ECE 588 – Electricity Resource Planning

13. Energy Storage Plant Simulation

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OUTLINE

- Scope
- Assumptions
- Constraints
- Outline of the algorithm
- Notation
- Algorithm
TOPIC SCOPE

- We consider the integration of a storage plant \((SP)\)
in production simulation and discuss the key changes in the simulation procedure.

- The simulation software has the full capability for the simulation of thermal units and limited energy plants \((LEPs)\) implemented.

SIMULATION PROCEDURE THRUST

Part 1. Order the thermal units based on their economics in order of increasing \(\$/MWh\).

Part 2. Simulate the production costing of the limited energy plants.

Part 3. Simulate the production costing of the system including the storage unit, using, in general, only the thermal blocks for charging the storage plant.
ASSUMPTIONS

- The blocks of the thermal plants are loaded in order of increasing costs
  \[ \lambda_{i-1} \leq \lambda_i \leq \lambda_{i+1} \]
- The unit parameters and costs in the charge/ discharge cycle of storage plant operation are fixed
- The simulation period duration equals the cycle duration of the SP operation, i.e., all the energy charged into storage must be discharged during the simulation period.

ECONOMIC CONSTRAINTS

- Operation of an energy storage unit is a cycle consisting of the 2 phases: charging & discharging
- The storage unit can economically displace the energy of a thermal plant whenever
  \[ \lambda_i < \eta, \lambda_\beta \]
  - \( \lambda \): costs/MWh of charging energy
  - \( \eta, \lambda_\beta \): effective costs/MWh of displaced energy
CHARGING CAPACITY CONSTRAINT ON CHARGED EXCESS ENERGY

Not all the excess energy can be used for charging as the charging capacity $c_c$ of the storage plant limits the amount of expected excess energy from unit $i$ useable for charging the storage. Taking into account the charging capacity $c_{storage}$

\[ \Delta_i^c \leq \tilde{\Delta}_i^c \]

RESERVOIR CONSTRAINT

- As the size of the reservoir is finite, the amount of energy it can store is limited by $\Delta_{max}$

\[ \Delta_j^c \xrightarrow{\text{transmission}} \eta_t \Delta_j^c \xrightarrow{\text{charging}} \eta_c \eta_j^c \Delta_j^c \]

- Therefore

\[ \eta_c \eta_t \sum_j \Delta_j^c \leq \Delta_{max}^s \]

block $j$ is used to charge plant $s$
and so not all the expected excess energy for charging may be utilized; the reduction in charging energy is done by cutting back, starting with the energy from the most expensive thermal block.

RESERVOIR CONSTRAINT

CONSERVATION OF ENERGY

- During the cycle all the charged energy must be discharged:

  \[ \eta_c \eta_l \delta^c \frac{\text{generation}}{\eta_g} \eta_s \eta_c \eta_l \delta^c \frac{\text{transmission}}{\eta_t} \eta_g \eta_c \eta_l^2 \delta^c \]

  expected stored energy   expected energy to meet load

- Once we know the stored energy, we are, in effect, dealing with a LEP; the issue is, simply, to determine the LEP loading point so as to utilize it most economically within the given constraints.
OUTLINE OF THE PROCEDURE

- **Algorithm A:** provisional schedule determination
  - provisional set of charging units
  - provisional set of displaced units
  - only a subset of the constraints is enforced

- **Algorithm B:** final schedule determination
  - final set of charging units
  - final set of displaced units
  - all of the constraints are enforced

PROVISIONAL SCHEDULE VERSUS FINAL SCHEDULE

<table>
<thead>
<tr>
<th>constraint</th>
<th>provisional schedule</th>
<th>final schedule</th>
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<tbody>
<tr>
<td>reservoir</td>
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<tr>
<td>conservation of energy</td>
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GOING FROM THE PROVISIONAL TO THE FINAL SCHEDULE

- Whenever all of the constraints cannot be enforced, the only recourse available is to reduce the charging energy utilized by the storage plant.

- The expected generation of the storage unit when loaded in position $\ell$ is

$$\bar{\mathcal{G}}_{\ell} \triangleq p_{s} T \int_{C_{\ell}}^{C_{\ell+1}} \mathcal{L}_{\ell}^{-1}(x) dx$$

GOING FROM THE PROVISIONAL TO THE FINAL SCHEDULE

- The difference between the expected generation of the storage unit and the expected stored energy to meet load when the plant is loaded in position $\ell$ is

$$\Delta \bar{\mathcal{G}}_{\ell} \triangleq \bar{\mathcal{G}}_{\ell} - \eta_{s} \sum_{j} \bar{\mathcal{G}}_{j}^{c}$$

- If $\Delta \bar{\mathcal{G}}_{\ell}$ is negative, we need to cut back charging for the storage plant; else $\Delta \bar{\mathcal{G}}_{\ell} \geq 0$ and the loading position $\ell$ is feasible.
NOTATION AND DEFINITIONS

\[ \mathcal{G} \triangleq \left\{ j_1, j_2, \ldots, j_n : \lambda_{j_i} \leq \lambda_{j_{i+1}} \right\} \]
subset of generation blocks
with excess energy of the
set of system resources

\[ \{1, 2, \ldots, N\} \supseteq \mathcal{G} \]

\[ K \triangleq \max_{1 \leq i \leq n} \left\{ j_i : \lambda_{j_i} \leq \eta_s \lambda_N \right\} \]

\[ \mathcal{G}_C \triangleq \left\{ j_1, j_2, \ldots, K \right\} \subseteq \mathcal{G} \]
provisional charging subset

NOTATION

\[ L \triangleq \min_{j_i < i \leq N} \left\{ i : \lambda_i \geq \frac{\lambda_{j_i}}{\eta_s} \right\} \]

\[ \mathcal{G}_D \triangleq \left\{ L, L+1, \ldots, N \right\} \]
provisional displacement subset

most expensive unit used
for charging

loading order of the
candidate unit for
displacement
ALGORITHM A

Step 1. Construct the subsets $\mathcal{J}_C$ and $\mathcal{J}_D$; if either $\mathcal{J}_C$ or $\mathcal{J}_D$ is empty, stop since economic operation of the storage plant is not feasible.

Step 2. Set $\mathcal{E}^c = 0$ and $i = 1$

Step 3. Compute $\mathcal{E}^c_{ji}$ and set

$$\mathcal{E}^c = \mathcal{E}^c + \mathcal{E}^c_{ji}$$

Step 4. If

$$\mathcal{E}^c \geq \frac{\mathcal{E}_{s}^{\max}}{\eta_c \eta_i}$$

set

$$\Delta \mathcal{E}^c = \mathcal{E}^c - \frac{\mathcal{E}_{s}^{\max}}{\eta_c \eta_i},$$

$$\mathcal{E}^c_{ji} = \mathcal{E}^c_{ji} - \Delta \mathcal{E}^c,$$

and

$$\mathcal{E}^c = \frac{\mathcal{E}_{s}^{\max}}{\eta_c \eta_i}$$

and go to step 6.
**ALGORITHM A**

Step 5. If \( j_{i+1} \in J_C \), set

\[
i = i + 1
\]

and proceed to step 3

Step 6. Set

\[
k = i
\]

and proceed to Algorithm B

**ALGORITHM B**

Step 1. Identify the first unit \( l \) that may be displaced

\[
l = \min_{J_k \leq i \leq N} \left\{ i : \lambda_i \geq \frac{\lambda_j}{\eta_s} \right\}
\]

Step 2. Compute

\[
\Delta s_1 = s_1 - \eta_s \sum_{i=1}^{k} \delta_{j_i}^s
\]

Step 3. If \( \Delta s_1 \geq 0 \), set

\[
\bar{k} = j_k \quad \text{and} \quad \bar{l} = l
\]

and go to step 7
**ALGORITHM B**

**Step 4.** If
\[
\bar{\mathcal{G}}^c_{j_k} \geq - \frac{\Delta \mathcal{G}_1}{\eta_s}
\]
then set
\[
\bar{\mathcal{G}}^c_{j_k} = \bar{\mathcal{G}}^c_{j_k} + \frac{\Delta \mathcal{G}_1}{\eta_s},
\]
\[
\bar{k} = j_k,
\]
and
\[
\bar{\ell} = \ell
\]
and go to step 7

---

**ALGORITHM B**

**Step 5.** For \(\ell - 1 \in \mathcal{J}_D\), set
\[
\ell = \ell - 1,
\]
\[
k = \max \left\{i : \lambda_{j_i} \leq \eta_s \lambda_{j_\ell} \right\},
\]
and
\[
\bar{\mathcal{G}}^c = \sum_{i=1}^{k} \bar{\mathcal{G}}^c_{j_i}
\]
and return to step 2

**Step 6.** Set
\[
\bar{\mathcal{G}}^c = \frac{\bar{\mathcal{G}}_{j_\ell}}{\eta_s},
\]
**ALGORITHM B**

\[
\begin{align*}
  k &= \max_{1 \leq i \leq n} \left\{ i : \sum_{m=1}^{i-1} \delta^c_{j_m} < \delta^c \right\}, \\
  \delta^c_{i_k} &= \delta^c - \sum_{i=1}^{k-1} \delta^c_{j_k}, \\
  \bar{k} &= j_k \\
\end{align*}
\]

and

\[
\bar{\ell} = \ell,
\]

load the storage plant as block \( \bar{\ell} \) and stop

**Step 7.** Use the LEP Algorithm to carry out the simulation of the storage plant

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**EXTENSION TO MULTIPLE STORAGE PLANTS**

- For the set \( \mathcal{S} \) of storage plants

\[
\mathcal{S} \triangleq \left\{ s_1, s_2, \ldots, s_m \right\}
\]

the plants are arranged in descending order of overall efficiency

\[
\eta_{s_i} \geq \eta_{s_{i+1}} \quad \forall i = 1, 2, \ldots, m - 1
\]

- We adapt the single storage plant procedure to simulate the system which includes such a set
set $s_1 = s_{i+1}$

SP Algorithm

LEP Algorithm

unload the units involved
check for constraint violations
cut back charging if needed
lump the units involved and dispatch them together

overlap with LEP or SP?

yes

no

set $s_i = s_{i+1}$

stop

$s_{i+1} \in \mathcal{S}$?

yes

no