A Configuration Based Pumped-storage Hydro Unit Model in MISO Day-ahead Market

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Outline

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Pumped-Storage Hydro Unit (PSHU)

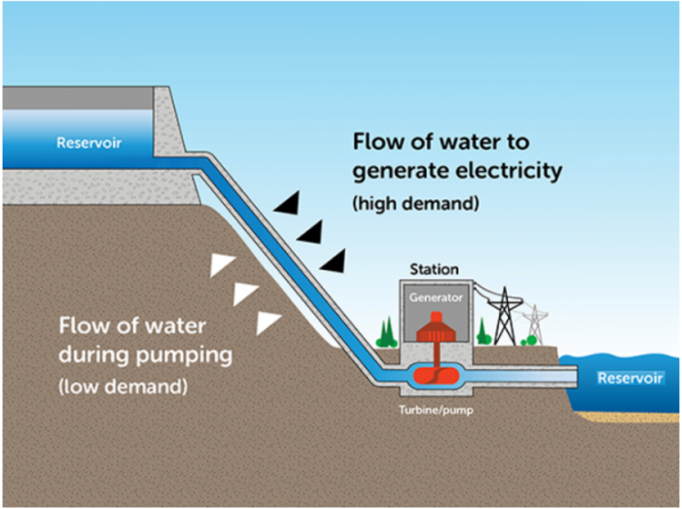

Figure: A Pumped-Storage Hydro Unit [Kenning, 2017]

Storage Technologies and Applications

Table: Storage Technologies and Applications [Barton et al., 2004]

Full Power Duration of Storage	Applications of Storage	Compressed Air Energy Storage (CAES)	Pumped-storage Hydro	Battery Technologies	Flywheel
3 Days	Weekly smoothing of loads and most weather variations	Y	Y		
8 Hours	Daily load cycle, PV, Wind, transmission line repair	Y	Y	Y	
2 Hours	Peak load lopping, standing reserve, wind power smoothing	Y	Y	Y	
20 Minutes	Spinning reserve, wind power smoothing, clouds on PV	Y	Y	Y	Y
3 Minutes	Spinning reserve, wind power smoothing of gusts		Y	Y	Y
20 Seconds	Line or local faults, voltage and frequency control, governor controlled generation			Y	Y

Motivation

- Pumped-storage hydro unit (PSHU) can provide a wide range of services and such services are substantially important to the system operation.
- Under current MISO practice, pumped-storage hydro unit owners specify pump/generate periods and offer costs/prices.
- As a market participant with limited information, PSHUs' forecast may be poor.
- PSHUs' decisions are **sub-optimal** to the system welfare.
- The pump/generate decisions made based on the forecasts may **impair profits**.
- The first step is to include the PSHUs more fully into MISO's **day-ahead market** clearing process – solving unit commitment (UC) and economic dispatch (ED) problems.

Literature Review

- Models of the operation of a PSHU with continuous variables.
  - Two continuous variables for a pump and a generator and state of charge constraints [Castronuovo and Lopes, 2004] [Duque et al., 2011].
  - A variable is introduced to represent the energy spilled from the pumped-storage hydro system [Brown et al., 2008].
  - A single variable represent generating (positive) and pumping (negative) [Ni et al., 2004].
- Models of the operation of the PSHU with integer variables.
  - An integer variable indicates the total number of turbines that are in pumping mode among the N identical turbines [Garcia-Gonzalez et al., 2008].
  - Binary variables (pump/generate) are introduced to each of the the PSHU in the system [Jiang et al., 2012].
  - Three modes, pumping, generating and idle are modeled for each of the PSHUs [Khodayar et al., 2013].

Conclusion of the Literature

- Pumped-storage hydro model has been studied for a stand alone system [Ma et al., 2015] or a market participant [Ma et al., 2014].
- The model of a PSHU in the day-ahead unit commitment problem remained obscure.
- Three modes are necessary for day-ahead market schedules, so there should be an "alloff" or "offline" mode specified.
  - There is typically a minimum output for the generating mode.
  - Pump is typically block loaded or with minimum pumping limit.
  - Constantly charging or discharging the pumped-storage hydro unit is not always the best strategy for system operation.

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Operation Modes

- Configuration based model for combined cycle gas unit [Chen and Wang, 2017] is applied.

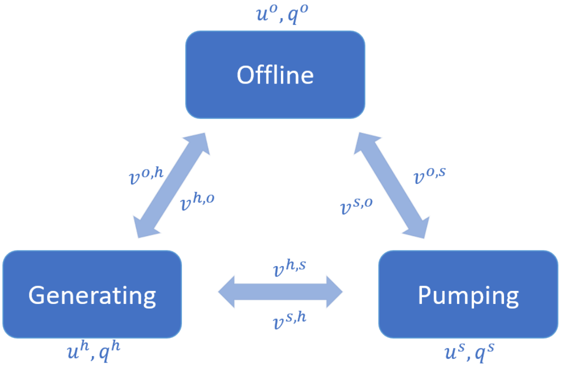

Figure: Mode transition diagram of a PSHU in two consecutive time intervals.

- Let q^h be the output of the generate mode and let q^s be the output of the pump mode.
- Let u be the unit commitment of each mode and let v be the transition between modes.

Formulation

The system operation costs are shown in (1).

$$\min_{q,u} \sum_{g \in G_{sh}} \sum_{t \in T} f^h_{g,t} - C^s_{g,t} q^s_{g,t} + \sum_{g \in G} \sum_{t \in T} C(q_{g,t}) \tag{1}$$

Energy balance constraint is shown in (2).

$$\sum_{g \in G} q_{g,t} + \sum_{g \in G_{sh}} q^h_{g,t} = D_t + \sum_{g \in G_{sh}} q^s_{g,t} \; \forall t \in T \tag{2}$$

The output of a PSHU $q^h_{g,t}$ and $q^s_{g,t}$ are constrained by their capacities and the amount of energy stored in the reservoir $e_{r,t}$.

$$\underline{Q}^h_g u^h_{g,t} \leq q^h_{g,t} \; \forall g \in G_{sh} \quad \forall t \in T \tag{3}$$

$$q^h_{g,t} \leq \overline{Q}^h_g u^h_{g,t} \quad q^h_{g,t} \leq \eta^h_g e_{r,t} \quad \forall g \in G_{sh} \quad \forall r \in R \quad \forall t \in T \tag{4}$$

$$\underline{Q}^s_g u^s_{gt} \leq q^s_{g,t} \leq u^s_{g,t} \overline{Q}^s_g \quad \forall g \in G_{sh} \quad \forall t \in T \tag{5}$$

Unit Commitment and Transition Logic [Dai et al., 2018]

The first constraint guarantees that the configurations are mutually exclusive:

$$\sum_{y \in \mathcal{Y}} u_{g,t}^{y} = 1, \; \forall g, \; \forall t. \tag{6}$$

where $\mathcal{Y}$ is the set of modes in a pumped storage unit.
The second constraint links on/off variables with transition variables:

$$u_{g,t}^{y} - u_{g,t-1}^{y} = \underbrace{\sum_{y' \in \mathcal{M}^{T,y}} v_{g,t}^{y'y}}_{\text{Entering State } y \text{ at } t} - \underbrace{\sum_{y' \in \mathcal{M}^{F,y}} v_{g,t}^{yy'}}_{\text{Leaving State } y \text{ at } t}, \forall g, \forall t, \forall y. \tag{7}$$

where $\mathcal{M}^{F,y}$ is the set of reachable configurations from y, and $\mathcal{M}^{T,y}$ is the set of reachable configurations to y.
At most one transition per interval:

$$\sum_{yy' \in \mathcal{M}} v_{g,t}^{yy'} \leq 1, \forall g, \forall t. \tag{8}$$

where $\mathcal{M}$ is the set of all ordered pairs of states correspond to feasible transitions.

Storage Energy Balance and State of Charge

$$e_{r,t+1} = e_{r,t} + \sum_{g \in G_{sh,r}} \eta_g^s q_{g,t}^s - \sum_{g \in G_{sh,r}} \frac{q_{g,t}^h}{\eta_g^h} \quad \forall r \in R \quad \forall t \in T \tag{9}$$

$$e_{r,1} = E_{r,1} \quad \forall r \in R \tag{10}$$

$$e_{r,T+1} = E_{r,T+1} \quad \forall r \in R \tag{11}$$

$$\underline{E_r} \leq e_{r,t} \leq \overline{E_r} \quad \forall r \in R \quad \forall t \in T \tag{12}$$

where η_g^h and η_g^s are the efficiencies of generating and pumping indicating energy losses at each mode. Energy stored in the reservoir r at time t is $e_{r,t}$ and it is constrained by the state of charges and the capacity of the reservoir
[Castronuovo and Lopes, 2004]-[Garcia-Gonzalez et al., 2008].

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Case Study of Two PSHU Turbines

- Day-ahead UC and ED problems are solved for a 24 hours net-load scenario.
- Reserve requirements ignored.
- Ramp constraints ignored.
- Transmission security constraints ignored.
- The PSHU has two turbines that share a same reservoir. Pump is block loaded.
- Maintenance and operation costs of the PSHU is ignored. Profits = income from generating mode - price paid for pumping mode.

Table: Units

Unit Mode	Cost/Price $	$\underline{q}^m$ MW	$\overline{q}^m$ MW	η_g^m
1: PSHU1 Pump	24	200	200	0.9
1: PSHU1 Gen	26	100	200	0.9
2: PSHU2 Pump	24	200	200	0.9
2: PSHU2 Gen	26	100	200	0.9
3: Thermal Gen 1	30	0	600	NA
4: Thermal Gen 2	20	0	300	NA
5: Thermal Gen 3	15	0	500	NA

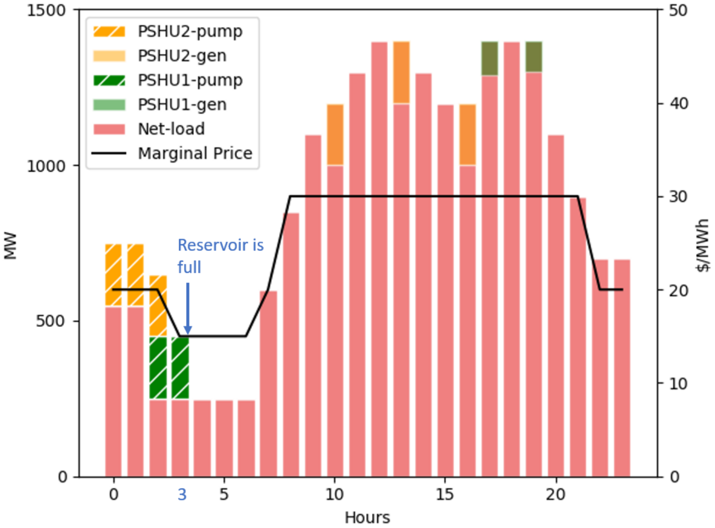
Example to Illustrate Current Practice in MISO

- PSHU owners offer opportunity costs for generation mode and bid prices for pump mode.
- State of charges of the reservoir are not enforced.
- The PSHU owner determines the pump/generate window.
- Pump window: 0 - 6 AM; Generate window: 7 AM - 11 PM.
- Maximum Daily Generation constraint is applied on PSHU for the generate mode.
- Although state of charges are not represented in the clearing algorithm, the PSHU must stop pumping when the reservoir is full.

Table: Reservoir

Reservoir	$\underline{E_r}$ MWh	$\overline{E_r}$ MWh	$E_{r,1}$ MWh	$E_{r,T+1}$ MWh
Reservoir	1000	3500	2600	2600

Economic Dispatch Results with Current Practice



- Net-load = system load - renewable energy (e.g. solar) not including PSHU outputs.

Data for Proposed Model

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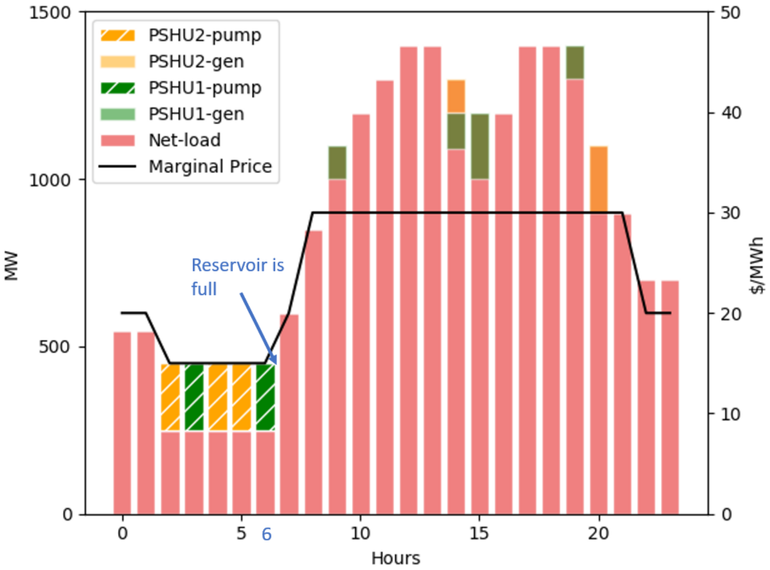
Remove Generation Costs and Pump Prices of PSHUs in Objective

$$\min_{p,u} \sum_{g \in G_{sh}} \sum_{t \in T} f^h_{gt} - C^s_{gt} q^s_{g,t} + \sum_{g \in G} \sum_{t \in T} C(q_{gt}) \qquad (1')$$

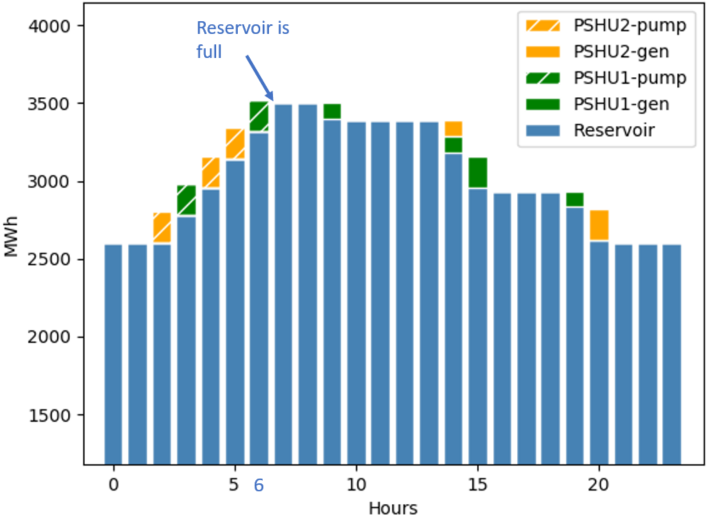
$$\sum_{g \in G} q_{gt} + \sum_{g \in G_{sh}} q^h_{gt} = D_t + \sum_{g \in G_{sh}} q^s_{gt} \; \forall t \in T \qquad (2)$$

- The objective doesn't contain costs or bid prices from PSHUs.
- The value of pumping and generation of a PSHU comes from the energy balance equation.

Economic Dispatch Results with Proposed Model



State of Charges at Reservoir



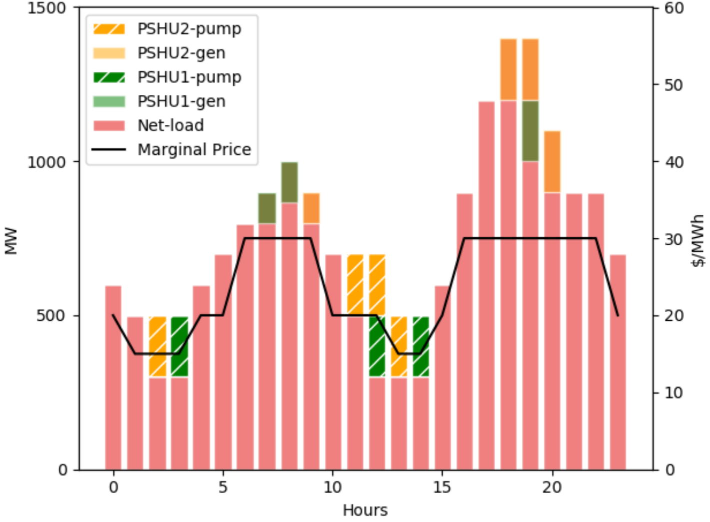
Generation Costs and PSHU Profits

- PSHU pumps and generates the same amount but at different times from the two approaches.
- In current MISO practice, PSHUs are dispatched according to the comparison of their offer/bid to the system generation costs.
- In the proposed model, because of the state of charge constraints, the PSHUs are positioned such that the system costs are reduced the most.
- The profits of PSHU owner in the current practice varies from their offer/bid. But the profits given by the proposed model is the maximum they can get.

Table: PSHU Owner Profits and Social Welfare

	Current Practice $	Proposed Model $
PSHU Profits	5,300	9,300
System Costs	429,200	426,461

A Different Scenario with Proposed Model



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Conclusion and Future Work

Conclusion

- A configuration based three modes pumped-storage hydro unit model in the day-ahead market is presented.
- A numerical study is presented with two identical turbines sharing a reservoir.
- The proposed model is compared with current MISO practice showing differences at unit dispatches and benefits in terms of system generation costs and PSHU owner's profits.
- Flexible operations of the PSHUs with the proposed model are demonstrated with examples.

Future Work

- Computational case study with MISO system is ongoing.
- Use an integer variable to represent the status of a multi-turbine PSHU.

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MISO

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