A Chance-constrained Unit Commitment Model for Power Systems with High Penetration of Renewable Energy

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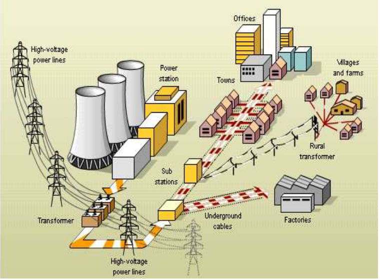
Objective

Development of a solution framework for Unit Commitment (UC) problems with random generation:



- Identify feasible (or ϵ-optimal) schedules
- Capable of representing uncertainty with large samples
- Applicable to reasonably-sized systems

Unit Commitment Problem

Find a cost-effective combination of units that serves the power demand of the system, while satisfies operating constraints of the units and transmission.

- Time horizon: $\mathcal{T}$
- Scheduling: u_g, v_g
- Dispatch: p_g

$$
\begin{aligned}
\min \quad & \textstyle\sum_{n\in\mathcal{N}}\sum_{t\in\mathcal{T}} c_n(p_{g_n}^t) + F u_{g_n}^t + S_n^t v_{g_n}^t \\
& (p_g, u_g, v_g) \in \mathcal{C}_{\text{dyn}}^{\text{gen}} \cap \mathcal{C}_{\text{stat}}^{\text{gen}}, \\
& \textstyle\sum_{n\in\mathcal{N}_k} p_{g_n}^t + {p_{\text{ij}}}_k^t = \mathbf{L}_k^t, k \in \mathcal{K}, \\
& |{p_{\text{ij}}}_l| \leq F_l, l \in \mathcal{B}, \\
& \textstyle\sum_{n\in\mathcal{N}} sp_n^t = Sr^t, \\
& \textstyle\sum_{n\in\mathcal{N}} sp_n^t + np_n^t = Sn^t
\end{aligned}
$$

- $\mathcal{C}_{\text{dyn}}^{\text{gen}}$: ramping, up/down times
- $\mathcal{C}_{\text{stat}}^{\text{gen}}$: generation limits

Unit Commitment Problem

Find a cost-effective combination of units that serves the power demand of the system, while satisfies operating constraints of the units and transmission.

- Time horizon: $\mathcal{T}$
- Scheduling: u_g, v_g
- Dispatch: p_g

$$
\begin{aligned}
\min \quad & C(p_g, u_g, v_g) \\
& (p_g, u_g, v_g) \in \mathfrak{C}^{\text{gen}}_{\text{dyn}} \cap \mathfrak{C}^{\text{gen}}_{\text{stat}}, \\
& \textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n} + {p_{\text{ij}}}^t_k = \mathbf{L}^t_k, k \in \mathcal{K}, \\
& |{p_{\text{ij}}}_l| \leq F_l, l \in \mathcal{B}, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n = Sr^t, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n + np^t_n = Sn^t
\end{aligned}
$$

- DC Power Flow
- Spinning Reserve
- Non-spinning Reserve

Given there is renewable generation, find a cost-effective combination of units that serves the power demand of the system, while satisfies operating constraints of the units and transmission.

$$
\begin{aligned}
\min \quad & C(p_g, u_g, v_g) \\
& (p_g, u_g, v_g) \in \mathcal{C}^{\text{gen}}_{\text{dyn}} \cap \mathcal{C}^{\text{gen}}_{\text{stat}}, \\
& \textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n} + \mathbf{p}^t_{r_k} + {p_{\text{ij}}}^t_k = \mathbf{L}^t_k, k \in \mathcal{K}, \\
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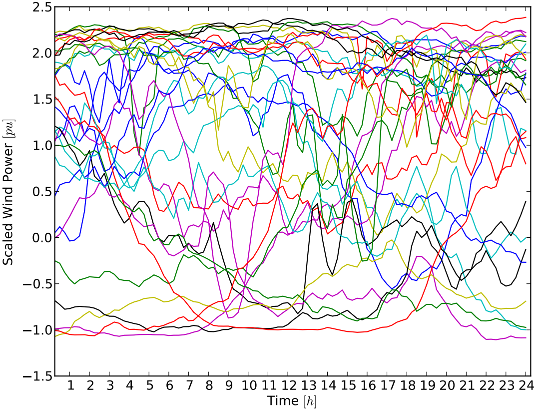
\end{aligned}
$$

- Forecast
- System reserve



January 2014, ELIA - Belgium system

Given a set of realization: $\omega \in \Omega$

$$
\begin{aligned}
\min \quad & C_1(u_g, v_g) + \mathbb{E}[C_2(p_g)] \\
& (p_g(\omega), u_g, v_g) \in \mathcal{C}^{\text{gen}}_{\text{dyn}} \cap \mathcal{C}^{\text{gen}}_{\text{stat}}, \\
& \textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n}(\omega) + \mathbf{p}^t_{r_k}(\omega) + {p_{\text{ij}}}^t_k(\omega) = \mathbf{L}^t_k, k \in \mathcal{K}, \\
& |{p_{\text{ij}}}_l(\omega)| \leq F_l, l \in \mathcal{B}, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n(\omega) = Sr^t, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n(\omega) + np^t_n(\omega) = Sn^t
\end{aligned}
$$

u_g, v_g is the (risk-neutral) commitment that minimizes the expected dispatch cost $\mathbb{E}[C_2(p_g)]$

Risk-averse UC and probabilistic reserve levels:

$$
\begin{aligned}
\min \quad & C(u_g, v_g, p_g) \\
& (p_g, sp, np, u_g, v_g) \in \mathcal{C}^{\text{gen}}_{\text{dyn}} \cap \mathcal{C}^{\text{gen}}_{\text{stat}}, \\
& \mathbb{P}\big[\textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n} + {p_{\text{ij}}}^t_k = \mathbf{L}^t_k - \mathbf{p}^t_{r_k}, k \in \mathcal{K}\big] \geq \pi, \\
& |{p_{\text{ij}}}_l| \leq F_l, l \in \mathcal{B}, \\
& \mathbb{P}\big[\textstyle\sum_{n \in \mathcal{N}} sp^t_n = Sr^t + \alpha \mathbf{p}^t_r\big] \geq \rho, \\
& \mathbb{P}[\textstyle\sum_{n \in \mathcal{N}} sp^t_n + np^t_n = Sn^t + \beta \mathbf{p}^t_r\big] \geq \rho
\end{aligned}
$$

(u_g, v_g, p_g) schedule determined by a risk-averse net-load operating level: $[L - p_r]_\pi$

(sp, np) system reserves allocated with a risk-averse renewable level: $[p_r]_\rho$

Risk-averse UC and probabilistic reserve levels:

$$\begin{aligned} \min \quad & C(u_g, v_g, p_g) \\ & (p_g, sp, np, u_g, v_g) \in \mathcal{C}^{\text{gen}}_{\text{dyn}} \cap \mathcal{C}^{\text{gen}}_{\text{stat}}, \\ & \textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n} + {p_{\text{ij}}}^t_k = w^t_k, k \in \mathcal{K}, \\ & |{p_{\text{ij}}}_l| \leq F_l, l \in \mathcal{B}, \\ & \textstyle\sum_{n \in \mathcal{N}} sp^t_n = Sr^t + \alpha z^t, \\ & \textstyle\sum_{n \in \mathcal{N}} sp^t_n + np^t_n = Sn^t + \beta z^t, \\ & w \in \mathcal{W}_\pi, z \in \mathcal{Z}_\rho \end{aligned}$$

Netload: $\mathcal{W}_\pi = \{w \in \mathbb{R}^{KT} : \mathbb{P}(\mathbf{L}^k_t - \mathbf{p}^t_{r_k} \leq w^t_k) \geq \pi\}$
Reserve renewable: $\mathcal{Z}_\rho = \{z \in \mathbb{R}^T : \mathbb{P}(\mathbf{p}^t_r \leq z^t) \geq \rho\}$

Decomposition Scheme

Introduce artificial variables: $\bar{p}_g, \bar{sp}, \bar{np}, \bar{w}, \bar{z}$

$$
\begin{aligned}
\min \quad & C(u_g, v_g, p_g) \\
& (\bar{p}_g, \bar{sp}, \bar{np}, u_g, v_g) \in \mathcal{C}^{\text{gen}}_{\text{dyn}} \cap \mathcal{C}^{\text{gen}}_{\text{stat}}, \\
& \textstyle\sum_{n \in \mathcal{N}_k} p^t_{g_n} + {p_{\text{ij}}}^t_k = \bar{w}^t_k, k \in \mathcal{K}, \\
& |{p_{\text{ij}}}_l| \le F_l, l \in \mathcal{B}, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n = Sr^t + \alpha \bar{z}^t, \\
& \textstyle\sum_{n \in \mathcal{N}} sp^t_n + np^t_n = Sn^t + \beta \bar{z}^t, \\
& p_g = \bar{p}_g, sp = \bar{sp}, np = \bar{np}, \\
& w = \bar{w}, z = \bar{z}, \\
& w \in \mathcal{W}_\pi, z \in \mathcal{Z}_\rho
\end{aligned}
$$

Decomposition Scheme

Relax artificial constraints: $\lambda_p, \lambda_{sp}, \lambda_{np}, \lambda_w, \lambda_z$

$$\begin{aligned} L(p,w,z) &= C(u_g, v_g, p_g) + \lambda_p^\top (p_g - \bar{p}_g) + \lambda_{sp}^\top (sp - \bar{sp}) \\ &+ \lambda_{np}^\top (np - \bar{np}) + \lambda_w^\top (w - \bar{w}) + \lambda_z^\top (z - \bar{z}), \end{aligned}$$

Dispatch - OPF

p_g, sp, np

$\bar{w}, \bar{z}$

Commitment

u_g, v_g

$\bar{sp}, \bar{np}, \bar{p}_g$

Netload

$\mathbb{P}(\mathbf{L}_k^t - \mathbf{p_r}_k^t \leq w) \geq \pi$

$w \in \mathcal{W}_\pi$

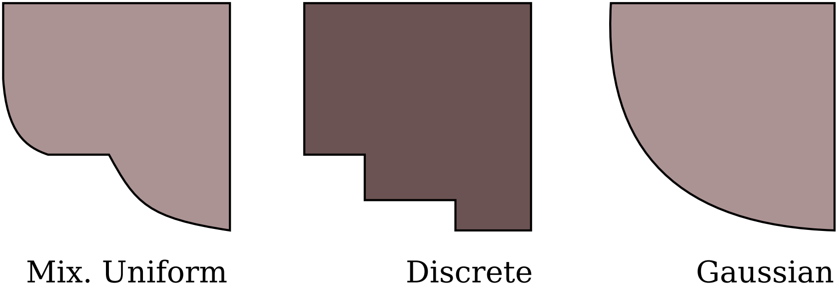
Reserve

$\mathbb{P}(\mathbf{p_r}^t \leq z) \geq \rho$

$z \in \mathcal{Z}_\rho$

Stochastic subproblem

Feasible set example in 2D:



Given realizations: $\mathcal{W}_\pi$ and $\mathcal{Z}_\rho$ are non-convex (discrete).

$$\mathcal{W}_\pi = \{w \in \mathbb{R}^{KT} : \mathbb{P}(\mathbf{L}_t^k - \mathbf{p}_{r_k}^t \leq w_k^t) \geq \pi\}$$

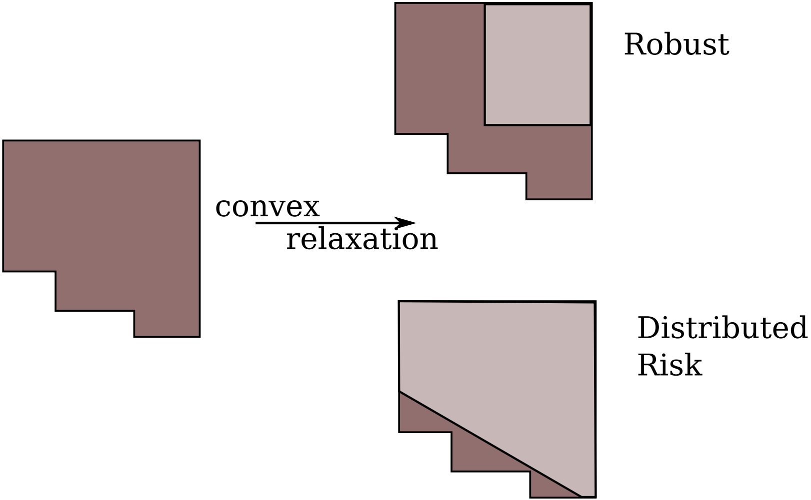
- Given a set of realizations $[\mathbf{L}_t^k - \mathbf{p}_{r_k}^t](\omega), \omega \in \Omega$ with probability $1/|\Omega|$
- Check the π-boundary: for every realization $e(\omega)$

$$e(\omega) = \begin{cases} 1 & [\mathbf{L}_t^k - \mathbf{p}_{r_k}^t](\omega) \leq w_k^t \\ 0 & \text{otherwise} \end{cases}$$

- $w \in \mathcal{W}_\pi$ if $\frac{1}{|\Omega|} \sum_{\omega \in \Omega} e(\omega) \geq \pi$

The subproblems: $\min\{\lambda_w^\top w | w \in \mathcal{W}_\pi\}$, $\min\{\lambda_z^\top z | z \in \mathcal{Z}_\rho\}$ are combinatorial problems, difficult to solve.

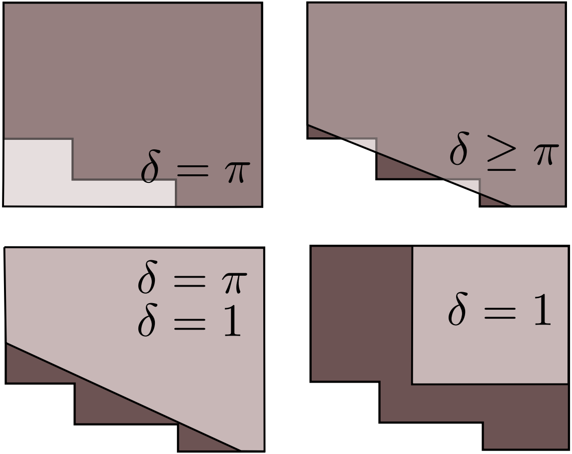
Relaxation Approach - Stochastic Subproblems



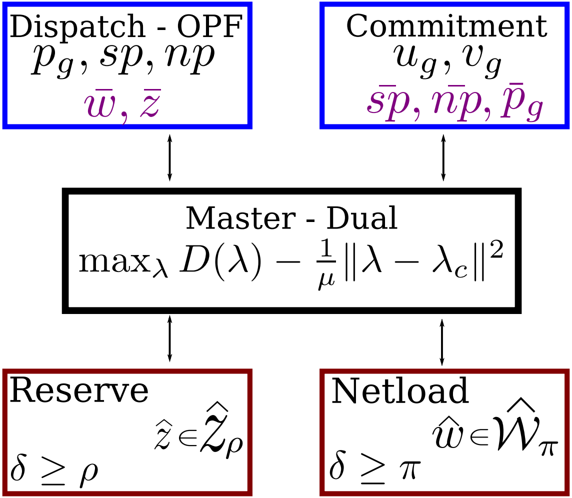
Relaxation Approach - Stochastic Subproblems

Scenarios $\omega \in \Omega, w(\omega), z(\omega)$

$$\hat{w}_k^t = [w_k^t]_\delta,\ \hat{z}^t = [z^t]_\delta,\ \delta \geq \pi$$



Approximate Bundle Method



Inexact information

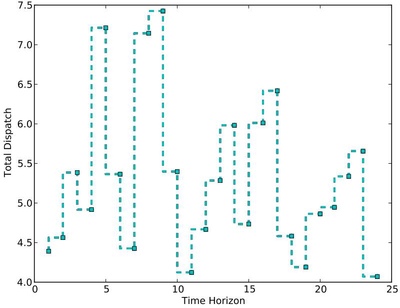
Results - IEEE118 bus system

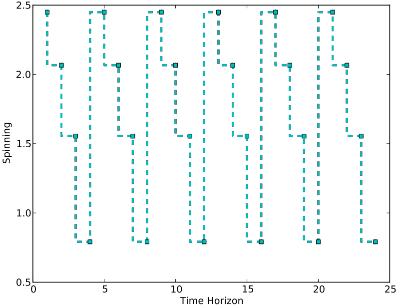
Wind farms: 53, 56, 32, 106, 6 – possible max generation 30%.

Nuclear: 30, 40, 37, 5.

Committed units:

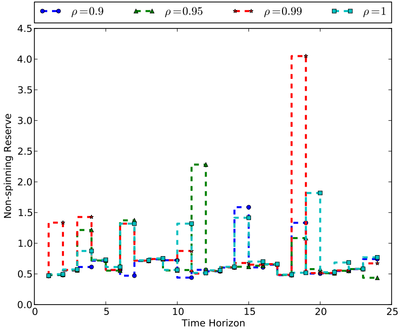
5,6,11,12,14,20,21,22,25,26,28,29,30,37,38,40,45,46,54

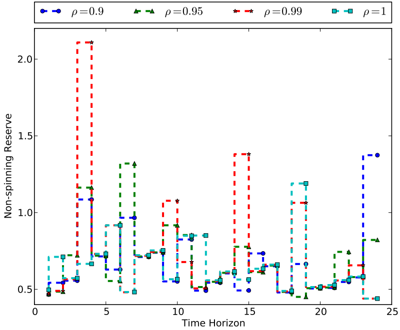




Results - IEEE118 bus system

Wind farms: 53, 56, 32, 106, 6. Nuclear: 30, 40, 37, 5. Committed units: 5,6,11,12,14,20,21,22,25,26,28,29,30,37,38,40,45,46,54





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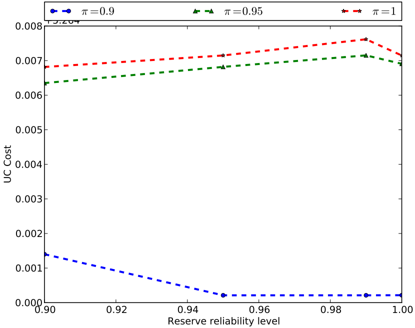
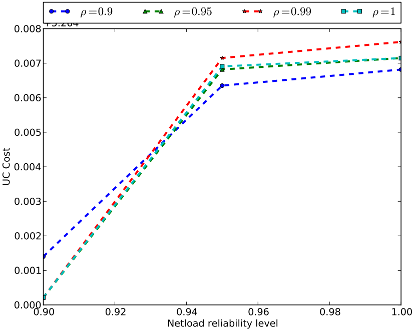
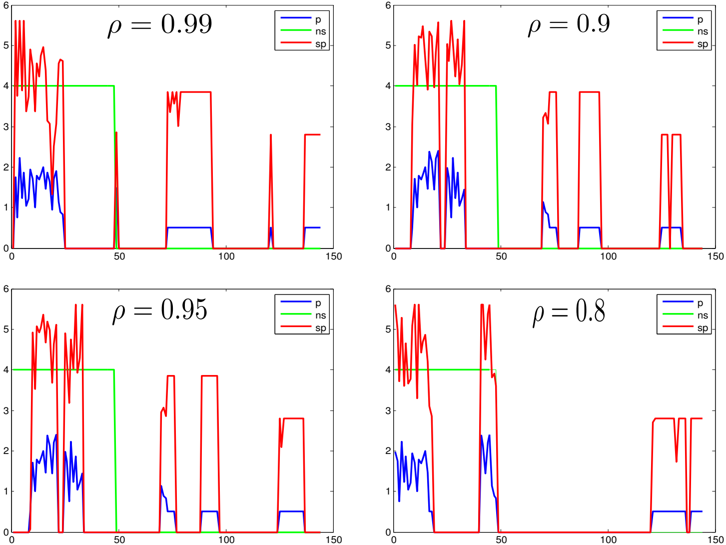




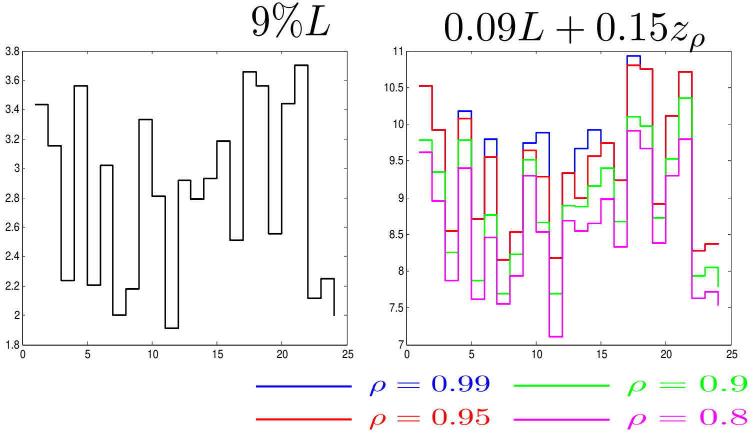
Results - IEEE30 bus system

Wind farms: 1,5,21,22,26. Generators:1,2,22,27,23. $\pi = 0.9$



Results - IEEE30 bus system

Wind farms: 1,5,21,22,26. Generators:1,2,22,27,23. $\pi = 0.9$



Conclusions

The approach described has a number of advantages

- The risk-parameters can be set up by the user.
- The formulation is flexible and it can be implemented with OPF tools available - MATPOWER.
- Different number of realization can be used to estimate the percentiles at each period of time and node (where is needed)- important to accommodate forecast errors.
- Probabilistic reserves could be used to prepare the system for possible variations of wind power.
- The approach could be used to analyze safety renewable integration levels.
- The approach identifies risk-averse commitment

Future directions

- Robust analysis of safety levels of renewable energy integration - UC
- Given UC and renewable integration levels: Refinement of dispatch
- Test the approach with different characterization of wind power: cluster representatives