A Comparative Study of Stochastic and Security Constrained Unit Commitment Using High Performance Computing

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Outline

Motivation and Research Objective

- Increased need for systematic approach to committing day-ahead reserves due to:
  - Renewable penetration
  - Demand response integration
- Four paradigms for systematic day-ahead scheduling:
  - Stochastic optimization
  - Security constrained optimization
  - Robust optimization
  - Probabilistically constrained optimization
- Our objective:
  - Compare relative performance of SUC and SCUC
  - Demonstrate benefits of parallel computation

Systematic Approaches to Unit Commitment

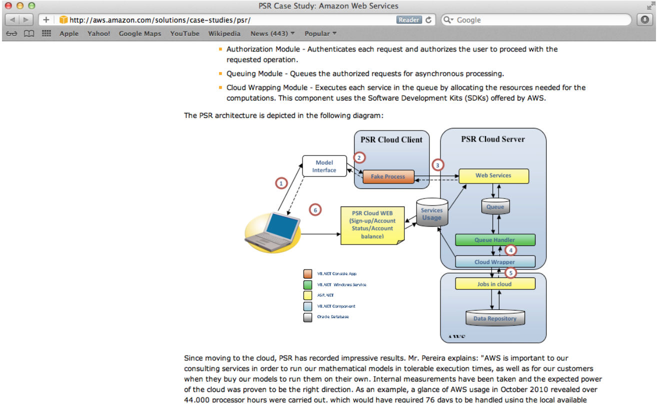
- Stochastic UC (Takriti 1996): minimize expected cost over weighted set of scenarios
  - Difficulty: scenario selection and probability assignment
  - Common solution approach: Lagrangian relaxation
- Security constrained UC: minimize no-contingency cost while withstanding failures without shedding load
  - (Wang 2008): exogenous reserve criteria, Benders
  - (Wu 2007): blend failures with scenarios, LR
- Robust UC (Jiang 2012, Bertsimas 2013): minimize cost of operation against worst-case uncertainty
  - Limited information about uncertainty required
  - Consistent with paradigm of system operators
- UC with probabilistic constraints (Ozturk 2004, Vrakopoulou 2013)
  - Limited information about uncertainty required

Parallel Computing Literature in Power Systems

- Monticelli et al. (1987): Benders decomposition algorithm for SCOPF
- Pereira et al. (1990): Applications of parallelization in various applications including SCOPF, composite (generator, transmission line) reliability, hydrothermal scheduling
- Falcao (1997): Survey of HPC applications in power systems
- Kim, Baldick (1997): Distributed OPF
- Bakirtzis, Biskas (2003) and Biskas et al. (2005): Distributed OPF

PSR Cloud

Industry practice for hydrothermal scheduling



Unit Commitment Model

- Domain $\mathcal{D}$ represents min up/down times, ramping rates, thermal limits of lines, reserve requirements, import constraints

$$(UC) : \min \sum_{g \in G} \sum_{t \in T} (K_g u_{gt} + S_g v_{gt} + C_g p_{gt})$$

$$s.t. \sum_{g \in G_n} p_{gt} = D_{nt}$$

$$P_g^- u_{gt} \leq p_{gt} \leq P_g^+ u_{gt}$$

$$e_{kt} = B_k(\theta_{nt} - \theta_{mt}), k = (m, n)$$

$$(\mathbf{p}, \mathbf{e}, \mathbf{u}, \mathbf{v}) \in \mathcal{D}$$

Stochastic Unit Commitment Model

$$(SUC): \min \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} \pi_s (K_g u_{gst} + S_g v_{gst} + C_g p_{gst})$$

$$s.t. \sum_{g \in G_n} p_{gst} = D_{nst},$$

$$P^-_{gs} u_{gst} \leq p_{gst} \leq P^+_{gs} u_{gst}$$

$$e_{kst} = B_{ks}(\theta_{nst} - \theta_{mst}), k = (m, n)$$

$$(\mathbf{p}, \mathbf{e}, \mathbf{u}, \mathbf{v}) \in \mathcal{D}_s$$

$$u_{gst} = w_{gt}, v_{gst} = z_{gt}, g \in G_s$$

1. First stage: DA market realization for slow generators G_s
2. Renewable supply, line / generator outages
3. Second stage: RT market realization

Scenario-Based Security Constrained Unit Commitment

$$(SCUC): \min \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} \pi_s (K_g u_{gst} + S_g v_{gst} + C_g p_{gst})$$

$$s.t. \sum_{g \in G_n} p_{gst} = D_{nst}$$

$$P^-_{gs} u_{gst} \leq p_{gst} \leq P^+_{gs} u_{gst}, g \in G$$

$$e_{kst} = B_{ks}(\theta_{nst} - \theta_{mst}), k = (m, n)$$

$$(\mathbf{p}, \mathbf{e}, \mathbf{u}, \mathbf{v}) \in \mathcal{D}_s$$

$$p_{lst} = 0, l \in L, s \in S, t \in T$$

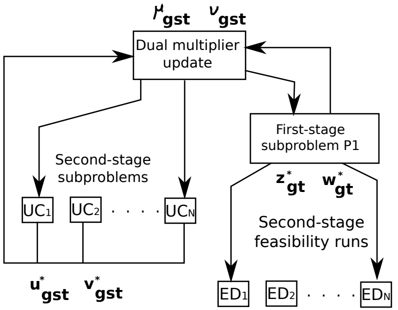
$$u_{gst} = w_{gt}, v_{gst} = z_{gt}, g \in G_s$$

- May not have feasible second-stage response

Scenario Selection [1 - 3]

- Stochastic UC: scenario selection algorithm inspired by importance sampling
  1. Generate a sample set $\Omega_S \subset \Omega$, where $M = |\Omega_S|$ is adequately large. Calculate the cost $C_D(\omega)$ of each sample $\omega \in \Omega_S$ against the best deterministic unit commitment policy and the average cost $\bar{C} = \sum_{i=1}^{M} \frac{C_D(\omega_i)}{M}$.
  2. Choose N scenarios from Ω_S, where the probability of picking a scenario ω is $C_D(\omega)/(M\bar{C})$.
  3. Set $\pi_s = C_D(\omega)^{-1}$ for all $\omega^s \in \hat{\Omega}$.
- Security Constrained UC:
  1. S is Cartesian product of renewable supply with no contingency and worst single-element contingencies
  2. Equal $\pi_s > 0$ for no-contingency scenarios, $\pi_s = 0$ for single-element contingency scenarios

Lagrange Relaxation for SUC [1 - 3]

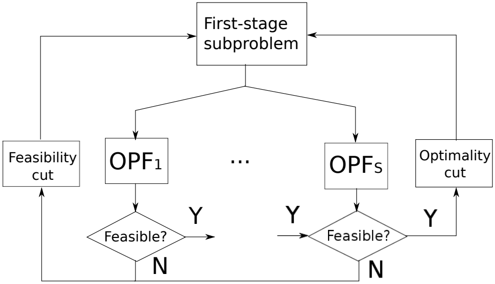


$$\mathcal{L} = \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} \pi_s (K_g u_{gst} + S_g v_{gst} + C_g p_{gst})$$
$$+ \sum_{g \in G_s} \sum_{s \in S} \sum_{t \in T} \pi_s (\mu_{gst}(u_{gst} - w_{gt}) + \nu_{gst}(v_{gst} - z_{gt}))$$

Benders Decomposition for SCUC

- Motivation:
  - Good feasibility cuts can be generated by severe contingencies
  - Optimality cuts can be rapidly computed in parallel
- Assumptions
  - Convexity of value function: unit commitment has to be fixed in the first stage for all generators
  - Ramping: assume away ramping constraints in order to decompose second-stage domain by time period, $\mathcal{D}_{st}$

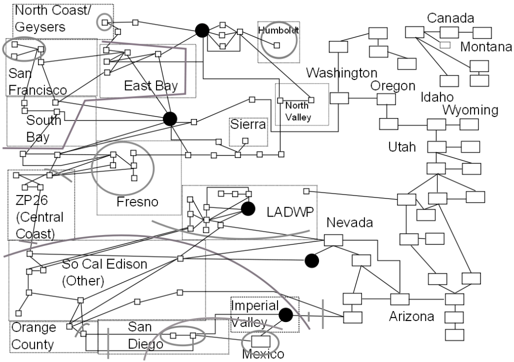
Benders Decomposition for SUC



- In order to avoid stall of standard feasibility cuts (Van-Slyke, Wets, 1969), pass entire set of power flow equations $\mathcal{D}_{st}$ for most severe contingency

WECC Model

- 130 units, 225 buses, 375 transmission lines



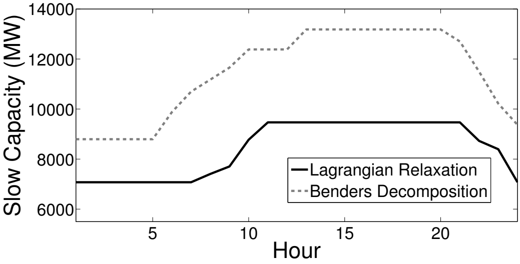
Unit Characteristics

Type	No. of units	Capacity (MW)
Nuclear	2	4,499
Gas	94	20,595.6
Coal	6	285.9
Oil	5	252
Dual fuel	23	4,599
Import	22	12,691
Hydro	6	10,842
Biomass	3	558
Geothermal	2	1,193
Wind (deep)	10	14,143
Fast thermal	88	11,006.1
Slow thermal	42	19,225.4

Implementation

- Lawrence Livermore National Laboratory
  - 8 CPUs per node, 2.4 GHz and 10 GB per node
  - MPI calling on CPLEX Java callable library
- 30 scenarios:
  - SUC: importance sampling
  - SCUC: Cartesian product of ten renewable production scenarios with no-contingency case and two most severe contingencies (Diablo and San Onofre nuclear plants)
- 1,000 Monte Carlo outcomes
  - Spring weekdays (calibrated against NREL wind data)
  - 1% generator failure probability
  - 0.1% line failure probability

Unit Commitment Schedules



- Conservative commitment of SCUC driven by assumption that all generators are slow.

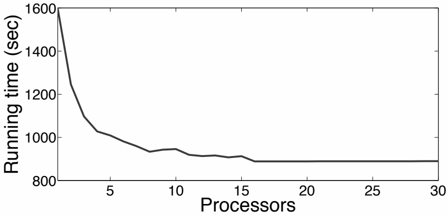
Performance

Table: Daily cost breakdown ($)

	Startup	Min. load	Load shed	Fuel	Total
SCUC	66.5	1,205.3	0	4,687.3	5,959.1
SUC	106.0	699.4	0.3	4,831.5	5,637.2

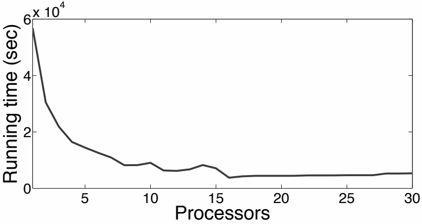
- SCUC is more reliable, at the expense of a 5.4% cost increase.

Running Time of Benders Decomposition



- Algorithm converged to optimal solution in 31 iterations. First feasible UC schedule detected in iteration 19.
- Marginal benefits vanish beyond 15 processors. Fully serial: 26.6 minutes. Fully parallel: 14.8 minutes.
- Approach is not scalable as number of scenarios increases (due to growth of first-stage subproblem).

Running Time of Lagrangian Decomposition



- Algorithm ran for 80 iterations. Lower bound: $5.868M. Upper bound: $5.911M.
- Marginal benefits vanish beyond 15 processors. Fully serial: 15.8 hours. Fully parallel: 47.7 minutes.
- Approach is scalable as number of scenarios increases.

Conclusions and Perspectives

- **Tradeoffs:** The SCUC model achieves greater reliability at the expense of a 5.4% cost increase
- **Parallelism:** Lagrange relaxation algorithm benefits more from parallelism
    - Second-stage problems of SUC are more difficult to solve
    - First-stage problem of SCUC is not decomposable
- **Future work:** Improve feasibility cuts in Benders algorithm in order to scale for larger number of scenarios

Thank you

Questions?

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References

[1] A. Papavasiliou, S. S. Oren, *Multi-Area Stochastic Unit Commitment for High Wind Penetration in a Transmission Constrained Network*, Operations Research, vol. 61, no. 3, pp. 578-592, May/June 2013.

[2] A. Papavasiliou, S. S. Oren and R. O'Neill, *Reserve Requirements for Wind Power Integration: A Scenario-Based Stochastic Programming Framework*, IEEE Transactions on Power Systems, Vol. 26, No. 4, November 2011.

[3] A. Papavasiliou, S. S. Oren, B. Rountree, *Applying High Performance Computing to Multi-Area Stochastic Unit Commitment for Renewable Penetration*, under review in IEEE Transactions on Power Systems.

Lagrangian Decomposition Algorithm

- Past work: (Takriti et al., 1996), (Carpentier et al., 1996), (Nowak and Römisch, 2000), (Shiina and Birge, 2004)
- Key idea: relax non-anticipativity constraints on both unit commitment and startup variables
  1. Balance size of subproblems
  2. Obtain lower and upper bounds at each iteration

  Lagrangian:

$$\mathcal{L} = \sum_{g \in G} \sum_{s \in S} \sum_{t \in T} \pi_s (K_g u_{gst} + S_g v_{gst} + C_g p_{gst})$$
$$+ \sum_{g \in G_s} \sum_{s \in S} \sum_{t \in T} \pi_s (\mu_{gst}(u_{gst} - w_{gt}) + \nu_{gst}(v_{gst} - z_{gt}))$$