Probabilistic Security-Constrained Unit Commitment with Generation and Transmission Contingencies

Miguel A. Ortega-Vazquez, Yury Dvorkin and Ricardo Fernández-Blanco

University of Washington

maov@uw.edu

22-24 June, 2015
Overview

1. Introduction
2. Deterministic Unit Commitment
3. Probabilistic Security-Constrained UC formulation
4. Test Results
5. Conclusions
Power systems are forever changing:
- Low production costs
- Reliable supply
- Green generation

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
Introduction

- Power systems are forever changing:
  - Low production costs
  - Reliable supply
  - Green generation

- 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**
Power systems are forever changing:
  - Low production costs
  - Reliable supply
  - Green generation

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\(^1\)

---


Existing Approaches

- Typically reserve is scheduled using deterministic criteria e.g. $N - 1$, and variants e.g. Wood 1996\(^1\)
- Some acknowledge the probabilistic nature of the contingencies and increase the reserve requirements until a reliability target is attained e.g. Gooi 1999\(^2\)

---


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

Some acknowledge the probabilistic nature of the contingencies and increase the reserve requirements until a reliability target is attained e.g. Gooi 1999

Some approximate the “system risk” via proxies, and enforce constraints to meet a predefined limit in the scheduling process e.g. Chattopadhyay 2002
Existing Approaches

- Some include a truncated COPT calculation in the scheduling process e.g. Bouffard 2004\(^4\)

---


Existing Approaches

- Some include a truncated COPT calculation in the scheduling process, e.g. Bouffard 2004\textsuperscript{4}
- Some optimize the reserve requirements exogenously and set them as constraints in a regular UC, e.g. Ortega-Vazquez 2007\textsuperscript{5}


Existing Approaches

- Some include a truncated COPT calculation in the scheduling process e.g. Bouffard 2004\(^4\)
- Some optimize the reserve requirements exogenously and set them as contraints in a regular UC, e.g. Ortega-Vazquez 2007\(^5\)
- Some approaches that explicitly model the contingency states in the scheduling stage e.g. Street 2014\(^6\)

---


Consequences of non-optimized reserve procurement

- Poor reserve quantification:
  - Excessive or insufficient reserves
  - Unnecessarily expensive system operation
  - High risk of system failures that could lead to blackouts
  - Inadequate resources when responding to unexpected situations
Consequences of non-optimized reserve procurement

- Poor reserve quantification:
  - Excessive or insufficient reserves
  - Unecessarily expensive system operation
  - High risk of system failures that could lead to blackouts
  - Inadequate resources when responding to unexpected situations

- Poor reserve allocation:
  - Frequent congestion problems in real time
  - Over-conservative operational limits
  - Underutilization of transmission assets
Consequences of non-optimized reserve procurement

- Poor reserve quantification:
  - Excessive or insufficient reserves
  - Unnecessarily expensive system operation
  - High risk of system failures that could lead to blackouts
  - Inadequate resources when responding to unexpected situations

- Poor reserve allocation:
  - Frequent congestion problems in real time
  - Over-conservative operational limits
  - Underutilization of transmission assets

- Poor chronological quantification and allocation:
  - Uneven “risk” across time + all of the above
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.

\[
\begin{align*}
\min_{y,v,p,r} & \quad \sum_{i \in I} \sum_{t \in T} C_{SU} \cdot y_{t,i} + \\
& \left[ \sum_{i \in I} \sum_{t \in T} C_{NL} \cdot v_{t,i} + \sum_{i \in I} \sum_{t \in T} C_i \cdot p_{t,i} \right] \\
& + \sum_{i \in I} \left( C_{RU} \cdot r_{U,i} + C_{RD} \cdot r_{D,i} \right) \\
D_b - \sum_{i \in I_b} p_i - p^w_b - \sum_{l \in L_b} f_l &= 0 \quad \forall b, \forall t \\
\text{Req}^U - \sum_{i \in I} r_{U,i} &\leq 0; \quad \text{Req}^D - \sum_{i \in I} r_{D,i} \leq 0 \\
h(v, p) &\leq 0
\end{align*}
\]

\(T\) : 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
Deterministic Unit Commitment

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

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

$$\pi_0 \left[ \sum_{i \in I} \sum_{t \in T} C^NL_i \cdot v_{t,i} + \sum_{i \in I} \sum_{t \in T} C_i \cdot p_{t,i} \right] +$$

$$\pi_0 \sum_{i \in I} \left( C^RU_i \cdot r^U_{t,i} + C^RD_i \cdot r^D_{t,i} \right) +$$

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

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

$$ENS_{t,b,0} = 0; \quad -R^u_{t,i,k} \leq p_{t,i,k} - p_{t,i,0} \leq R^d_{t,i} \quad \forall i, \forall t, \forall k; \quad h(v, p) \leq 0$$

$K$ : set of contingencies

$VoLL$ : value of lost load

$ENS$ : energy not served

$\pi_k$ : probability of contingency $k$
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 $\pi_k$

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

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

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

  $$\pi_k = \prod_{l \in L_k} \Lambda_l(k) \cdot \prod_{i \in I} (1 - v_i \cdot \Gamma_i) \cdot \prod_{l \in L \mid l \neq k} (1 - \Lambda_l) \quad \forall k \in K_L$$
Probabilities of the contingencies $\pi_k$

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

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

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

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

- 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\(^7\): 

\[
-R_{i}^{\text{dn}} \leq p_{t,i,u,0} - p_{t-1,i,u,0} \leq R_{i}^{\text{up}}, \quad \forall u \in U \\
p_{t-1,i,u_{\text{max}},0} - p_{t,i,u_{\text{min}},0} \leq R_{i}^{\text{dn}} \\
-p_{t-1,i,u_{\text{max}},0} + p_{t,i,u_{\text{cf}},0} \leq R_{i}^{\text{up}} \\
p_{t-1,i,u_{\text{cf}},0} - p_{t,i,u_{\text{min}},0} \leq R_{i}^{\text{dn}} \\
-p_{t-1,i,u_{\text{min}},0} + p_{t,i,u_{\text{cf}},0} \leq R_{i}^{\text{up}}
\]

Solving the problem

- Decompose the problem into subproblems
  - Tackle each problem independently
  - Determine the optimal reserve requirements
Solving the problem

- Decompose the problem into subproblems
  - Tackle each problem independently
  - Determine the optimal reserve requirements
- Linearize terms of the objective function
  - Replace products of variables by equivalent mixed-integer linear expressions
  - Apply special ordered sets 2 (SOS2) to the product of continuous variables
  - Additional variables required
  - Accuracy is a function of the surfaces and grid points
Solving the problem

- Decompose the problem into subproblems
  - Tackle each problem independently
  - Determine the optimal reserve requirements
- Linearize terms of the objective function
  - Replace products of variables by equivalent mixed-integer linear expressions
  - Apply special ordered sets 2 (SOS2) to the product of continuous variables
  - Additional variables required
  - Accuracy is a function of the surfaces and grid points
- 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
Optimal reserve requirements

- The reserve requirements increase as the $VoLL$ increases:
  - Higher $VoLL$s 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 $VoLL$s
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**

![Graph showing expected costs for different load levels and wind scenarios.](image)
Optimal reserve provision should take into account its three fundamental dimensions: amount, location and timing
Conclusions

- Optimal reserve provision should take into account its three fundamental dimensions: amount, location and timing.
- The optimal amount of reserve can only be attained when its cost is balanced against the benefits.
Conclusions

- Optimal reserve provision should take into account its three fundamental dimensions: amount, location and timing
- 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
Conclusions

- Optimal reserve provision should take into account its three fundamental dimensions: amount, location and timing.
- 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.
Conclusions

- Optimal reserve provision should take into account its three fundamental dimensions: amount, location and timing.
- 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).