Modeling and Optimal Control of a Hydrogen Storage System for Wind Farm Output Power Smoothing

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Paper key contributions

- Operate devices by means of logic commands (ON, OFF,...)
- The modeling recipe is given by MLD + MPC + multi-objective
- Convert/electrify suitable amounts of energy/hydrogen
- The minimum weighted power variation over the prediction horizon is computed first (high priority)
- Then it is used as a constraint in the minimization of the load tracking error stage
- Minimise costs for long term profitability
- Ensure the safety of operations

Microgrid under investigation

Mixed logical dynamical modeling I

Automaton for the electrolyzer ($i = e$) and the fuel cell ($i = f$).

The devices are modeled with 5 state automata described by

- logic states δ_i^{α}
- states transitions $\sigma_{\alpha_i}^{\beta}$

Logic states and transitions in

- dynamic models
- constraints
- cost functions

- The 5 states of the devices ON, OFF, STB, CLD, WRM characterize the model

Mixed logical dynamical modeling II

$P_i(k)$ depends on the logic state corresponding to the operating condition of the i -th device that is $P_i^\alpha = P_i \delta_i^\alpha(k)$

$$\begin{cases} P_i(k) = 0 & \iff \delta_i^{\text{OFF}}(k) = 1 \\ P_i(k) = P_i^{\text{CLD}} & \iff \delta_i^{\text{CLD}}(k) = 1 \\ P_i(k) = P_i^{\text{STB}} & \iff \delta_i^{\text{STB}}(k) = 1 \\ P_i(k) = P_i^{\text{WRM}} & \iff \delta_i^{\text{WRM}}(k) = 1 \\ P_i(k) \in [P_i^{\min}, P_i^{\max}] & \iff \delta_i^{\text{ON}}(k) = 1 \end{cases}$$

Two (boolean) slack variables $z_i^{\geq \gamma}(k), z_i^{\leq \bar{\gamma}}(k)$ are introduced

$$z_i^{\geq \gamma}(k) = \begin{cases} 1 & P_i(k) \geq \gamma \\ 0 & P_i(k) < \gamma \end{cases}$$
$$z_i^{\leq \bar{\gamma}}(k) = \begin{cases} 0 & P_i(k) > \bar{\gamma} \\ 1 & P_i(k) \leq \bar{\gamma} \end{cases}$$

$$(\gamma, \bar{\gamma}) \in \{(0, 0), (P_i^{\text{CLD}}, P_i^{\text{CLD}}), (P_i^{\text{STB}}, P_i^{\text{STB}}), (P_i^{\text{WRM}}, P_i^{\text{WRM}}), (P_i^{\min}, P_i^{\max})\}$$

Mixed logical dynamical modeling III

- **MLD constraints of the devices logic states**

$P_i(k)$ can be linked to δ_i^α with inequalities through $z_i^{\geq \gamma}, z_i^{\leq \bar{\gamma}}$ (Big M-reformulation)

$$\begin{array}{ll} P_i(k) - \gamma < Mz_i^{\geq \gamma}(k) & -P_i(k) + \bar{\gamma} < Mz_i^{\leq \bar{\gamma}}(k) \\ -P_i(k) + \gamma \leq M(1 - z_i^{\geq \gamma}(k)) & P_i(k) - \bar{\gamma} \leq M(1 - z_i^{\leq \bar{\gamma}}(k)) \\ (1 - \delta_i^\alpha(k)) + z_i^{\geq \gamma}(k) \geq 1 & (1 - \delta_i^\alpha(k)) + z_i^{\leq \bar{\gamma}}(k) \geq 1 \end{array}$$

The following constrain must be added

$$\sum_{\alpha} \delta_i^\alpha(k) = 1$$

where $\alpha \in \mathcal{A}, \mathcal{A} = \{\text{OFF}, \text{CLD}, \text{STB}, \text{WRM}, \text{ON}\}$

Mixed logical dynamical modeling IV

- **MLD constraints of the devices state transitions**

The AND operator ($\wedge$) can be written in terms of inequalities

$$\mu_3 = \mu_1 \mu_2 \iff \begin{cases} \mu_3 \leq \mu_1 \\ \mu_3 \leq \mu_2 \\ \mu_3 \geq \mu_1 + \mu_2 - 1 \end{cases}$$

where $\mu_j \in \{0, 1\}$, $j \in \{1, 2, 3\}$, $\mu_1 = \delta_i^\alpha(k-1)$, $\mu_2 = \delta_i^\beta(k)$ and $\mu_3 = \sigma_{\alpha,i}^\beta(k)$. All the inadmissible transitions, i.e., those not shown in automata, are set to 0

$$\begin{aligned} \sigma_{\text{OFF},i}^{\text{STB}}(k) &= \sigma_{\text{OFF},i}^{\text{WRM}}(k) = \sigma_{\text{OFF},i}^{\text{ON}}(k) = \sigma_{\text{CLD},i}^{\text{OFF}}(k) \\ &= \sigma_{\text{CLD},i}^{\text{WRM}}(k) = \sigma_{\text{CLD},i}^{\text{ON}}(k) = \sigma_{\text{STB},i}^{\text{ON}}(k) = \sigma_{\text{STB},i}^{\text{CLD}}(k) \\ &= \sigma_{\text{WRM},i}^{\text{OFF}}(k) = \sigma_{\text{WRM},i}^{\text{CLD}}(k) = \sigma_{\text{WRM},i}^{\text{STB}}(k) = \sigma_{\text{ON},i}^{\text{CLD}}(k) \\ &= \sigma_{\text{ON},i}^{\text{WRM}}(k) = 0 \end{aligned}$$

Mixed logical dynamical modeling V

- **Operating constraints**

$$\delta_i^{\text{CLD}}(k) - \delta_i^{\text{CLD}}(k-1) \leq \delta_i^{\text{CLD}}(\tau^{\text{CLD}})$$

$$\delta_i^{\text{CLD}}(k) + \dots + \delta_i^{\text{CLD}}(k - T^{\text{CLD}}) \leq T^{\text{CLD}}$$

$$\tau^{\text{CLD}} = k+1, \dots, k + T^{\text{CLD}}$$

$$\delta_i^{\text{WRM}}(k) - \delta_i^{\text{WRM}}(k-1) \leq \delta_i^{\text{WRM}}(\tau^{\text{WRM}})$$

$$\delta_i^{\text{WRM}}(k) + \dots + \delta_i^{\text{WRM}}(k - T^{\text{WRM}}) \leq T^{\text{WRM}}$$

$$\tau^{\text{WRM}} = k+1, \dots, k + T^{\text{WRM}}$$

- **Ramp up constraints**

$$|(P_i(k+1) - P_i(k))\delta_i^{\text{ON}}| \leq R_i$$

Mixed logical dynamical modeling VI

- **Hydrogen dynamics**

$$H(k+1) = H(k) + \eta_e(k)P_e(k)\delta_e^{\text{ON}}(k)T_s - \frac{P_f(k)\delta_f^{\text{ON}}(k)T_s}{\eta_f(k)}$$

- **Operating ranges**

$$P_i^{\min} \leq P_i(k) \leq P_i^{\max}$$

$$H^{\min} \leq H(k) \leq H^{\max}$$

- **Power balance**

$$P_w(k) - P_e(k)\delta_e^{\text{ON}}(k) + P_f(k)\delta_f^{\text{ON}}(k) - P_{\text{avl}}(k) - P_{\text{dump}}(k) = 0$$

ESS operating costs

$$\begin{aligned} J_i(k+j) := & \left(\frac{S_{\text{rep},i}}{NH_i} + C_i^{\text{OM}} \right) \delta_i^{\text{ON}}(k+j) \\ & + C_{\text{ON},i}^{\text{OFF}} \sigma_{\text{ON},i}^{\text{OFF}}(k+j) \\ & + C_{\text{CLD},i}^{\text{STB}} \sigma_{\text{CLD},i}^{\text{STB}}(k+j) \\ & + C_{\text{STB},i}^{\text{OFF}} \sigma_{\text{STB},i}^{\text{OFF}}(k+j) \\ & + s(k+j) P_i^{\text{STB}} \delta_i^{\text{STB}}(k+j) \\ & + s(k+j) P_i^{\text{CLD}} \delta_i^{\text{CLD}}(k+j) \\ & + s(k+j) P_i^{\text{WRM}} \delta_i^{\text{WRM}}(k+j) \end{aligned}$$

where

- $S_{\text{rep},i}$: the i -device stack replacement cost
- C_i^{OM} : the i -device O&M cost
- $C_{\text{ON},i}^{\text{OFF}}, C_{\text{CLD},i}^{\text{STB}}, C_{\text{STB},i}^{\text{OFF}}$: the i -th device cycle costs
- $P_i^{\text{STB}}(k)$: the power at standby
- $s(k)$: the power spot price

Cost functions

- **Power smoothing cost function**

$$J_s(k) := \sum_{j=0}^{T-1} \sum_{\tau=1}^{\tau_B} \omega^{k+j,\tau} y^{k+j,\tau},$$

where $y^{k+j,\tau}$ is the power increment such that

- $y^{k+j,\tau} \geq 0$
- $y^{k+j,\tau} \geq |P_{\text{avl}}(k+j) - P_{\text{avl}}(k+j-\tau)| - \bar{y}^\tau$

with $\bar{y}^\tau$ is a given power reference depending on τ

- **Load tracking cost function**

$$J_l(k) := \frac{1}{T} \sum_{j=0}^{T-1} \left(P_{\text{avl}}(k+j) - P_{\text{ref}}(k+j) \right)^2.$$

- **Global cost function**

$$J(k) := \sum_{j=0}^{T-1} \rho_l J_l(k+j) + \rho_e J_e(k+j) + \rho_f J_f(k+j),$$

Multi-objective optimization I

$$\min_{\mathcal{C}_k} \left\{ J_s(k), J(k) \right\}$$

Subject to

Discrete logical states constraints,

Mode transitions constraints,

Physical constraints,

Hydrogen level dynamics,

Power smoothing constraints.

$$\min_{\mathcal{C}_k} J_s(k)$$

s.t.

All constraints.

$$\min_{\mathcal{C}_k} J(k)$$

s.t.

All constraints,

$$J_s(k) \leq J_s^*.$$

Multi-objective optimization II

- At each time step k , given the initial state $H(k)$, the MPC provides the optimal control sequences

$$\mathcal{C}_k := \{ \mathbf{P}_{i,k}^{T-1}, \mathbf{P}_{avl,k}^{T-1}, \mathbf{P}_{dump,k}^{T-1}, \boldsymbol{\delta}_{i,k}^{\alpha,T-1}, \boldsymbol{\sigma}_{\alpha,i,k}^{\beta,T-1}, \mathbf{z}_{i,k}^{\gamma,T-1} \},$$

where

$$\mathbf{P}_{i,k}^{T-1} = (P_i(k), \dots, P_i(k+T-1))^{\top}$$

$$\mathbf{P}_{avl,k}^{T-1} = (P_{avl}(k), \dots, P_{avl}(k+T-1))^{\top}$$

$$\mathbf{P}_{dump,k}^{T-1} = (P_{dump}(k), \dots, P_{dump}(k+T-1))^{\top}$$

$$\boldsymbol{\delta}_{i,k}^{\alpha,T-1} = (\delta_i^{\alpha}(k), \dots, \delta_i^{\alpha}(k+T-1))^{\top}$$

$$\boldsymbol{\sigma}_{\alpha,i,k}^{\beta,T-1} = (\sigma_{\alpha_i}^{\beta}(k), \dots, \sigma_{\alpha_i}^{\beta}(k+T-1))^{\top}$$

$$\mathbf{z}_{i,k}^{\gamma,T-1} = (z_i^{\gamma}(k), \dots, z_i^{\gamma}(k+T-1))^{\top}$$

Results I

Figure: Wind and operator power profiles

Results II

Figure: Smoothed available power profiles

Results III

Figure: Hydrogen levels

H₂ A Ξ L U S

Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation

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Thank you for your attention