Enhancing Reliability Unit Commitment with Robust Optimization

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* The opinions expressed in this presentation are the authors’ and not necessarily those of ISO New England
Outline

• Current Process for Market Operations
• Operational Challenges
• Managing Uncertainties in Unit Commitment
  – Deterministic UC
  – Stochastic Programming
  – Robust Optimization
• Two-Stage Robust Optimization Approach
• A Conceptual Five-Bus Example
• Conclusion
Current Process for Market Operations

- **Day-head Market**
  - A Financial Market

- **Reliability Unit Commitment**
  - Physical unit commitment to meet reliability needs
  - Commitment of units with long runtime

- **Real-time Dispatch and Pricing**
  - Commitment of fast-start units
  - Meeting the real-time load
Operational Challenges

• Real-time Challenges:
  – Increased penetration of intermittent resources
  – Increased frequency of interchange scheduling
  – Increased demand response participation
  – Real-time operating parameter re-declaration
  – Real-time performance of dispatchable resources

• Real-time Commitment/Dispatch
  – Rely on fast-start units: Increased production cost
  – Emergency procedure: Load reduction/shedding

• Is there a better unit commitment schedule to reduce the real-time operational risk?
The Unit Commitment Problem

- The mathematical formulation of the unit commitment problem in a compact form:

\[
\min_{u, p} \sum_{i=1}^{n} \sum_{t=1}^{T} (f_{it}(u_{it}) + f_{it}^e(p_{it}))
\]

\[
s.t. \quad \sum_{i=1}^{n} p_{it} = \sum_{n} d_{nt}, \forall t \in T \\
\sum_{i} r_{it} \geq Q_t \quad \forall t \in T \\
(u, p, r) \in S
\]

- \(f_{it}(u_{it})\) and \(f_{it}^e(p_{it})\) are the startup and no-load cost, and the incremental cost
- \(u_{it} \in \{0, 1\}\) is the commitment status for generator i at time t
- \(p_{it}, r_{it} \geq 0\) are the energy and reserve output for generator i at time t
- \(d_{nt}\) is the demand at bus n at time t
- \(Q_t\) is the reserve requirement at time t
- \(S\) is a feasible set
Uncertainties Parameters Affecting UC

• Type of uncertainties
  – Units’ Initial Conditions
  – Load Forecast
    • Load Forecasting Errors
    • Demand Response
  – Resources’ Generating Capabilities
    • Wind Power
    • Solar
  – Contingency Events
    • Generator’s Forced Outages
    • Transmission Line Outages
Modeling of Uncertainty in UC

- Deterministic UC
  - Enforcing additional Reserve Requirements
- Stochastic programming
  - Minimizing the expected cost
- Robust optimization
  - Minimizing the cost for the worst case
Stochastic Programming

- A conventional way to model UC problem with real time uncertainties
- Require the knowledge of the probability distribution of the uncertain parameters
- Minimize the expected cost of the unit commitment problem
- The stochastic UC with demand uncertainty is the following:

$$\min_{u, p_\omega} \left\{ \sum_{i \in I, t \in T} f_{it}(u_{it}) + \sum_{\omega \in \Omega} \pi_\omega \left( \sum_{i \in I, t \in T} f_{it}^e(p_{it\omega}) \right) \right\}$$

s.t.

$$\sum_{i \in I} p_{it\omega} = \sum_{n} d_{nt\omega}, \forall t \in T, \forall \omega \in \Omega$$

$$\sum_{i} r_{it\omega} \geq Q_{t\omega}, \forall t \in T, \forall \omega \in \Omega$$

$$(u, p_\omega, r_\omega) \in S, \ \omega \in \Omega$$

$\pi_\omega$ is probability for the scenario $\omega$

$p_{it\omega}, r_{it\omega}$ are the power and reserve output for generator i at time t for scenario $\omega$

$\Omega$ is the set of scenarios of the levels of demand d.
Robust Optimization

- Robust optimization models random demand using uncertainty sets rather than probability distributions.
- Minimize the worst-case cost in that set.
- The robust optimization counterpart of the original problem is the following:

\[
\min_u \left\{ \sum_{i \in I, t \in T} f_{it}(u_{it}) + \max_{d \in U} \left( \min_p \sum_{i \in I, t \in T} f_{it}^e(p_{it}(u, d)) \right) \right\}
\]

\[s.t. \quad \sum_{i \in I} p_{it} = \sum_{n} d_{nt}, \forall t \in T, d_{nt} \in U\]
\[\sum_{i} r_{it} \geq Q_t \quad \forall t \in T\]
\[(u, p, r) \in S\]

\[p_{it} \geq 0 \text{ is the power output for generator } i \text{ at time } t\]
\[U \text{ is the uncertainty set of the real-time nodal demand } d.\]
# Stochastic Programming vs. Robust Optimization

<table>
<thead>
<tr>
<th></th>
<th>Stochastic Programming</th>
<th>Robust Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>Random variables</td>
<td>Uncertainty sets</td>
</tr>
<tr>
<td><strong>Information required</strong></td>
<td>Distributions</td>
<td>Convex hull of data realization</td>
</tr>
</tbody>
</table>
| **Advantage**  | Able to quantify expectations such as evaluating probability of outcomes | •Distribution free  
                |                        | •Computationally tractable for many classes of optimization |
| **Disadvantage** | •Computationally challenging  
                | •How to obtain exact distribution? | •Unable to provide probability measure such as expectations  
                |                               | •How to choose the right uncertainty set? |
Risk Management

- Risk is inevitable. It would be desirable to set up a corporate risk management policy.
- What is the right risk metric?
  - LOLP, EUE, etc..
  - Chance Constraints
- What is the N-1 protection criterion? – worst case
- Can we find the least cost unit commitment schedule that sustain any of the credible events? --- robust unit commitment.
- No risk has been quantified by these methods. Monte Carlo simulation can be used to quantify the risk.
The Uncertainty Set in Robust UC

- Choosing uncertainty sets that yield a good trade-off between performance and conservatism is central to robust optimization.
- Bertsimas, Sim and Thiele proposed the concept of “budget of uncertainty” to model the trade-off.
- In order to not overprotect the system, the random demand $d_{nt}$ at node $n$ at time $t$ can be modeled as,
  \[
  d_{nt} = \overline{d}_{nt} + \overline{d}_{nt} z_{nt}, \quad |z_{nt}| \leq 1
  \]
  \[
  \sum_{n=1}^{m} |z_{nt}| \leq \Gamma_t, \text{ for each time interval } t
  \]
- $\Gamma$ is called the “budget of uncertainty”.
- $\Gamma = 0$ yields the normal deterministic problem.
- $\Gamma = m$ leads to the most conservative case.
# Three Random Loads

<table>
<thead>
<tr>
<th>Budget of Uncertainty</th>
<th>Load 1 (MW)</th>
<th>Load 2 (MW)</th>
<th>Load 3 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma = 0$</td>
<td>150</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>$\Gamma = 1$</td>
<td>[150-15, 150+15]</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>[250-25, 250+25]</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>200</td>
<td>[350-35, 350+35]</td>
</tr>
<tr>
<td>$\Gamma = 2$</td>
<td>[150-15, 150+15]</td>
<td>[250-25, 250+25]</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>[250-25, 250+25]</td>
<td>[350-35, 350+35]</td>
</tr>
<tr>
<td>$\Gamma = 3$</td>
<td>[150-15, 150+15]</td>
<td>[250-25, 250+25]</td>
<td>[350-35, 350+35]</td>
</tr>
</tbody>
</table>
Bender’s Decomposition Algorithm for RO Two-Stage UC Problem

Master Problem (MIP)
- Constants: worst-case dispatch cost function,
- Variables: unit commitment decisions.
- Domain: start-up and shut-down constraints.

Subproblem (MIP)
- Constants: unit commitment solution
- Variables: economic dispatch decisions and worst-case demand level
- Domain: energy balance constraints, reserve constraint, transmission constraints, resource level constraints (ramp rate, capacity etc.), uncertainty budget constraints

Worst-case solutions for the given unit commitment solution

Updated Unit commitment solutions
# A Five-Bus Example

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>[EcoMin, EcomMax] (MW)</th>
<th>Offer Price ($/MWh)</th>
<th>Start-up Cost ($/MWh)</th>
<th>No-load Cost ($/MWh)</th>
<th>Initial Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alta</td>
<td>[10,150]</td>
<td>25</td>
<td>1000</td>
<td>0</td>
<td>ON</td>
</tr>
<tr>
<td>Park City</td>
<td>[50,350]</td>
<td>30</td>
<td>1000</td>
<td>10</td>
<td>ON</td>
</tr>
<tr>
<td>Solitude 1</td>
<td>[50,300]</td>
<td>60</td>
<td>1000</td>
<td>30</td>
<td>ON</td>
</tr>
<tr>
<td>Solitude 2</td>
<td>[10,300]</td>
<td>140</td>
<td>1600</td>
<td>60</td>
<td>OFF</td>
</tr>
<tr>
<td>Brighton</td>
<td>[180,400]</td>
<td>20</td>
<td>2000</td>
<td>20</td>
<td>ON</td>
</tr>
<tr>
<td>Sundance</td>
<td>[100,300]</td>
<td>50</td>
<td>1500</td>
<td>16</td>
<td>ON</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>Level (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load B</td>
<td>[400-25,400+25]</td>
</tr>
<tr>
<td>Load C</td>
<td>[370-10,370+10]</td>
</tr>
<tr>
<td>Load D</td>
<td>[325-15,325+15]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Line</th>
<th>Normal (MW)</th>
<th>LTE (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>AD</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>AE</td>
<td>425</td>
<td>525</td>
</tr>
<tr>
<td>BC</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>CD</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>DE</td>
<td>350</td>
<td>450</td>
</tr>
</tbody>
</table>
A Five-Bus Example with Deterministic UC

• Case D1:
  – Use expected load level (400+370+325 =1095 MW)
  – Reserve requirements:
    • 10-min spinning = 50 MW
    • 10-min total = 100 MW
    • 30-min operating = 200 MW.

• Case D2:
  – Use expected load level (1095 MW)
  – Additional Reserve requirements (total load variation 50MW):
    • 10-min spinning = 100 MW
    • 10-min total = 150 MW
    • 30-min operating = 250 MW.
A Five-Bus Example -- Deterministic UC

• For both cases
  • All units except Solitude 2 are committed (total cost is $38,255)
  • Line CD is binding at 500 MW after contingency AB loss.

• Is such commitment good for any load realization?
  – What if the loads at B and C are increased by 25 and 10 MW respectively?
    • Under line AB contingency, line CD flow will be 505 MW, which is higher than its emergency limit 500 MW.
    • We failed to protect the system from such contingency.
A Five-Bus Example Robust UC

- Case R1 – with one load variation
- Case R2 – with two load variations
- Case R3 – with three load variations
- All reserve requirements are the same as case D1.
- The robust UC solution always finds load variation at the extreme point.

<table>
<thead>
<tr>
<th>Case</th>
<th>Solitude 2</th>
<th>All other units</th>
<th>Worst Load Variation</th>
<th>Worst Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Off</td>
<td>On</td>
<td>LoadB</td>
<td>39,755</td>
</tr>
<tr>
<td>R2</td>
<td>On</td>
<td>On</td>
<td>LoadB and LoadC</td>
<td>42,416</td>
</tr>
<tr>
<td>R3</td>
<td>On</td>
<td>On</td>
<td>LoadB, LoadC and LoadD</td>
<td>42,866</td>
</tr>
</tbody>
</table>
Conclusion

- With the increased penetration of renewable resources and demand response, a robust unit commitment to cover the “worst” case scenario is needed in the reliability commitment process.

- Compared to the deterministic unit commitment, it is more efficient in identifying the proper commitment needed for the worst case scenario.

- Compared to the stochastic unit commitment, the robust unit commitment:
  - More consistent with the N-1 protection criterion (the worst case)
  - Do not require the knowledge of probability distribution
  - Requires less computational efforts
QUESTIONS?