Porbabilistic Security-Constrained Unit Commitment with Generation and Transmission Contingencies

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Overview

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  - Low production costs
  - Reliable supply
  - Green generation

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- Reliable supply: Contingencies are unforeseen events for which historical data exists – **probabilistic events**
- Green generation: As any weather-driven source the production from these sources is **stochastic**
- Need to develop tools that explicitly take into account the probabilistic nature of the contingencies as well as the stochasticity of renewable sources **in the scheduling process**:
  - **Optimal amounts of reserve** in the system
  - **Optimal allocation of the reserve** in the grid

Existing Approaches

- Typically reserve is scheduled using deterministic criteria *e.g.* $N-1$, and variants *e.g.* Wood 1996[1]

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- Some approximate the "system risk" via proxies, and enforce constraints to meet a predefined limit in the scheduling process *e.g.* Chattopadhyay 2002[3]

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- Some optimize the reserve requirements exogenously and set them as contraints in a regular UC, *e.g.* Ortega-Vazquez 2007[5]

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- Some approaches that explicitly model the contingency states in the scheduling stage *e.g.* Street 2014[6]

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- Poor chronological quantification and allocation:
  - Uneven "risk" accross time + *all of the avobe*

Deterministic Unit Commitment (DUC)

Unit Commitment (UC) is a cost-minimization problem that schedules and dispatches the generation resources to meet the demand, while subject to the generation and transmission constraints

$$\min_{y,v,p,r^U,r^D} \sum_{i\in I}\sum_{t\in T} C_i^{SU}\cdot y_{t,i} +$$

$$\left[\sum_{i\in I}\sum_{t\in T} C_i^{NL}\cdot v_{t,i} + \sum_{i\in I}\sum_{t\in T} C_i \cdot p_{t,i}\right]$$

$$+\sum_{i\in I}\left(C_i^{RU}\cdot r_{t,i}^U + C_i^{RD}\cdot r_{t,i}^D\right)$$

$$D_b - \sum_{i\in I_b} p_i - p_b^w - \sum_{l\in L_b} f_l = 0 \quad \forall b, \forall t$$

$$Req^U - \sum_{i\in I} r_{t,i}^U \le 0; \quad Req^D - \sum_{i\in I} r_{t,i}^D \le 0$$

$$\mathbf{h}(v,p) \le 0$$

T : set of time intervals

B : set of buses

I : set of generators

I_b : set of generators at bus b

L : set of transmission lines

L_b : set of TL connected at b

$v \in \{0;1\}$: on/off status of generators

$p \in \mathbb{R}^{0+}$: output of generators

C^{SU}, C^{NL} and C start up, no-load and incremental costs

DUC assumptions

- Wind power generation and nodal demands are assumed to be known
- The reserve is distributed among the cheapest units, regardless of their individual reliability and location in the grid
- The reserve allocation does not consider the contingency states; therefore the feasibility of the energy re-distribution under contingency states is not guaranteed
- The reserve constraints do not take into account the probability of the contingencies
- The cost of the reserve is not compared against its benefits in terms of reduced expected cost of interruptions

Probabilistic Generation and Transmission SCUC

Minimize the expected pre-contingency operating costs plus the expected energy not served costs in post-contingency

$$\min_{y,v,p,r^U,r^D,\pi_k} \pi_0 \sum_{i\in I}\sum_{t\in T} C_i^{SU}\cdot y_{t,i}+$$

$$\pi_0\Big[\sum_{i\in I}\sum_{t\in T} C_i^{NL}\cdot v_{t,i} + \sum_{i\in I}\sum_{t\in T} C_i\cdot p_{t,i}\Big]+$$

$$\pi_0 \sum_{i\in I}\left(C_i^{RU}\cdot r_{t,i}^{U} + C_i^{RD}\cdot r_{t,i}^{D}\right)+$$

$$\sum_{k>0}\pi_k\sum_{t\in T}\sum_{b\in B} VoLL_b\cdot ENS_{t,b,k}$$

K : set of contingencies

$VoLL$: value of lost load

ENS : energy not served

π_k : probability of contingency k

$$D_b - \sum_{i\in I_b} p_i - p_b^w - \sum_{l\in L_b} f_l - ENS_{t,b,k} = 0 \quad \forall b,\forall t,\forall k$$

$$ENS_{t,b,0}=0; \quad -R_i^{\mathrm{up}} \le p_{t,i,k} - p_{t,i,0} \le R_i^{\mathrm{dn}}\ \forall i,\forall t,\forall k; \quad \mathbf{h}(v,p)\le 0$$

Probabilistic SCUC characteristics

- Large-scale, non-linear, non-convex, MILP optimization problem
- At each time period, for each of the schedules considered, the post-contingency states are explicitly modeled
- Transmission and power flow constraints are explicitly modeled
- Reserve allocation is based on: reserve cost, generators and transmission reliability, pre- and post-contingency energy distribution on the grid
- The probabilities of the contingencies are functions of the commitment variables

Probabilities of the contingencies π_k

- Dividing the set of contingencies K, in generation K_G and transmission K_L; the probabilities can be expressed as:

$$\pi_0 = \prod_{i \in I} (1 - v_i \cdot \Gamma_i) \cdot \prod_{l \in L} (1 - \Lambda_l)$$

$$\pi_k = \prod_{i \in I_k} v_{i(k)} \cdot \Gamma_{i(k)} \cdot \prod_{i \in I | i \neq k} (1 - v_i \cdot \Gamma_i) \cdot \prod_{l \in L} (1 - \Lambda_l) \quad \forall k \in K_G$$

$$\pi_k = \prod_{l \in L_k} \Lambda_{l(k)} \cdot \prod_{i \in I} (1 - v_i \cdot \Gamma_i) \cdot \prod_{l \in L | l \neq k} (1 - \Lambda_l) \quad \forall k \in K_L$$

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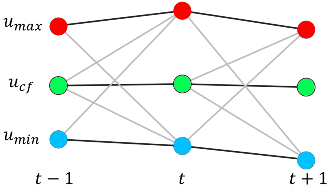
- Elements of the objective function:
  - Products of binary variables
  - Products of integer and continuous variables
  - Products of continuous variables

Recourse

- Additional constraints are enforced to ensure that sufficient recourse is allocated to accommodate deviations from forecasted quantities
- This is done via interval optimization[7]:



$$-R_i^{\mathrm{dn}} \le p_{t,i,u,0} - p_{t-1,i,u,0} \le R_i^{\mathrm{up}}, \quad \forall u \in U$$
$$p_{t-1,i,u_{\max},0} - p_{t,i,u_{\min},0} \le R_i^{\mathrm{dn}}$$
$$-p_{t-1,i,u_{\max},0} + p_{t,i,u_{\mathrm{cf}},0} \le R_i^{\mathrm{up}}$$
$$p_{t-1,i,u_{\mathrm{cf}},0} - p_{t,i,u_{\min},0} \le R_i^{\mathrm{dn}}$$
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[7] Y. Dvorkin, H. Pandžić, M. Ortega-Vazquez, and D. S. Kirschen, "A hybrid stocastic/interval approach to tranmission-constrained unit commitment," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 621–631, Mar. 2015.

Solving the problem

- Decompose the problem into subproblems
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- Enforce the reserve requirements in a complete problem with explicit local reserve requirements and recourse

Test System and Data

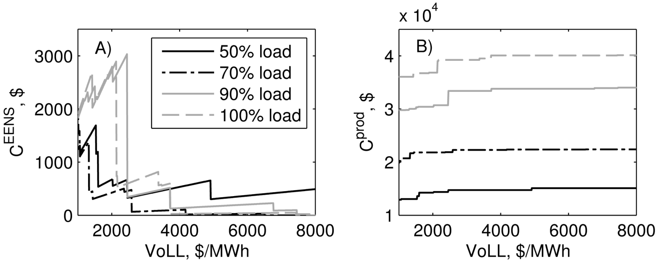
- One-area IEEE Reliability Test System:
    - 24 buses and 38 transmission lines
    - 32 controllable generators (3105 MW)
    - 9 wind farms (780 MW approx. 25%)
    - Transmission limits are reduced by 15%
    - Positive and negative correlation of aggregated load/wind profiles
- Deterministic Unit Commitment:
    - Conventional reserve requirements
    - $(N-1)$ contingency reserve
    - $(3+5)$ reserve policy for load and wind generation uncertainty

Simulations

- The DUC and the proposed approach are tested using Monte Carlo (MC) simulations:
  - Wind and load realizations are generated using multivariate normal-distribution
  - Transmission and generation contingencies are modeled using the state sampling approach using a uniform distribution
  - The minimum number of MC trials is calculated using the variance reduction method
  - Real-time commitment of flexible generators (U12, U20, U76) if required to mimic SO's reaction

Optimal reserve requirements

- As the $VoLL$ increases:
  - The operating costs increase
  - The $EENS$ cost "tends" to reduce
  - The "sawtooth" shapes are due to changes in commitment decisions



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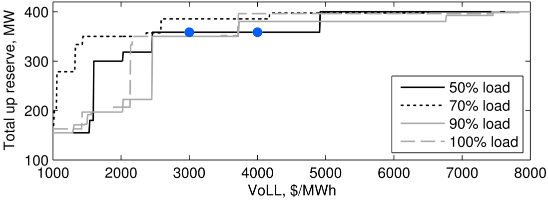
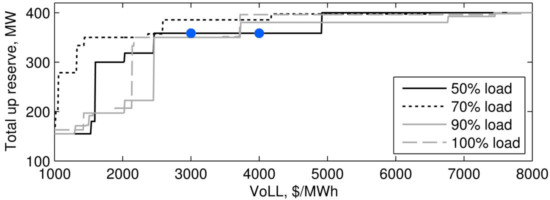
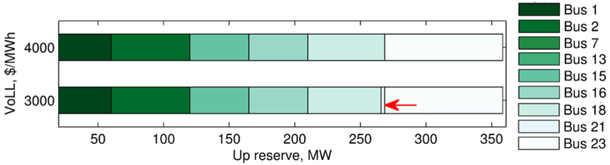


- The reserve requirements increase as the $VoLL$ increases:
  - Higher $VoLLs$ justify higher larger amounts of reserve
- Two observations for all load levels:
  - “Plateaus”: an incremental change in $VoLL$ does not result in an increment in the reserve requirement
  - Saturation: the reserve requirement does not change for high $VoLLs$

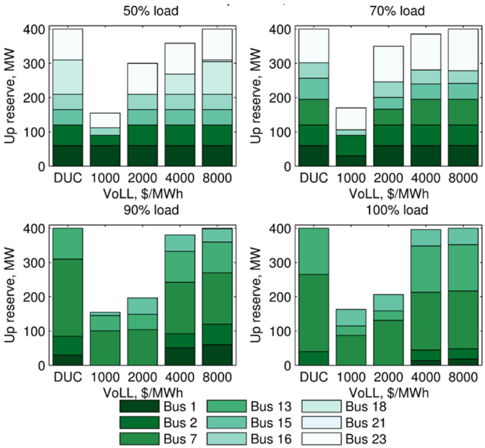
Optimal Reserve Requirements & Allocation



- While the reserve procurement is the same in amount, its allocation is different:



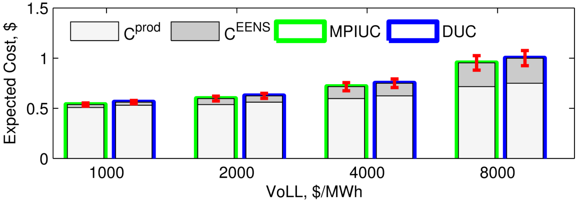
DUC against the proposed approach



- DUC ignores the post-contingency power re-distribution
- DUC is insensitive to the system's $VoLL$

Expected costs (no wind)

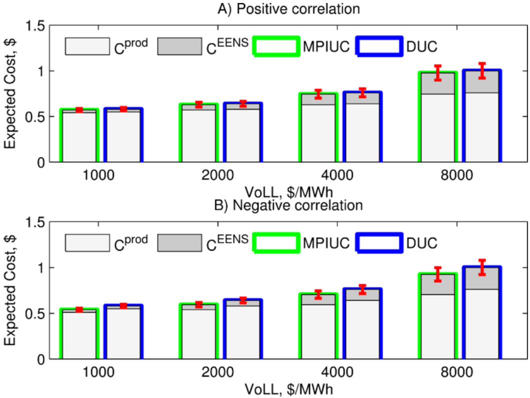
- System with no wind power generation:



- The proposed approach (MPIUC) systematically outperforms DUC

Expected costs (wind)

- System with wind: A) Positive correlation with the demand B) Negative correlation with the demand



- Cost savings are larger for the case with the negative load/wind correlation

Conclusions

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- The optimal amount of reserve can only be attained when its cost is balanced against the benefits
- The energy re-distribution and probabilities of contingencies must be explicitly taken into account when performing the cost/benefit analysis
- The proposed methodology systematically outperforms approaches based on deterministic criteria
- By allocating sufficient recourse, cost savings are attained even under unfavorable wind materializations (negative correlation with demand)