Energy Storages Modeling

Varaiya Energy Group

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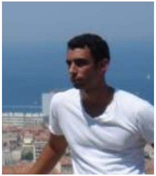
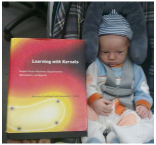
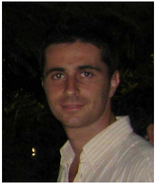
entirely written in LaTeX2ε using Beamer and Tik Z

Varaiya Energy Group: Composition





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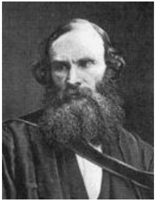
Objectives of this presentation

"If you can not measure it, you can not improve it." - Lord Kelvin



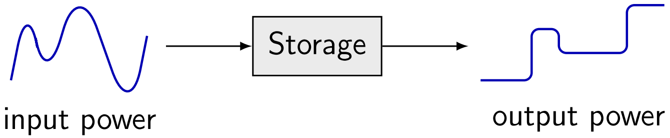
Main points:

1. despite the diversity of the storaging technologies, it is possible to capture every peculiarity into a single model
2. with generic models we can:
   - develop abstract controllers
   - help the design process

Definition of Energy Storage

Definition

Energy storage := device with the capability of sculpting power signals (subject to operational constraints)



Remark

There are ***no constraints on how to store*** the energy. For example: • kinetic • chemical • gravitational

Summary of technologies

- CAES
- Electrochemical
- Flywheels
- Pumped Hydro
- SMES
- Thermal (?)

Summary of applications

- ancillary & reliability services:
  - spinning reserve
  - *voltage regulation*
  - *area / frequency control*
  - transmission line stability
  - power supply against outages
  - smoothing of renewables ramping effects
- implementation of new market strategies
- load levelling / peak reduction
- generation capacity / transmission / distribution facilities deployment deferral

[Schoenung and Hassenzahl, 2007]

Summary of usages

Application category	*Technology*
Load leveling and spinning reserve	Electrochemical (Lead-acid, Na/S, Zn/Br, Ni/Cd), CAES, Pumped Hydro
Peak shaving and transmission deferral	Electrochemical (Lead-acid, Na/S, Zn/Br, Ni/Cd, Li-Ion), CAES, Flywheels
End use power quality and reliability	Electrochemical (Lead-acid, Li-Ion), Flywheels, SMES

[Schoenung and Hassenzahl, 2007]

Development of a Generic Model

Requirements

- should ***consider every characteristic of every technology***
- should be ***widely applicable***

Development of a Generic Model

Requirements

- should ***consider every characteristic of every technology***
- should be ***widely applicable***
- should be ***as simple as possible***

William of Ockham, c. 1288 - c. 1348

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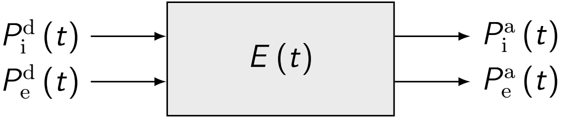
- maximal ramping capabilities on the transferred power
- (possible) delays in power / energy conversions
- (possible) impossibility of simultaneous power injection / extraction
- (possible) waiting-time when switching between power injection / extraction

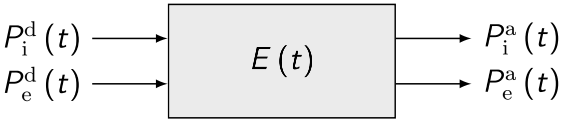
What we want to have as a block scheme



signal	*physical meaning*
$P_i^d(t)$	desired injected power at time t
$P_e^d(t)$	desired extracted power at time t
$P_i^a(t)$	actually injected power at time t
$P_e^a(t)$	actually extracted power at time t

Conceptual division into sub-blocks

Our target:



Our conceptual division:

1. dynamics of stored energy
2. conversion of the injected power into stored energy
3. conversion of the stored energy into the extracted power

Sub-block 1: dynamics of stored energy

Hybrid first-order system:

$$\dot{E}(t) = \begin{cases} \eta_{\mathrm{i}} P_{\mathrm{i}}^{\mathrm{a}}(t) - \eta_{\mathrm{e}} P_{\mathrm{e}}^{\mathrm{a}}(t) - P_{\mathrm{diss}}(t) & \text{if } E(t) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where:

$$P_{\mathrm{diss}}(t) := \gamma E(t) + \gamma_{\mathrm{man}} \tag{2}$$

Sub-block 2: conversion of the injected power into stored energy

Constraints to be taken into account:

- constraints on the maximal power:

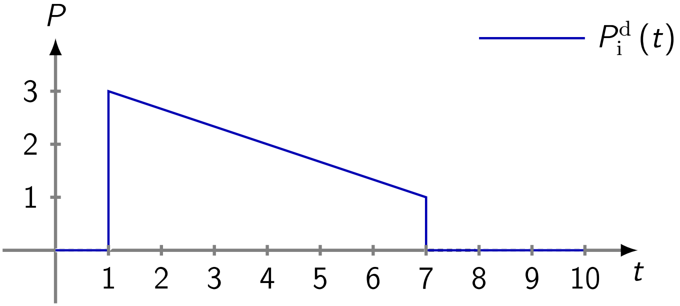
$$P_{\mathrm{i}}^{\mathrm{a}}(t) \in \left[0, P_{\mathrm{i}}^{\max}\right] \tag{3}$$

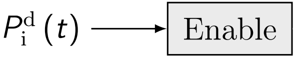
- constraints on the ramping capabilities:

$$\dot{P}_{\mathrm{i}}^{\mathrm{a}}(t) \in \left[-\dot{P}_{\mathrm{i}}^{\max}, \dot{P}_{\mathrm{i}}^{\max}\right] \tag{4}$$

- (possible) forbidden simultaneous injection / extraction

Sub-block 2: graphical example





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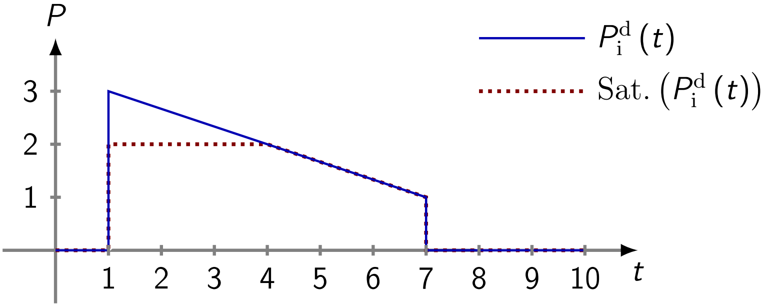
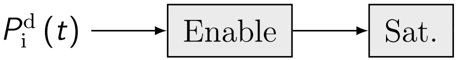
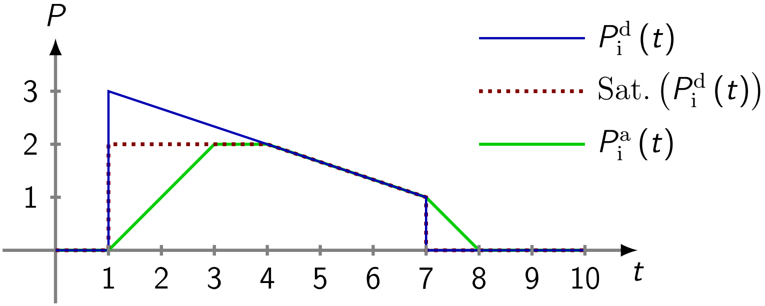




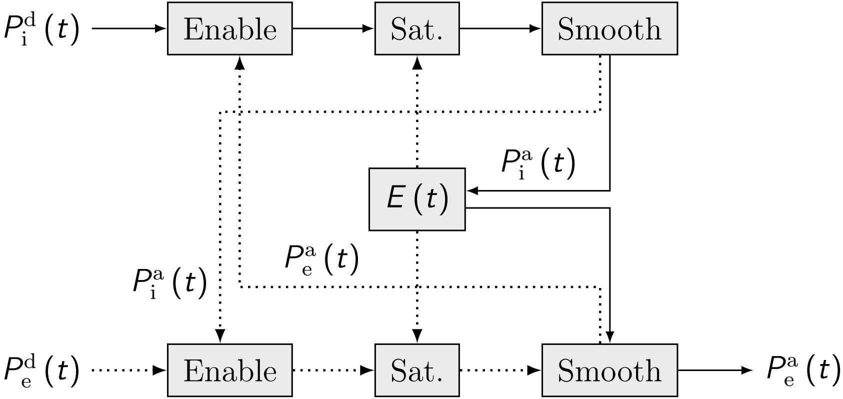
Sub-block 2: graphical example



Sub-block 3: conversion of the stored energy into the extracted power

. . . same as before . . .

Proposed General Block Scheme



Parameters considered by the proposed model

parameter	*physical meaning*
d_{i} / d_{e}	time delays between injection / extraction of power and conversion into / from stored energy
$P_{\mathrm{i}}^{\max}$ / $P_{\mathrm{e}}^{\max}$	maximal injectable / extraible power
$\dot{P}_{\mathrm{i}}^{\max}$ / $\dot{P}_{\mathrm{e}}^{\max}$	maximal injected / extracted power ramp
T_{inj} / T_{ext}	(possible) delays in commuting between injection and extraction modalities
$E_{\min}$ / $E_{\max}$	minimal / maximal amount of storable energy
η_{i} / η_{e}	power injection / extraction efficiencies
γ / γ_{man}	energy leakage factors

Summary of common values in [Varagnolo et al., 2010]

Transformation of the Proposed Hybrid Model

caveat: previous model is non-standard!!

For DP or MPC purposes transform it into:

$$\begin{cases} x(t+1) &= & Ax(t) & +B_1 u(t) & +B_2 \delta(t) & +B_3 z(t) & +B_4 \\ y(t) &= & Cx(t) & +D_1 u(t) & +D_2 \delta(t) & +D_3 z(t) & +D_4 \\ 0 &\leq & E_0 x(t) & +E_1 u(t) & +E_2 \delta(t) & +E_3 z(t) & +E_4 \end{cases} \quad (5)$$

with:

- $x(t)$ state vector
- $u(t)$ input vector
- $y(t)$ output vector
- $z(t)$ auxiliary continuous variables
- $\delta(t)$ auxiliary binary variables

Need for a Model Simplification

Previous model is fairly complicated. Need to:

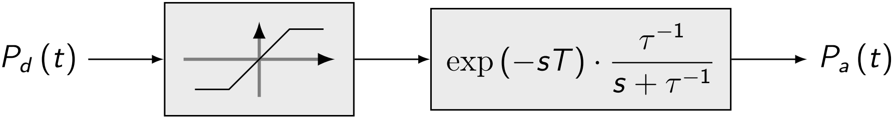
- simplify
- then validate

Model Simplification

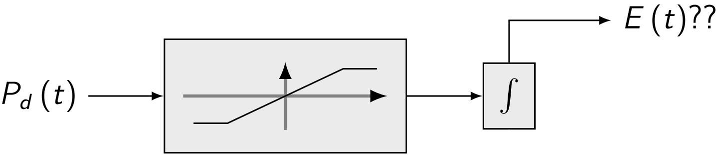
1. "injection" and "extraction" signals become a single one
2. power $\leftrightarrow$ energy transformations are ***first-order*** systems

Reduced Model Block Scheme

If not considering the energy dynamics:

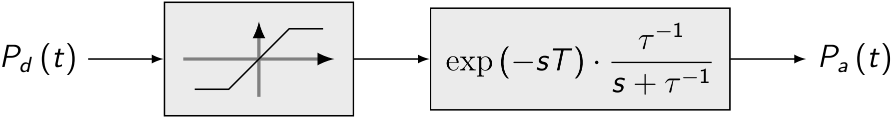


Energy dynamics require additional blocks:



Reduced Model Block Scheme

If not considering the energy dynamics:



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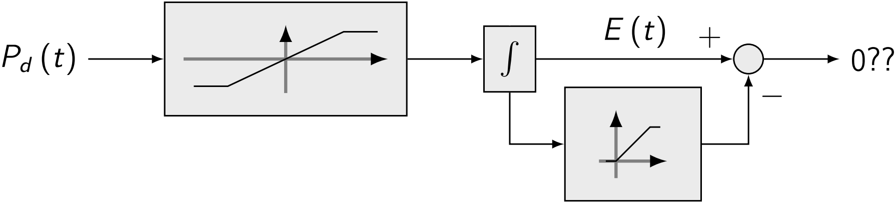

Validation and comparison of the proposed models

Validation

- generic model should be validated vs. real data
- simplified model should be validated vs.:
    - real data
    - "higher fidelity" models

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Comparison

1. formalize a problem and solve it ***in the same framework***
2. then:
   - compare the resulting resignals
   - compare the problem-specific costs
   - compare the sensitivities (e.g. Lagrange multipliers)

Examples on how the models can be used

Recap: ***general models can be used both for control and design purposes***. Toy-examples:

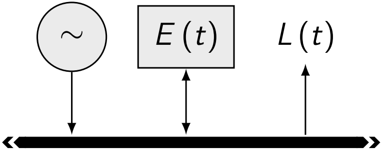
Control-oriented problem

Service of deterministic loads with co-located generation

Design-oriented problem

Deployment of energy storages for energy arbitrage

Example: service of deterministic loads with co-located generation

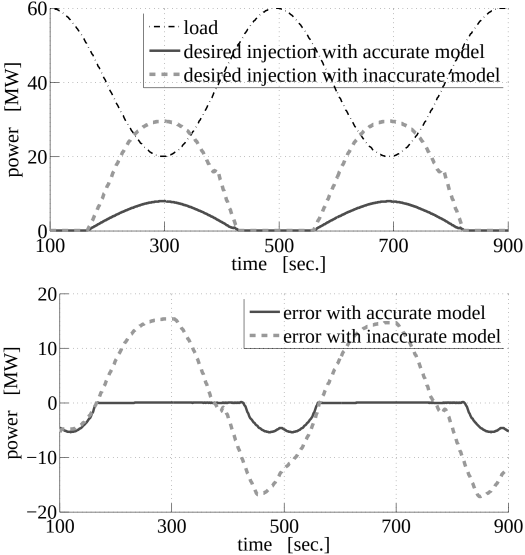


$$P_{\mathrm{gen}}(t) = T(z)\, r(t)$$
$$|r(t)| \leq R$$

Optimization problem:

$$\begin{aligned} \text{minimize} \quad & \sum_{t=1}^{T} \left| P_{\mathrm{gen}}(t) + P_{\mathrm{e}}(t) - P_{\mathrm{i}}(t) - L(t) \right| \\ \text{subject to:} \quad & \bullet \ \textit{dynamics of the storage} \\ & \bullet \ \text{dynamics of the generator} \end{aligned} \tag{6}$$

Example (cont'd): importance of accurate models

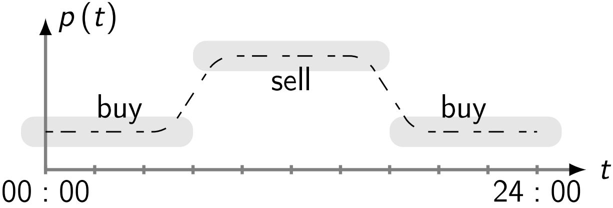


Example: deployment of energy storages for energy arbitrage

Assume to know the Deployment + Operation and Management costs:

$$C\left(P_{\max}, E_{\max}\right) = C_{\mathsf{d}}\left(P_{\max}, E_{\max}\right) + C_{\mathsf{m}}\left(P_{\max}, E_{\max}\right) \qquad (7)$$

Assume to know the daily average energy prices:



Example: deployment of energy storages for energy arbitrage

... then:

$$\begin{aligned}
\text{maximize} \quad & \gamma \left(\sum_{t=0}^{T} \Big(P_{\mathrm{e}}(t) - P_{\mathrm{i}}(t) \Big) p(t) \right) - C\left(P_{\max}, E_{\max}\right) \\
\text{subject to:} \quad & \textbf{\textit{dynamics of the storage}} \\
& 0 \leq E(t) \leq E_{\max} \qquad \forall t \in \{0, \dots, T\} \\
& 0 \leq P_{\mathrm{i}}(t) \leq P_{\max} \qquad \forall t \in \{0, \dots, T\} \\
& 0 \leq P_{\mathrm{e}}(t) \leq P_{\max} \qquad \forall t \in \{0, \dots, T\} \\
& E(0) = E(T)
\end{aligned} \tag{8}$$

Remark: $E_{\max}$, $P_{\max}$ ***are decision variables***

Summary and Conclusions

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- overview of constraints
- generic hybrid model
- first-order filters based approximation
- examples

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Conclusions

- it is possible to develop a single model capturing all technology-specific characteristics
- with generic models we can:
  - generalize the control design procedure
  - help the storage design process

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damiano.varagnolo@dei.unipd.it
www.dei.unipd.it/∼varagnolo/
google: damiano varagnolo

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Schoenung, S. M. and Hassenzahl, W. V. (2007).
Technical report DOE Energy Storage Systems Program.

Varagnolo, D., Bitar, E., Giani, A., Khargonekar, P., Poolla, K., and Varaiya, P. (2010).
In: IEEE Conference on Decision and Control (submitted) , Atlanta, USA:.