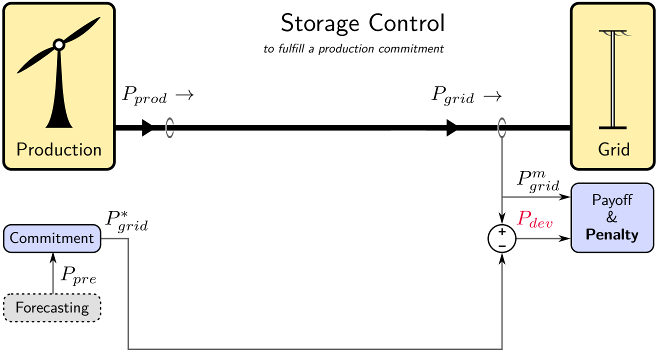
Why an Energy Storage System (ESS) ?

example usage: a wind-storage system

Objective: the wind farm must respect a **day-ahead commitment**.



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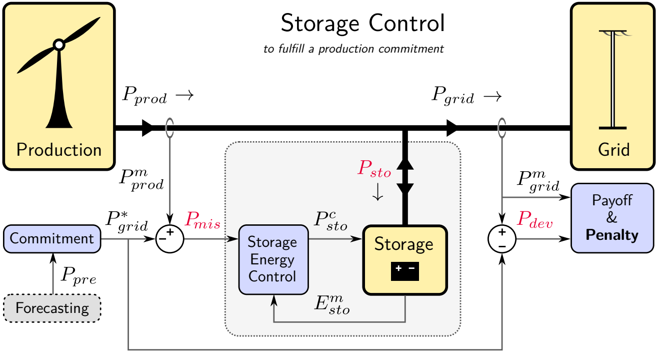

$\rightarrow$ an ESS is used to mitigate commitment errors:

$$P_{dev} = P_{mis} - P_{sto}$$

The issue of storage aging

Technological problem: ESS (electrochemical) can only perform a **limited number of charge/discharge cycles** over its lifetime.

To avoid the high cost of premature replacements, aging should be taken into account:

- in the system design: aging-aware ESS sizing
- in the energy management: aging-aware ESS control

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- in the energy management: aging-aware ESS control

Main question being addressed

How to embed the limitation of storage aging,
as a strict constraint,
in the energy management optimization ?

aging constraint: $N_{cycl}(T_{life}) \leq N_{life}$

example: $T_{life} = 20$ years, $N_{life} = 3000$ cycles

Modeling battery aging: some background

Battery aging is a complex physical (chemical/thermal/mechanical) process. It usually split into two:

- **cycling** aging: happens when charging/discharging.
- **calendar** aging: happens *even* at rest ($\neq$ *only* at rest).

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Basis of this work on aging-aware energy management

A simple **empirical** model of **cycling** aging: "energy counting"

Modeling **cycling** aging

Cycling aging is modeled using the **energy counting** method:

$$N_{cycl}(t) = \frac{1}{2E_{rated}} \underbrace{\int_0^t |P_{sto}| dt}_{\text{exchanged energy}}$$

$N_{cycl}(t)$ is the number of *equivalent full cycles* at each instant.

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→ aging constraint can be re-expressed as a constraint on the **lifetime average** of $|P_{sto}|$:

$$\langle |P_{sto}| \rangle_{T_{life}} \leq P_{exch} \quad \text{with} \quad P_{exch} = \frac{2E_{rated}N_{life}}{T_{life}}$$

ex: $E_{rated} = 1\,\text{h},\ N_{life} = 3000,\ T_{life} = 20\ \text{yr} \rightarrow P_{exch} = 0.034\,\text{pu}$

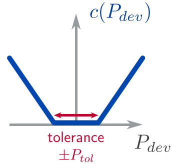
Outline of the presentation

Optimal energy management

ESS energy management is treated as an **optimization problem**: minimize J, the *average* of an instant penalty *cost*:

$$J = \frac{1}{K}\mathbb{E}\left\{\sum_{k=0}^{K-1} cost(k)\right\} \quad \text{with } K \to \infty$$

$$\text{with } cost(k) = \max\left\{0, |P_{dev}(k)| - P_{tol}\right\}$$



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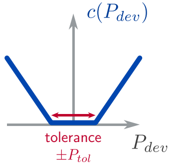


$$\text{with } cost(k) = \max\left\{0, |P_{dev}(k)| - P_{tol}\right\}$$

...while respecting the aging constraint:

$$\langle |P_{sto}| \rangle_{T_{life}} \leq P_{exch}$$

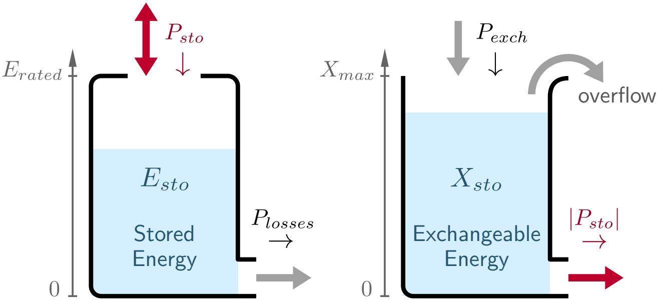
Algorithmic difficulty of this optimization

a constraint on a T_{life} horizon (~10 years) is not manageable!

→ a reformulation is needed

Reformulation of the aging constraints

To deal with cycling aging on a "reasonable" horizon, I introduce a new state variable: X_{sto} a buffer of "exchangeable energy":



$$X_{sto}(k+1) = \mathrm{sat}\{X_{sto}(k) + (P_{exch} - |P_{sto}(k)|)\Delta_t\}$$

similarity with the dynamics of the storage $E_{sto}(k+1) = E_{sto}(k) + P_{sto}(k)\Delta_t$

Reformulation of the aging constraints: properties

Aging limitation is guaranteed

Keeping the "exchangeable energy" buffer non empty ($X_{sto} \geq 0$) is a sufficient condition to satisfy the aging constraint $\langle |P_{sto}| \rangle_{T_{life}} \leq P_{exch}$

Reformulation of the aging constraints: properties

Aging limitation is **guaranteed**

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Always **feasible** solution

Constraint on the state $X_{sto} \geq 0$ can be transfered to the control variable:

$$|P_{sto}(k)| \leq P_{exch} + X_{sto}(k)/\Delta_t$$

which is always feasible.

Outline of the presentation

Validation test case

Input data for the simulation:
The ESS control is simulated with a 132 MW wind farm from NREL "Eastern Wind Dataset" (publicly available):

- 3 years of production/forecast data, with a 1 hour timestep.
- mean production of the farm: 0.343 pu
- RMS forecast error: $\sigma_P = 0.195$ pu.

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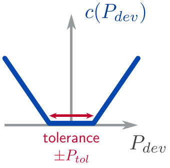
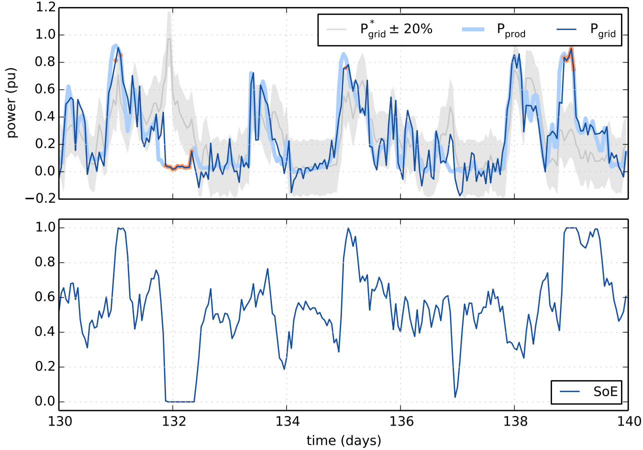
Penalty for commitment errors:



The tolerance for the deviation penalty is set at 0.2 pu

Simulation results

10 days extract, with over tol. P_{grid} highlighted in orange



No storage:

- 28 % over tol.

Optimal control:

- 6 372 cycles
- 8.5 % over tol.

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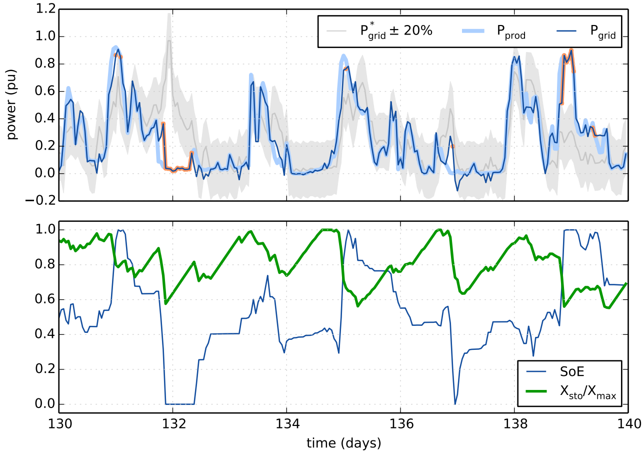


No storage:

- 28 % over tol.

Optimal control:

- 6 372 cycles
- 8.5 % over tol.

Optimal control with aging lim:

- 2 966 cycles
- 10 % over tol.

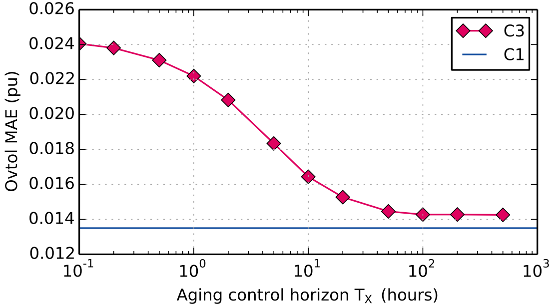
→ The aging limiting control is effective.

→ Aging limitation comes with a slight performance drop.

Choosing the Aging Control Horizon

Our aging limiting control is based on a buffer of "exchangeable energy" X_{sto}. The buffer size (X_{max}) needs to be hand-picked.

Effect of the "aging control horizon" ($T_X = X_{max}/P_{exch}$)



→ an horizon of 2-3 days is enough (for this example).

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Conclusion

Contribution

A formulation of cycling aging which fits naturally in the ESS control optimization.
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Going further

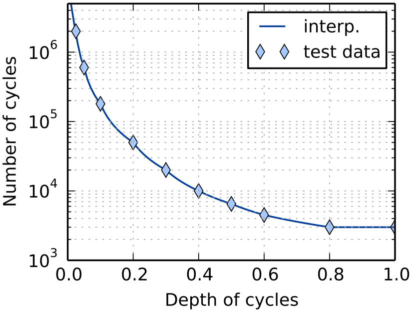
Adapt the method to also deal with calendar aging.

(calendar aging often depends on operational conditions like SoE, in particular for super capacitors)

Bonuses

- Lithium-ion aging curve
- A similar approach for calendar aging ?
- Aging as a constraint vs. as a penalty ?

Lithium-ion aging curve



Aging curve of a Lithium-ion NCA battery by SAFT (Lippert, 2010):

- 3000 cycles at full discharge depth.
- many more small cycles (180k at 10%)

Relation to the "energy counting" model used in this work

assumption $N_{cycles} \propto 1/DoD$ (conservative)

A similar approach for calendar aging ?

Similar ideas could lead to a reformulation of the calendar aging. However, there is one extra difficulty:

- calendar aging **depends on the state** (T, SoE) instead of just the control variable (P_{sto})
- so I'm not sure it is possible to get an always feasible constraint on the control.

Aging as a constraint vs. as a penalty ?

Option 1: penalize cycling with its *real levelized cost*: can be over overwhelming!

Option 2: tunable penalty $\rightarrow$ burden of parameter tuning for the control designer.

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Argument against penalizing aging:

1. once operation starts, the battery is already paid
2. calendar aging will kill the battery anyway
3. so this is my claim: the marginal cost of cycling *within the allowed cycling bound* is zero.

$\rightarrow$ use instead a constraint on maximum number of cycles.