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Modeling Flexible Generator Operating Regions via Chance-constrained Stochastic Unit Commitment

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Stochastic unit commitment

Standard unit commitment (UC) problem: which thermal generators should be scheduled to meet power demand, while ensuring feasible operations?

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Stochastic unit commitment

Standard unit commitment (UC) problem: which thermal generators should be scheduled to meet power demand, while ensuring feasible operations?

Stochastic unit commitment (UC) problem: which thermal generators should be scheduled to meet power demand, while ensuring feasible operations, under uncertainty (of demand, prices, renewables...)?

But...

- Thermal generator operational limits are based on engineering judgments
- Can be exceeded in practice, for short periods
- System operators do run thermal generators beyond these limits

Proposed model

- Allow thermal generators to “occasionally” violate operational limits
- Violations should be few (else, increased maintenance costs)
- Violations should not be large (there are absolute ratings of generators)
- 1% savings in energy production is worth \approx \$1 billion per year in the U.S. alone

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Proposed model

- Let $y_t^{g,\omega}$ denote a “non-nominal” operation in hour t for generator g in scenario ω
- During non-nominal operations, generator’s operating region expands from $[\underline{P}^g, \overline{P}^g]$ to $[\underline{\underline{P}}^g, \overline{\overline{P}}^g]$
- Non-nominal mode of generation is more expensive
- Number of non-nominalities is few:

$$\frac{1}{|\Omega||\mathcal{T}||\mathcal{G}|} \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} \sum_{\omega \in \Omega} y_t^{g,\omega} \leq \varepsilon \leftarrow \text{almost a chance-constraint!}$$

Recall, challenges of chance-constraint (CC) models

- CC models are computationally intractable
- A known NP-hard problem
- Existing algorithms not scalable to practical sized problems
- Feasible region is non-convex

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We use:

$$\overline{\overline{P}}^g = (1 + \beta) \overline{P}^g$$

$$\underline{\underline{P}}^g = (1 - \beta) \underline{P}^g$$

$$\overline{C}^g = (1 + \gamma) C^{L^g, g}$$

$$\underline{C}^g = (1 + \gamma) C^{L^g, g}.$$

WECC240++ system with 85 thermal generators, 50 scenarios and
RTS-GMLC system with 73 thermal generators, 16 scenarios

Computational results for the RTS-GMLC 16 scenario case for 10 July 2020.

Under second review: *Computational Management Science*

Table: MIP gap = 0.1%

ε	β	γ	Cost (M\$)	Savings (%)	Time (sec)	MIP gap (%)
0			3.89	0.00%	33	-
0.01	0.05	0.1	3.84	1.21%	46	-
		0.2	3.84	1.20%	48	-
	0.1	0.1	3.83	1.51%	82	-
		0.2	3.83	1.50%	106	-
0.05	0.05	0.1	3.83	1.53%	65	-
		0.2	3.83	1.45%	100	-
	0.1	0.1	3.81	2.08%	1800	0.22%
		0.2	3.82	1.82%	1800	0.15%

- Increase $\varepsilon \Rightarrow$ increase savings
- Increase $\beta \Rightarrow$ increase savings
- Increase $\gamma \Rightarrow$ decrease savings

Cost savings for the RTS-GMLC 16 scenario case for 10 July 2020.

Under second review: *Computational Management Science*

Table: MIP gap = 0.1%

ϵ	β	γ	Optimal	Limited	No nuclear
0.01	0.05	0.1	1.21%	0.71%	1.06%
		0.2	1.20%	0.69%	1.04%
	0.1	0.1	1.51%	1.14%	1.15%
		0.2	1.50%	1.10%	1.11%
0.05	0.05	0.1	1.53%	0.70%	1.22%
		0.2	1.45%	0.69%	1.15%
	0.1	0.1	2.08%	1.14%	1.41%
		0.2	1.82%	1.10%	1.28%

Limited = at most one non-nominal operation per generator per day

No nuclear = no non-nominal operation for the nuclear unit in this system

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Chance Constraint Setting

This is a linear Joint Chance Constraint:

$$P(x_t \leq y_t^\omega + w_t^\omega, \forall t \in T) \geq 1 - \varepsilon$$

Background:

- Two-stage stochastic program with recourse
- First stage decision, x_t , second-stage decision, y_t^ω
- Possibly integer restrictions on x and/or y
- i.i.d. samples of uncertainty w_t^ω

Stochastic unit commitment model

Indices and Sets:

$g \in \mathcal{G}$	Thermal generators.
$t \in \mathcal{T}$	Hourly time steps: $1, \dots, T$; i.e., $[a, b) \in \mathcal{T} \times \mathcal{T}$ such that $b \geq a + UT^g$.
$l \in \mathcal{L}^g$	Piecewise production cost intervals for generator g : $1, \dots, L_g$.
$s \in \mathcal{S}^g$	Start-up categories for generator g , from hottest (1) to coldest (S_g).
$\omega \in \Omega$	Scenarios: $\omega_1, \dots, \omega_N$.

Parameters: First Stage

$C^{l,g}$	Marginal cost for piecewise segment l for generator g (\$/MWh).
\overline{C}^g	Marginal cost for production above \overline{P}^g (\$/MWh).
\underline{C}^g	Marginal cost for production below \underline{P}^g (\$/MWh).
$C^{R,g}$	Cost of generator g running and operating at minimum production \underline{P}_g (\$/h).
$C^{S,g}$	Start-up cost of category s for generator g (\$).
DT^g	Minimum down time for generator g (h).
\overline{P}^g	Maximum power output for generator g under normal operations (MW).
$\overline{\overline{P}}^g$	Maximum power output for generator g under non-nominal operations (MW).
\underline{P}^g	Minimum power output for generator g under normal operations (MW).
$\underline{\underline{P}}^g$	Minimum power output for generator g under non-nominal operations (MW).
$\overline{\overline{P}}^{l,g}$	Maximum power available for piecewise segment l for generator g (MW) (with $\overline{\overline{P}}^{0,g} = \underline{P}^g$).
RD^g	Ramp-down rate for generator g (MW/h).
RU^g	Ramp-up rate for generator g (MW/h).
SD^g	Shutdown ramp rate for generator g (MW/h).
SU^g	Start-up ramp rate for generator g (MW/h).
TC^g	Time down after which generator g goes cold (h).
$\underline{T}^{s,g}$	Time offline after which the start-up category s is available (h) (with $\underline{T}^{1,g} = DT^g$, $\underline{T}^{S_g,g} = TC^g$).
UT^g	Minimum up time for generator g (h).

Stochastic unit commitment model

Parameters: Second Stage

D_t^ω	Load (demand) at time t in scenario ω (MW).
\overline{W}_t^ω	Maximum power from renewables at time t in scenario ω (MW).
\underline{W}_t^ω	Minimum power from renewables at time t in scenario ω (MW).

Variables: First Stage

u_t^g	Commitment status of generator g at time t , $\in \{0, 1\}$.
v_t^g	Start-up status of generator g at time t , $\in \{0, 1\}$.
w_t^g	Shutdown status of generator g at time t , $\in \{0, 1\}$.
$x_{[t,t']}^g$	Indicator arc for shutdown at time t , start-up at time t' , uncommitted for $i \in [t, t')$, for generator g , $\in \{0, 1\}$, $[t, t')$ such that $t + DT^g \leq t' \leq t + TC^g - 1$.

Variables: Second Stage

$p_t^{g,\omega}$	Power above minimum from generator g at time t in scenario ω (MW).
$\overline{p}_t^{g,\omega}$	Power above maximum from generator g at time t in scenario ω (MW).
$\underline{p}_t^{g,\omega}$	Power below minimum from generator g at time t in scenario ω (MW).
$p_{t,l}^{g,\omega}$	Power from piecewise interval l for generator g at time t in scenario ω (MW).
$r_t^{h,\omega}$	Power from renewables at time t in scenario ω (MW).
$y_t^{g,\omega}$	Non-nominal operation status of generator g at time t in scenario ω (MW).

Stochastic unit commitment

$$\min \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} \left(\sum_{l \in \mathcal{L}^g} \mathbb{E}[C^{l,g} p_t^{l,g,\omega} + \overline{C}^g \overline{P}_t^{g,\omega} + \underline{C}^g \underline{P}_t^{g,\omega}] + C^{R,g} u_t^g + c_t^{SU,g} \right) \quad (1)$$

subject to:

$$u_t^g - u_{t-1}^g = v_t^g - w_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G} \quad (2a)$$

$$\sum_{i=t-UT^g+1}^t v_i^g \leq u_t^g \quad \forall t \in [UT^g, T], \forall g \in \mathcal{G} \quad (2b)$$

$$\sum_{i=t-DT^g+1}^t w_i^g \leq 1 - u_t^g \quad \forall t \in [DT^g, T], \forall g \in \mathcal{G} \quad (2c)$$

$$\sum_{t'=t-TC^g+1}^{t-DT^g} x_{[t',t]}^g \leq v_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G} \quad (2d)$$

$$\sum_{t'=t+DT^g}^{t+TC^g-1} x_{[t,t']}^g \leq w_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G} \quad (2e)$$

$$c_t^{SU,g} = C^{S,g} v_t^g + \sum_{s=1}^{S^g-1} (C^{s,g} - C^{S,g}) \left(\sum_{t'=t-\underline{T}^{s,g}+1}^{t-\overline{T}^{s,g}} x_{[t',t]}^g \right) \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G} \quad (2f)$$

Stochastic unit commitment

$$p_t^{g,\omega} \leq (\bar{P}^g - \underline{P}^g)u_t^g - (\bar{P}^g - SU^g)v_t^g - (\bar{P}^g - SD^g)w_{t+1}^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^{>1}, \forall \omega \in \Omega \quad (3a)$$

$$p_t^{g,\omega} \leq (\bar{P}^g - \underline{P}^g)u_t^g - (\bar{P}^g - SU^g)v_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^1, \forall \omega \in \Omega \quad (3b)$$

$$p_t^{g,\omega} \leq (\bar{P}^g - \underline{P}^g)u_t^g - (\bar{P}^g - SD^g)w_{t+1}^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^1, \forall \omega \in \Omega \quad (3c)$$

$$p_t^{g,\omega} - p_{t-1}^{g,\omega} \leq (SU^g - RU^g - \underline{P}^g)v_t^g + RU^g u_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (3d)$$

$$p_{t-1}^{g,\omega} - p_t^{g,\omega} \leq (SD^g - RD^g - \underline{P}^g)w_t^g + RD^g u_{t-1}^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (3e)$$

$$p_t^{g,\omega} = \sum_{l \in \mathcal{L}^g} p_t^{l,g,\omega} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (3f)$$

$$p_t^{l,g,\omega} \leq (\bar{P}^{l,g} - \bar{P}^{l-1,g})u_t^g \quad \forall t \in \mathcal{T}, \forall l \in \mathcal{L}^g, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (3g)$$

Stochastic unit commitment

$$y_t^{g,\omega} \leq u_t^g - v_t^g - w_{t+1}^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^{>1}, \forall \omega \in \Omega \quad (4a)$$

$$y_t^{g,\omega} \leq u_t^g - v_t^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^1, \forall \omega \in \Omega \quad (4b)$$

$$y_t^{g,\omega} \leq u_t^g - w_{t+1}^g \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^1, \forall \omega \in \Omega \quad (4c)$$

$$\overline{p}_t^{g,\omega} \leq (\overline{P} - \underline{P}) y_t^{g,\omega} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (4d)$$

$$\underline{p}_t^{g,\omega} \leq (\underline{P} - \underline{P}) y_t^{g,\omega} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (4e)$$

$$\sum_{g \in \mathcal{G}} (p_t^{g,\omega} + \overline{p}_t^{g,\omega} - \underline{p}_t^{g,\omega} + \underline{P} u_t^g) + r_t^\omega = D_t^\omega \quad \forall t \in \mathcal{T}, \forall \omega \in \Omega \quad (5)$$

$$\frac{1}{|\mathcal{G}||\mathcal{T}||\Omega|} \sum_{\omega \in \Omega} \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} y_t^{g,\omega} \leq \epsilon \quad (6)$$

$$p_t^{j,g,\omega} \in \mathbb{R}_+ \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{L}^g, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (7a)$$

$$p_t^{g,\omega}, \overline{p}_t^{g,\omega}, \underline{p}_t^{g,\omega} \in \mathbb{R}_+ \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega \quad (7b)$$

$$r_t^{n,\omega} \in [\underline{W}_t^{n,\omega}, \overline{W}_t^{n,\omega}] \quad \forall t \in \mathcal{T}, \forall n \in \mathcal{N}, \forall \omega \in \Omega \quad (7c)$$

$$u_t^g, v_t^g, w_t^g \in \{0, 1\} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G} \quad (7d)$$

$$x_{[t,t')}^g \in \{0, 1\} \quad \forall [t, t') \in \mathcal{X}^g, \forall g \in \mathcal{G} \quad (7e)$$

$$y_t^{g,\omega} \in \{0, 1\} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}, \forall \omega \in \Omega. \quad (7f)$$

Computational results for the WECC240++ 50 scenario test case for 11 May 2013.

Table: MIP gap = 0.1%

ε	β	γ	Cost (K\$)	Savings (%)	Time (sec)	MIP gap (%)
0			64.41	0.00%	183	-
0.01	0.05	0.1	64.20	0.33%	275	-
		0.2	64.21	0.31%	242	-
	0.1	0.1	64.03	0.59%	258	-
		0.2	64.04	0.58%	317	-
0.05	0.05	0.1	63.86	0.85%	275	-
		0.2	63.90	0.80%	343	-
	0.1	0.1	63.35	1.64%	378	-
		0.2	63.42	1.55%	371	-

- Increase $\varepsilon \Rightarrow$ increase savings
- Increase $\beta \Rightarrow$ increase savings
- Increase $\gamma \Rightarrow$ decrease savings

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