Alternative Sources of Ancillary Services for Electricity

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Outline

1. Motivation and Outline
2. Structure of the multi-period SuperOPF
   - Objective Function
   - FOC’s
3. Parameters
   - Test Network
   - Wind Characterization
   - Cases Simulated
4. Results
5. Conclusions
Motivation

Adoption of renewables = change in marketplace for generators

- Wholesale customer Rate Payments

\[
\text{Billing Cost} + \lambda_i \times d_i + c_p i \times q_i
\]

- More Stochastic generation:
  Lower income from energy (lower \( \lambda_i \)) + Higher capacity Prices
  = More Missing Money

How to compensate services that help maintain reliability?
Ancillary Services for Electricity

A.J. Lamadrid

Motivation and Outline

Structure of the multi-period SuperOPF
  • Objective Function
  • FOC’s

Parameters
  • Test Network
  • Wind Characterization
  • Cases Simulated

Results

Conclusions
The overall idea

- Deal with the full problem with co-optimization, in a security constrained framework.
- Integrate storage as part of a dynamic problem.
- Include economic management of constraints, including ramping.
- Endogenously determine optimal amount of reserves.
Cooptimization

Co-optimization $\rightarrow$ Minimize the Expected Cost of Dispatch over Different States of the System
The Concept, Energy Storage

Stored Energy MWh

- $s_{\text{max}}$
- $s_{\text{min}}$

$t$ $t+1$ $t+2$ $t+3$ $t+4$

Objective Function
FOC's
Parameters
Test Network
Wind Characterization
Cases Simulated
Results
Conclusions
The Concept, Ramping

MW injections

central “high-probability” path

load following ramp up capacity

load following ramp down capacity

$t$ time

$\text{MW injections}$

$t$, $t+1$, $t+2$, $t+3$, $t+4$ time
The Concept, Ramping

$$p^0, p_+^1, p^3$$

$$r_{p+}$$

$$r_{p-}$$

upward reserve

downward reserve

MW injections

contingencies

$$k$$
Simplified Objective Function

\[
\min_{G_{itsk}, R_{itsk}, LNS_{itsk}} \sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}^t} \sum_{k \in \mathcal{K}} \pi_{tsk} \left\{ \sum_{i \in \mathcal{I}} \left[ C_{G_i}(G_{itsk})^+ \right. \right.
\]
\[
\left. + \text{Inc}_{its}^+(G_{itsk} - G_{itsc})^+ + \text{Dec}_{its}^-(G_{itsc} - G_{itsk})^+ \right\} + \sum_{j \in \mathcal{J}} \text{VOLL}_{j}^L \text{N}\left(G_{tsk}, R_{tsk}\right)_{itsk} \right\} + \sum_{t \in \mathcal{T}} \rho_t \sum_{i \in \mathcal{I}} \left[ C_{R_it}^+(R_{it}^+) + C_{R_it}^-(R_{it}^-) + C_{L_it}^+(L_{it}^+) \right. \right.
\]
\[
\left. + C_{L_it}^-(L_{it}^-) \right] + \sum_{t \in \mathcal{T}} \rho_t \sum_{s_2 \in \mathcal{S}^t} \sum_{s_1 \in \mathcal{S}^t-1} \sum_{i \in \mathcal{I}} \sum_{ts_2}^0 \left[ R_{p_it}^+(G_{its2} - G_{its1})^+ + R_{p_it}^-(G_{its2} - G_{its1})^+ \right].
\]
### Variables in simplified formulation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{T}$</td>
<td>Set of time periods considered, $n_t$ elements indexed by $t$.</td>
</tr>
<tr>
<td>$\mathcal{S}^t$</td>
<td>Set of scenarios in the system in period $t$, $n_s$ elements indexed by $s$.</td>
</tr>
<tr>
<td>$\mathcal{K}$</td>
<td>Set of contingencies in the system, $n_c$ elements indexed by $k$.</td>
</tr>
<tr>
<td>$\mathcal{I}$</td>
<td>Set of generators in the system, $n_g$ elements indexed by $i$.</td>
</tr>
<tr>
<td>$\mathcal{J}$</td>
<td>Set of loads in the system, $n_l$ elements indexed by $j$.</td>
</tr>
<tr>
<td>$\pi_{tsk}$</td>
<td>Probability of contingency $k$ occurring, in scenario $s$, period $t$.</td>
</tr>
<tr>
<td>$\rho_t$</td>
<td>Probability of reaching period $t$.</td>
</tr>
<tr>
<td>$G_{itsk}$</td>
<td>Quantity of apparent power generated (MVA).</td>
</tr>
<tr>
<td>$G_{itc}$</td>
<td>Optimal contracted apparent power generated (MVA).</td>
</tr>
<tr>
<td>$C_G(\cdot)$</td>
<td>Cost of generating $(\cdot)$ MVA of apparent power.</td>
</tr>
<tr>
<td>$\text{Inc}_{it}^+ (\cdot)^+$</td>
<td>Cost of increasing generation from contracted amount.</td>
</tr>
<tr>
<td>$\text{Dec}_{it}^- (\cdot)^+$</td>
<td>Cost of decreasing generation from contracted amount.</td>
</tr>
<tr>
<td>$\text{VOLL}_i$</td>
<td>Value of Lost Load, ($)$.</td>
</tr>
<tr>
<td>$\text{LNS}(\cdot)_{jtsk}$</td>
<td>Load Not Served (MWh).</td>
</tr>
<tr>
<td>$R_{it}^+ &lt; \text{Ramp}_i$</td>
<td>$(\text{max}(G_{itsk}) - G_{itc})^+$, up reserves quantity (MW) in period $t$.</td>
</tr>
<tr>
<td>$C_R^+ (\cdot)$</td>
<td>Cost of providing $(\cdot)$ MW of upward reserves.</td>
</tr>
<tr>
<td>$R_{it}^- &lt; \text{Ramp}_i$</td>
<td>$(G_{itc} - \text{min}(G_{itsk}))^-$, down reserves quantity (MW).</td>
</tr>
<tr>
<td>$C_R^- (\cdot)$</td>
<td>Cost of providing $(\cdot)$ MW of downward reserves.</td>
</tr>
<tr>
<td>$L_{it}^+ &lt; \text{Ramp}_i$</td>
<td>$(\text{max}(G_{i,t+1,s}) - \text{min}(G_{its}))^+$, load follow up (MW) $t$ to $t+1$.</td>
</tr>
<tr>
<td>$C_L^+ (\cdot)$</td>
<td>Cost of providing $(\cdot)$ MW of load follow up.</td>
</tr>
<tr>
<td>$L_{it}^- &lt; \text{Ramp}_i$</td>
<td>$(\text{max}(G_{its}) - \text{min}(G_{i,t+1,s}))^-$, load follow down (MW).</td>
</tr>
<tr>
<td>$C_L^- (\cdot)$</td>
<td>Cost of providing $(\cdot)$ MW of load follow down.</td>
</tr>
<tr>
<td>$\text{R}_{it}^+ (\cdot)^+$</td>
<td>Cost of increasing generation from previous time period.</td>
</tr>
<tr>
<td>$\text{R}_{it}^- (\cdot)^+$</td>
<td>Cost of decreasing generation from previous time period.</td>
</tr>
</tbody>
</table>
First Order Conditions

Denote by $C_{E,i,t}$ the cost of providing energy from an ESS, $\mu_{PHYSR_E^+}^{i,t}$ and $\mu_{PHYS R^-}^{i,t}$, the KKT multipliers for ESS units, and $\lambda_{i,t}$ The locational marginal price at bus $i$ in period $t$. The FOC’s can be re-arranged to show:

$$
\frac{\partial C_{E,i,t+1}(e_{i,t+1})}{\partial e_{i,t+1}} - \frac{\partial C_{E,i,t}(e_{i,t})}{\partial e_{i,t}} + (-\mu_{PHYSR_E^+}^{i,t} + 2 \times \mu_{PHYSR_E^+}^{i,t+1} - \\
\mu_{PHYSR_E^+}^{i,t+2} - (-\mu_{PHYSR_E^-}^{i,t} + 2 \times \mu_{PHYSR_E^-}^{i,t+1} - \mu_{PHYSR_E^-}^{i,t+2}) - \\
\alpha(\mu_{ESS PHYS}^{i,t+1} - \mu_{ESS PHYS}^{i,t+1}) = \lambda_{i,t+1} - \lambda_{i,t}
$$

(3)

Dynamic link for optimally pricing the energy stored in an ESS.
The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation
Ancillary Services for Electricity
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Motivation and Outline
Structure of the multi-period SuperOPF
Objective Function FOC's
Parameters
  Test Network
  Wind
  Characterization
  Cases Simulated
Results
Conclusions

The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation
The overall formulation

The diagram illustrates the overall formulation with a single large LP/QP model that decomposes into smaller subproblems.
The overall formulation
The overall formulation

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Reduction of North Eastern America[Allen, Lang, and Ilic(2008)]
The geographical area
Specifications for a Windy Day

1. Three wind cuts occur.
2. Outages geographically distributed.
3. Timing of outages set by moving weather system.

Research Questions
- How much potential wind is dispatched?
- How much capacity is needed for reliability?
Cases studied

1. No Wind
2. Wind in three locations, buses 72926, 70002 and 77406.
3. Wind + Ramping Costs (RC).
5. Wind + DL, buses 74316, 74327, 71797 and 79800.
Effects of Adding Wind

- **Lower Operating Costs/ More Wind Dispatched**, Displacement of natural gas.
- Uncertainty added to the system
Effects of ramping cost + storage

- Displacement of some coal generation
- Baseload units managed without big operational swings
Effects of storage

- Charging in low demand periods
- Overall flattening of load-generation
Comparing all cases

Fuel Utilization over a day

<table>
<thead>
<tr>
<th>Case</th>
<th>Hour of the day</th>
<th>nuclear</th>
<th>hydrom</th>
<th>refuse</th>
<th>coal</th>
<th>ng</th>
<th>oil</th>
<th>wind</th>
<th>ess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Case 2</td>
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<td></td>
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<tr>
<td>Case 3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 5</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Deferrable Load Pattern (74316, Dunwodie)

Real Power Output, ESS @ bus 18, Gen 132

Reserves and Ramp reserves, ESS @ bus 18, Gen 132
## Summary of Key Results

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Costs ($1000/day)</td>
<td>102,266</td>
<td>83,015</td>
<td>83,527</td>
<td>78,981</td>
<td>79,272</td>
</tr>
<tr>
<td>Ramping Costs ($1000/day)</td>
<td>0</td>
<td>0</td>
<td>1,538</td>
<td>873</td>
<td>0</td>
</tr>
<tr>
<td>Gen. Net Revenue ($1000/day)</td>
<td>261,258</td>
<td>203,362</td>
<td>209,807</td>
<td>187,660</td>
<td>177,732</td>
</tr>
<tr>
<td>Congestion Rents ($1000/day)</td>
<td>10,618</td>
<td>31,010</td>
<td>30,397</td>
<td>18,275</td>
<td>17,245</td>
</tr>
<tr>
<td>GenCap All (MW)</td>
<td>138,596</td>
<td>127,625</td>
<td>127,844</td>
<td>121,301</td>
<td>121,752</td>
</tr>
<tr>
<td>Wind Energy (MWh)</td>
<td>719</td>
<td>254,939</td>
<td>242,666</td>
<td>250,703</td>
<td>257,868</td>
</tr>
</tbody>
</table>

**Deferrable loads →**

- Overall reduction of capacity needed
- More wind used
- Reduction of operating costs
Composition of payments in the Wholesale Market

Daily Cost ($)

- Case 1
- Case 2
- Case 3
- Case 4
- Case 5

Operating Costs
Ramping Costs
Generators Net Revenue
Congestion Rents

Wholesale payments
## Annualized Capital Costs

<table>
<thead>
<tr>
<th>Case</th>
<th>No W.</th>
<th>Wind</th>
<th>W. + ramp</th>
<th>W. + ramp + DL</th>
<th>W. + DL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating Costs ($/MWh)</strong></td>
<td>18.57</td>
<td>12.28</td>
<td>12.46</td>
<td>11.41</td>
<td>11.52</td>
</tr>
<tr>
<td><strong>Capital Cost ($/MWh)</strong></td>
<td>34.97</td>
<td>33.88</td>
<td>33.88</td>
<td>33.41</td>
<td>33.45</td>
</tr>
<tr>
<td><strong>Total Operating + Capital Cost ($/MWh)</strong></td>
<td>53.54</td>
<td>46.15</td>
<td>46.33</td>
<td>44.82</td>
<td>44.97</td>
</tr>
</tbody>
</table>
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1 Motivation and Outline

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Conclusions

- Framework for evaluating dynamic decisions
- Potential for demand management by system planners
- Deferrable loads help reduce the capacity needed in the system
- Also, cost reduction thanks to more Wind (modeling here).
- Sensitivity of LMP’s to ramping services
Thank you
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