Stochastic Unit Commitment with Intermittent Distributed Wind Generation via Markovian Analysis and Optimization

Yaowen Yu[*], Peter B. Luh[*], and Mikhail A. Bragin[*]

Eugene Litvinov[+], Tongxin Zheng[+], Feng Zhao[+], and Jinye Zhao[+]

*: UConn, +: Independent System Operator New England
SNET Professor of Communications & Information Technologies
Electrical & Computer Engineering, University of Connecticut
Peter.Luh@uconn.edu, http://www.engr.uconn.edu/msl/

June 2013

This work was supported in part by ISO New England, and in part by National Science Foundation under grants ECCS-1028870

Introduction – Wind integration

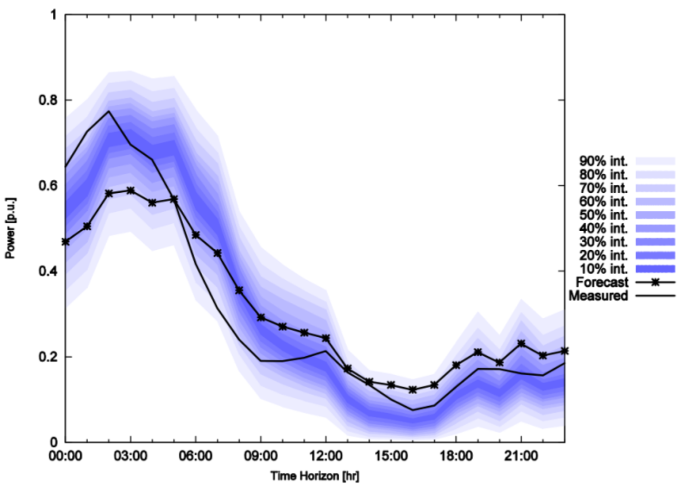
- Motivation
  - U.S. Department of Energy's goal: 20% wind by 2030 [1]
  - Obama's clean-energy goals – Clean power sources providing 80% of the nation's energy by 2035 (wind, solar, nuclear, clean coal and natural gas) [2]

- Challenge – Effective and robust integration
  - Grid integration of intermittent and uncertain wind generation with high levels of penetration
  - Texas blackout in Feb. 2008

1. S. Lindenberg, B. Smith, K. O'Dell and E. DeMeo, "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply," DOE/GO-102008-2567, July 2008. [Online]. *Available: http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf*
2. Obama State of the Union address, January 26, 2011 *http://www.soundhealthinc.com/political/obama3.pdf*

Difficulties when considering wind generation

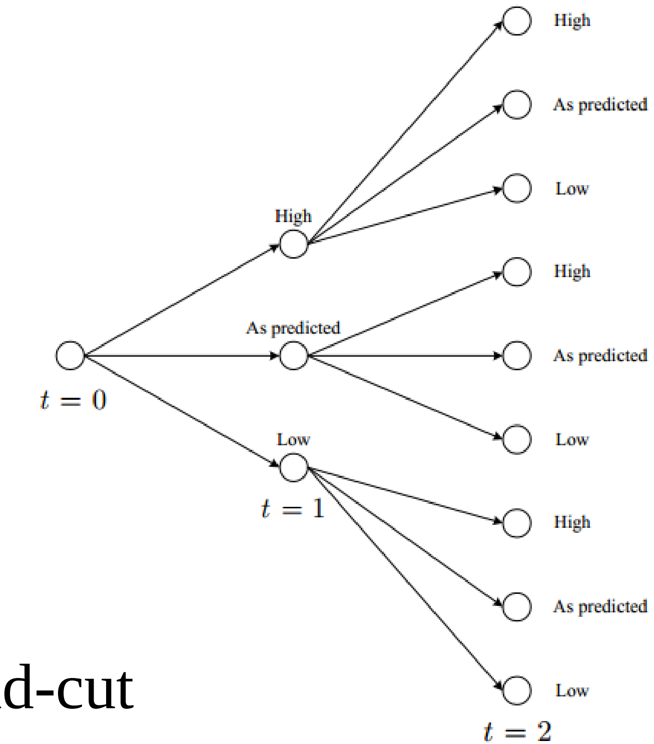
- Intermittent and uncertain nature of wind generation
  - Wind generation cannot be dispatched as conventional generation
  - Large uncertainty in wind generation
    - Accuracy of demand forecast 1%~3%
    - Accuracy of day-ahead wind power forecast: 15%~20%



- Balancing modeling accuracy & computational efficiency
  - To ensure sufficient generation and ramping capabilities for realizations of wind generation

The Research Side – Stochastic Programming

- Modeling wind generation - Representative scenarios
- Formulation:
  - Minimize the sum of expected energy and no-load/startup costs
  - Subject to constraints for each scenario
- Solution methodology
  - Benders' decomposition with branch-and-cut
  - Lagrangian relaxation with branch-and-cut
  - Pure branch-and-cut
- The number of scenarios
  - Too many – Complexity
  - Too few – Hard to capture low-probability high-impact events



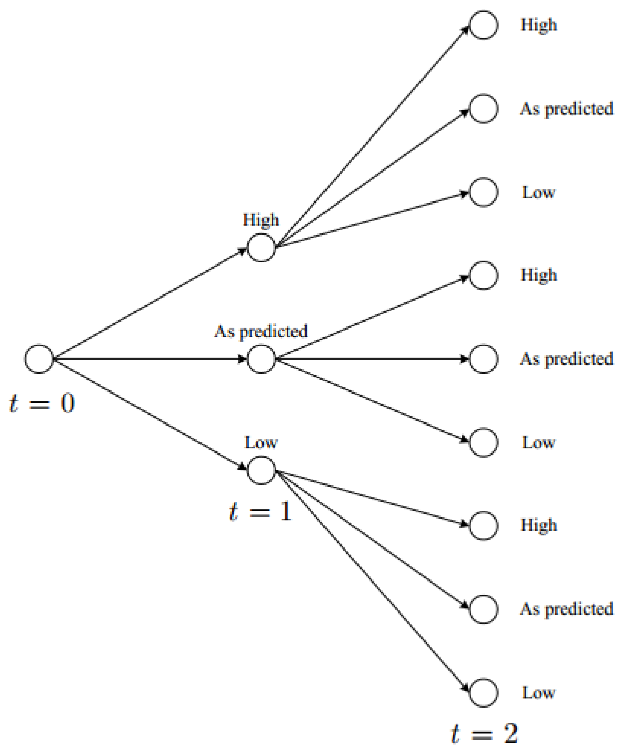
A scenario tree

Outline

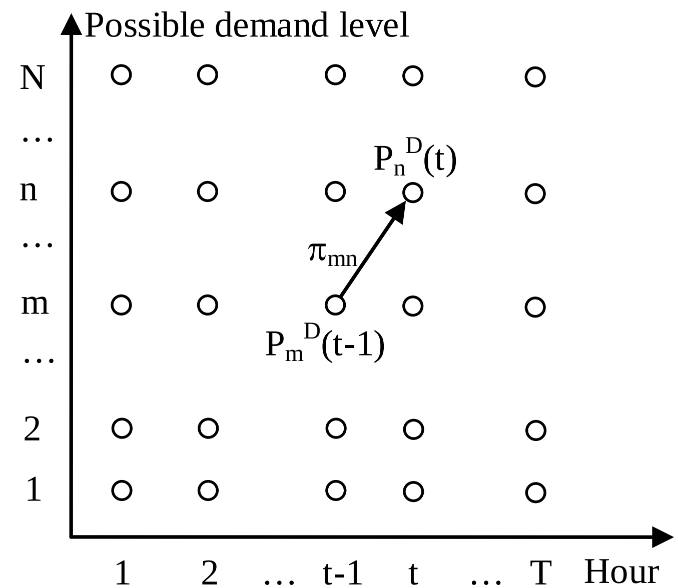
- Wind integration w/o transmission
  - Modeling wind generation – A Markov chain
  - Stochastic UC formulation – Based on states
  - Solution methodology – Branch-and-cut
  - Numerical testing results
- Wind integration with transmission
  - Difficulties when considering transmission
  - Power flow level reduction with set-aside capacities
  - Numerical testing results

Modeling Wind Generation

- Modeling aggregate wind generation – A Markov chain
  - Given the present, the future is independent of the past



A scenario tree



A Markov chain

  - Advantage: The state at a time instant summarizes the information of all previous instants in a probabilistic sense for reduced complexity

- Probability of transition from state *m* to state *n* established based on historical data:

$$\pi_{mn} = \frac{observed\ transitions\ \ from\ state\ m\ to\ n}{ocurrences\ of\ \ state\ m}$$

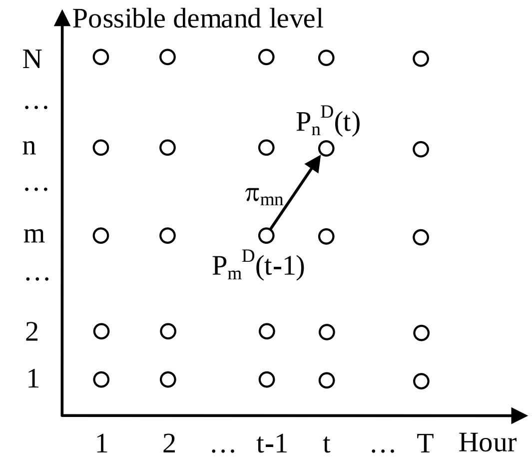
  – The aggregated wind generation of New England area from April to September 2006 [3] with 10 states:

$$\begin{bmatrix} 0.785 & 0.215 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.115 & 0.711 & 0.168 & 0.006 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.167 & 0.652 & 0.169 & 0.012 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.005 & 0.204 & 0.604 & 0.176 & 0.011 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.016 & 0.204 & 0.599 & 0.174 & 0.007 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.002 & 0.210 & 0.631 & 0.148 & 0.008 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.007 & 0.187 & 0.679 & 0.126 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.205 & 0.700 & 0.095 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.184 & 0.776 & 0.041 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.171 & 0.829 \end{bmatrix}$$

3. The National Renewable Energy Laboratory, Eastern Wind Dataset, 2010, [Online]. Available: http://www.nrel.gov/electricity/transmission/eastern_wind_methodology.html

- Wind generation is integrated into system demand
  - $P_n^D(t)$: the n^{th} level of the net system demand at time t
  - The probability of state $P_n^D(t)$ is:

$$\varphi_n(t) = \sum_{m=1}^{N} \pi_{mn} \varphi_m(t-1)$$



- Is wind generation really Markovian?
  - In day-ahead, yes [4], [5]
  - In real time, wind generation may maintain an increasing (or a decreasing) trend over several consecutive timeframes
    - Prewhitening
- The underlying idea when generating scenarios?
  - A Markov chain

4. D. Brooks, E. Lo, R. Zavadil, S. Santoso, and J. Smith, "Characterizing the Impacts of Significant Wind Generation Facilities on Bulk Power System Operations Planning," Xcel Energy – North Case Study Final Report, prepared for Utility Wind Integration Group, Arlington, VA, May 2003, [Online]. Available: http://www.uwig.org/UWIGOpImpactsFinal7-15-03.pdf
5. J. Mur-Amada, Á. A. Bayod-Rújula, "Wind Power Variability Model," in *Proceedings of 9th International Conference Electrical Power Quality and Utilisation*, Barcelona, Oct. 2007.

Stochastic Unit Commitment Formulation

- Based on states instead of scenarios
  - Select one set of unit commitment decisions to satisfy all possible states and state transitions
  - Multiple sets of state dependent dispatch decisions
- Minimize the sum of expected energy and startup/no-load costs

Energy cost | Start-up cost | No-load cost

$$\min_{\{x_i(t)\}_{i,t},\{p_{i,n}(t)\}_{i,n,t}} \sum_{i=1}^{I}\sum_{t=1}^{T}\left\{\sum_{n=1}^{N}\left[\varphi_n(t)C_{i,n}(p_{i,n}(t))\right]+x_i(t)\big(1-x_i(t-1)\big)S_i+x_i(t)S_i^{NL}\right\}$$

  - System demand constraint for each state at every hour

$$\sum_{i=1}^{I} p_{i,n}(t)=P_n^D(t),\forall n,\forall t$$

- Individual unit constraints
  - Generation capacity constraints for each state

$$x_i(t)\,p_{i\,\min} \le p_{i,n}(t) \le x_i(t)\,p_{i\,\max}, \forall i, \forall t, \forall n$$

  - Time-coupling ramp rate constraints for any state transition whose probability is nonzero

$$p_{i,m}(t-1) - \Delta_i \le p_{i,n}(t) \le p_{i,m}(t-1) + \Delta_i,$$

$$\forall i, \forall n, \forall t, \underline{\forall m \in \{m \mid \pi_{mn} \neq 0\}}$$ (Ramp-up and ramp-down)

- Summary of the formulation
  - A linear mixed-integer optimization problem
  - Binary decision variables $\{u_i(t)\}$ and $\{x_i(t)\}$
  - Continuous decision variables $\{p_{i,n}(t)\}$
  - Uncertainty described by the transition probabilities $\{\pi_{mn}\}$, state probabilities $\{\varphi_n(t)\}$, and net demand levels $\{P_n^D(t)\}$

Solution Methodology – Branch-and-Cut

- Branch-and-cut method is efficient in solving deterministic linear integer and mixed-integer optimization problems
  - Widely used by ISOs, utility companies and semiconductor manufacturers
  - A high level language with less time to code
- Generally difficult to obtain convex hulls
  - For NP-hard problems, obtaining an explicit description of the convex hull is also NP-hard
  - For certain kinds of problems whose convex hull is easy to obtain, the method is very efficient

- However, commercial packages such as CPLEX and GUROBI do not provide infrastructure to explicitly describe stochastic processes
- For our formulation
  - State transition probabilities given, state probabilities calculated before optimization
  - The objective and constraints formulated in a linear manner
  - Branch-and-cut can be used to solve the overall problem
- The difficulty depends on
  - The number of ramp rate constraints
    - Coupling different states at different hours, forming a complicated convex hull
  - Large uncertainty of high levels of penetration
    - Difficult to find feasible solutions

Numerical Testing Results

- Problem: ISO-New England’s 24-hour problem with 309 conventional units
  - The aggregated wind generation of New England area from April to September 2006
  - If net system demand cannot be satisfied, penalties will be incurred
- CPLEX 12.4 on a laptop with Intel Core(TM) i7-2820QM 2.30GHz CPU and 8GB memory
- The Markovian approach – 10 states in optimization
- Simulation: 1,000 Monte Carlo runs
  - Scenarios generated based on a detailed 50-state transition matrix
  - To sample the rare event, *importance sampling* is used
  - Consider each scenario as a deterministic case

Case 1: Different wind penetration levels

Penetration		5%	9%	14%	20%	24%
Capacity (GW)		2.3	4.17	6.6	9	11
Optimiza-tion	Gap	0.2%	0.2%	0.2%	0.2%	0.2%
	CPU time	1min02s	1min11s	2min41s	7min30s	38min19s
	Cost (k$)	15,251	13,923	12,690	12,918	16,397
Simulation	Cost (k$)	15,188	13,803	12,473	12,276	15,909
	STD (k$)	729	1,006	1,308	2,050	11,759
	UCDE (k$)	15,182	13,803	12,458	12,185	14,496
	Penalty (k$)	6	0	15	91	1,413

- Can accommodate up to 20% wind penetration efficiently
- More penalties for higher levels of penetration, so the cost does not continue to decrease

- The deterministic approach
  - A special case of the Markovian formulation with only one state at each time instant
  - Average net system demand plus 10% at each hour
- The stochastic programming approach
  - Three thousand scenarios were generated from the normal distribution based on the detailed 50-state transition matrix
  - The reduced 10 and 20 scenarios were used in optimization

Case 2: Compare our approach with stochastic programming and the deterministic method with rare events

- High-impact low-probability events are considered in transition matrices
  - With sudden wind drops (similar to the Texas 2008 case)
- Wind penetration level: 5%

With rare events		Markovian	SP		Deterministic
			10 scenarios	20 scenarios	
Optimiza-tion	Gap	0.01%	0.01%	0.01%	0.01%
	CPU time	1min57s	1min57s	6min1s	4s
	Cost (k$)	10,857	10,475	10,504	13,206
Simulation	Penalty Scenarios	80	253	250	997
	Cost (k$)	10,474	10,676	10,676	12,523
	STD (k$)	477	6,449	5,080	491

Outline

- Wind integration w/o transmission
  - Modeling wind generation – A Markov chain
  - Stochastic UC formulation – Based on states
  - Solution methodology – Branch-and-cut
  - Numerical testing results
- Wind integration with transmission
  - Difficulties when considering transmission
  - Power flow level reduction with set-aside capacities
  - Numerical testing results

Difficulties when considering transmission

- Transmission capacities – Another level of complications
  - With congestion (lines at the limit of their capacity), wind generation cannot be aggregated together
  - Wind states for farms at different nodes may not be the same
    - Nearby wind farms: Generation aggregated
    - Wind farms far apart: States assumed independent
- A line flow: Depending on injections from many nodes
  - Power flow using power transfer distribution factor (PTDF)

$$f_{i,j}(t) = \sum_{q} \left(a_{i,j}^{q} \cdot P_q(t) \right), \forall i, \forall j, \forall t \qquad (1)$$

Net nodal injection = wind generation + conventional generation - demand

$$f_{i,j,\underline{n_1,\cdots,n_I}}(t) = \sum_{q} \left(a_{i,j}^{q} \cdot P_{q,\underline{n_1,\cdots,n_I}}(t) \right) \qquad (2)$$

A large number of levels. What can be done?

Power flow level reduction + set-aside capacities

- Interval optimization [6], [7], [8]
  - The ranges of wind generation uncertainty increase significantly over time
  - To ensure feasibility of all the intervals, results are too conservative

Key ideas: Markovian optimization + interval analysis

  - Local states: Wind generation state at the node considered
  - Intervals: Considering the combination of all the states
    - The pessimistic realization: All wind farms provide their minimum possible outputs (at lowest possible states)
    - The optimistic realization: All wind farms provide their maximum possible outputs

6. J. W. Chinneck and K. Ramadan, "Linear programming with interval coefficients," *Journal of the Operational Research Society*, Vol. 51, No. 2, pp. 209-220, 2000.
7. Y. Wang, Q. Xia, and C. Kang, "Unit commitment with volatile node injections by using interval optimization," *IEEE Transactions on Power Systems*, Vol. 26, No. 3, pp. 1705-1713, 2011.
8. L. Wu, M. Shahidehpour, and Z. Li, "Comparison of Scenario-Based and Interval Optimization Approaches to Stochastic SCUC," *IEEE Transactions on Power Systems*, Vol. 27, No. 2, pp. 913-921, 2012.

- Divide the generation of a conventional unit into two parts
  - The state-dependent part: To coordinate fluctuation of local wind states
  - The interval part: To coordinate fluctuation of wind generation in intervals
- System demand constraints
  - Feasible for the pessimistic and optimistic realizations
- Transmission capacity constraints
  - State-dependent nodal injections translated to “set-aside” transmission capacities
  - Interval generations translated to flows
- The objective function
  - The total expected generation cost adjusted by pessimistic and optimistic cases plus start-up cost and no-load cost

- Markovian analysis
  - The generation of a conventional unit is divided into two parts: state-dependent and interval-dependent parts

$$x_{ik}(t)\,p_{ik}^{\min} \le \underline{p_{ik,n_i}}(t) + \Delta \underline{p_{ik}^{r}}(t) \le x_{ik}(t)\,p_{ik}^{\max}, \forall i, \forall k, \forall t, \forall n_i, \forall r \qquad (3)$$

    - $r = r_1$ for the pessimistic realization
    - $r = r_2$ for the optimistic realization ($\Delta p_{ik}^{r_1}(t) \ge \Delta p_{ik}^{r_2}(t)$)
  - Interval generation of units sums up to the node

$$\sum_k \Delta p_{ik}^{r}(t) = \Delta P_i^{r}(t), \forall i, \forall t, \forall r \qquad (4)$$

  - Ramp rate constraints

$$p_{ik,m_i}(t-1) + \Delta p_{ik}^{r'}(t-1) - \underline{R_{ik}} \le p_{ik,n_i}(t) + \Delta p_{ik}^{r}(t)$$

$$\le p_{ik,m_i}(t-1) + \Delta p_{ik}^{r'}(t-1) + R_{ik}, \forall i, \forall k, \forall t, \qquad (5)$$

$$\forall m_i \in \{m_i \mid \varphi_{m_i}(t-1) > 0\}, \forall n_i \in \{n_i \mid \pi_{m_i n_i} \ne 0\}, \forall r', \forall r$$

    - Only hold for possible states and state transitions

– Nodal injection

$$P_{i,n_i,r}(t) = \underline{P^D_{i,n_i}(t) + \sum_k p_{ik,n_i}(t)} + \Delta P_i^r(t), \forall i, \forall t, \forall n_i \in \{n_i \mid \varphi_{n_i} > 0\}, \forall r \quad (6)$$

State-dependent nodal injection $\equiv P_{i,n_i}(t)$

– The order of state-dependent nodal injection is consistent with the order of states

$$P_{i,n_i-1}(t) \le P_{i,n_i}(t), \forall i, \forall t, n_i \in \{n_i \mid \varphi_{n_i}(t) > 0\}, n_i - 1 \in \{n_i - 1 \mid \varphi_{n_i-1}(t) > 0\} \quad (7)$$

- Interval analysis [6], [7], [8]
  - System demand constraints – For the worst demand case
    - The pessimistic realization

$$\sum_i \left(P_{i,\min n_i}(t)\right) + \sum_i \Delta P_i^{\underline{r_1}}(t) = 0, \forall t, \forall n_i \in \{n_i \mid \varphi_{n_i} > 0\} \quad (8)$$

- The optimistic realization

$$\sum_i \left(P_{i,\max n_i}(t)\right) + \sum_i \Delta P_i^{\underline{r_2}}(t) = 0, \forall t, \forall n_i \in \{n_i \mid \varphi_{n_i} > 0\} \quad (9)$$

– Transmission capacity constraints

- Do not know which combination of states causes the worst case flow. Convert the combinations into intervals, and set-aside amounts of transmission capacities
- The state dependent nodal injection
  - State-dependent nodal injections translated to “set-aside” transmission capacities
    - » The center (constraints)

$$\overline{P_i}(t) = \frac{1}{2}\left[\min_{n_i} P_{i,n_i}(t) + \max_{n_i} P_{i,n_i}(t)\right] = \frac{1}{2}\left[P_{i,\min n_i}(t) + P_{i,\max n_i}(t)\right], \tag{10}$$

$$\forall i, \forall t, n_i \in \left\{n_i \mid \varphi_{n_i}(t) > 0\right\}$$

    - » The fluctuation

$$rad\left(P_i(t)\right) = \frac{P_{i,\max n_i}(t) - P_{i,\min n_i}(t)}{2}, \forall i, \forall t, n_i \in \left\{n_i \mid \varphi_{n_i}(t) > 0\right\} \tag{11}$$

– The interval of a line flow

» The center

PTDF

$$\bar{f}_{i,j}(t) = \sum_q \left(a_{i,j}^q \cdot \bar{P}_q(t) \right), \forall i, \forall j, \forall t \tag{12}$$

» The worst case fluctuation – Set-aside transmission capacity

$$\Delta f_{i,j}(t) \equiv rad\left(f_{i,j}(t)\right) = \sum_q \left[\underline{\left| a_{i,j}^q \right|} \cdot rad\left(P_q(t)\right) \right], \forall i, \forall j, \forall t \tag{13}$$

- The interval nodal injection
  - Interval generations translated to flows

$$\sum_q \left[a_{i,j}^q \cdot \Delta P_q^r(t) \right], \forall i, \forall j, \forall t \tag{14}$$

- Transmission capacity constraints for the worst case fluctuation

$$-f_{i,j}^{\max}(t) + \underline{\Delta f_{i,j}(t)} \leq \bar{f}_{i,j}(t) + \sum_q \left[a_{i,j}^q \cdot \Delta P_i^r(t) \right] \leq f_{i,j}^{\max}(t) - \underline{\Delta f_{i,j}(t)}, \forall i, \forall j, \forall t, \forall r \tag{15}$$

– The worst system demand and flow fluctuation my not be realized at the same time ⇒ conservative.

- The objective function
  - To minimize the total expected generation cost adjusted by the pessimistic and optimistic costs, start-up cost, and no-load cost

Expected generation cost – Markovian part

Weights of worst case realizations

$$\min_{\{x_{ik}(t)\}_{ik,t},\{p_{ik,n_i}(t)\}_{ik,n_i,t},\{\Delta p_{ik}^{r_1}(t)\}_{ik,t},}$$

$$\sum_r w^r(t)=1,\ \forall t$$

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{Ki}\left\{\sum_{n_i=1}^{Ni}\left[\varphi_{n_i}(t)\sum_{r=r_1}^{r_2} w^r(t)C_{ik,n_i}\left(p_{ik,n_i}(t)+\Delta p_{ik}^r(t)\right)\right]\right. \qquad (16)$$

$$\left.+\,x_{ik}(t)[1-x_{ik}(t-1)]S_{ik}+x_{ik}(t)S_{ik}^{NL}\right\}$$

Start-up cost

No-load cost

Adjustment from the pessimistic and optimistic realizations - Interval part

  - The expected generation cost is more accurate than the base case cost in interval optimization [7], [8]
- A linear mixed-integer optimization problem
- The Major difference from interval optimization
  - State probabilities and transitions are considered

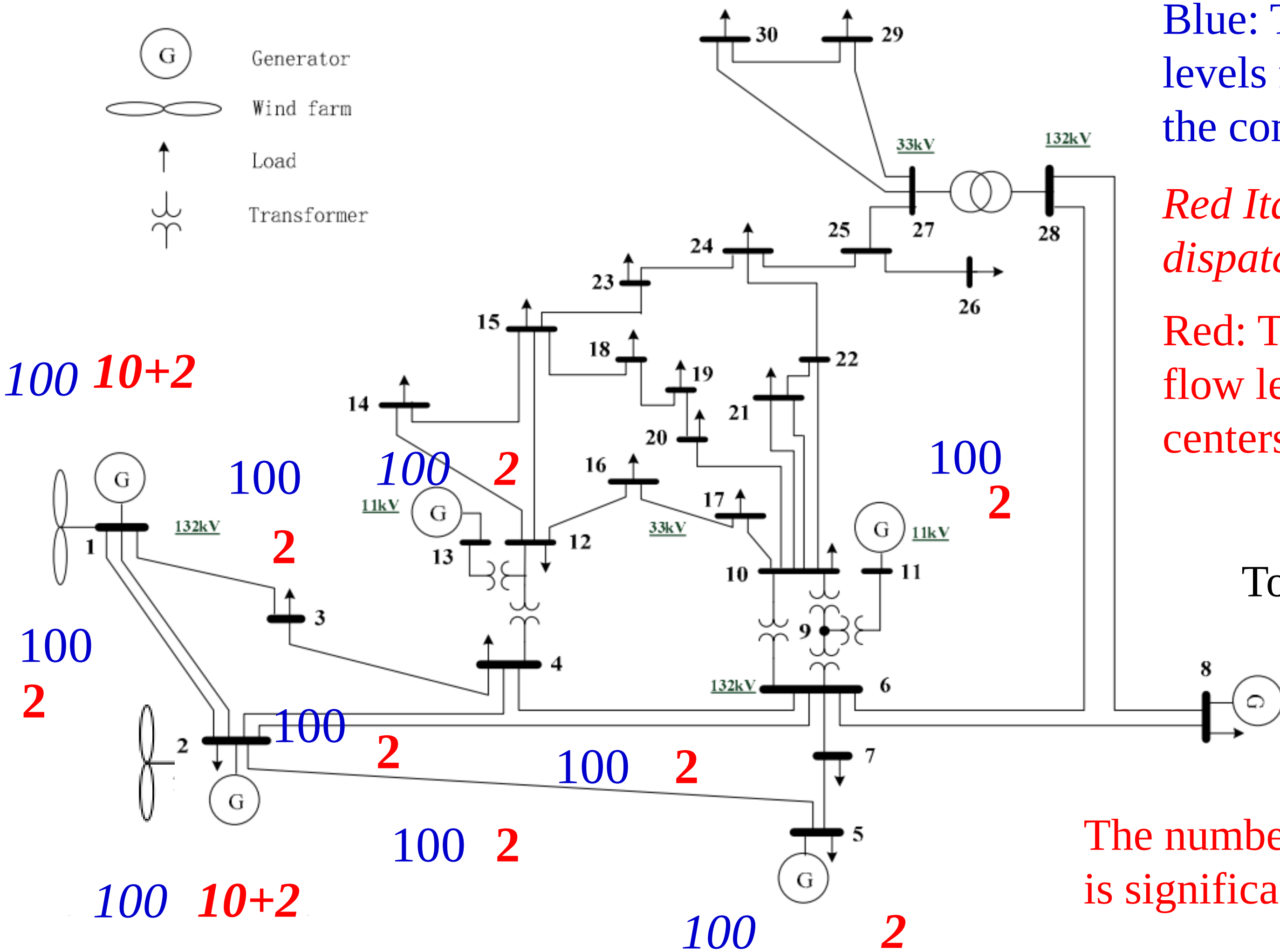
- Illustrative results of the new method
  - 10 states for each wind farm

Blue Italic: The number of dispatch decisions following all the combination of states

Blue: The number of power flow levels following all the combination of states

Red Italic: The number of dispatch decisions

Red: The number of power flow levels represented by the centers and the fluctuations



Total number of flow levels:

$4100\ (= 10^2 \times 41)$

$82\ (= 2 \times 41)$

The number of possible flow levels is significantly reduced

IEEE 30-bus system with 2 wind farms and 41 transmission lines

Numerical Testing: WECC 240-bus system [9]

- Generators
  - 16 wind areas in CAISO area
    - 10 states in optimization and 50 states in simulation per area
  - 768 gas-fired generators
  - 17 aggregated coal plants and 4 aggregated nuclear plants
  - Aggregated hydroelectric generators
- Transmission
  - 28 Interfaces – Groups of transmission lines
- Considering wind curtailment and load shedding

9. J. E. Price and J. Goodin, "Reduced network modeling of WECC as a market design prototype," in *Proceedings of IEEE Power and Energy Society 2011 General Meeting*, Detroit, Michigan, July 2011

- Wind penetration level: 3.4%
- Use $w^r(t) = 0.5, \forall r, \forall t$ for simplicity

	Optimization	Simulation (1000 scenarios)	
Stopping MIP gap	0.1%	AVR	STD
CPU Time	31min05s		
Obj. cost (10^6 \$)	38.535	41.221	0.346
UCED cost (10^6 \$)	38.527	41.221	0.346
Load shedding cost (10^6 \$)	0.008	0	0
Wind curtailment (MWh)	538.949 (small)	0	0

- The problem is efficiently solved by using branch-and-cut
  - Stopping MIP gap is reached before branching according to the CPLEX engine log
- Zero load shedding and wind curtailment in simulation demonstrate the reliability of the approach

Conclusion

- An important but difficult issue with no practical solution yet available
- A major breakthrough for effective grid integration of intermittent wind generation, with key innovations:
  - Markov processes as opposed to scenarios to model wind generation for reduced complexity
  - Markovian optimization + interval analysis to overcome the complexity caused by transmission constraints
  - Branch-and-cut to solve the stochastic unit commitment problem effectively
- The new approach in combination with surrogate Lagrangian relaxation to be presented next has the potential to solve larger problems efficiently

Our recent publications

1. B. Zhang, P. B. Luh, E. Litvinov, T. Zheng, F. Zhao, J. Zhao and C. Wang, "Electricity Auctions with Intermittent Wind Generation," in *Proceedings of the IEEE Power and Energy Society 2011 General Meeting*, Detroit, Michigan, July 2011.
2. Y. Yu, P. B. Luh, E. Litvinov, T. Zheng, F. Zhao, J. Zhao, "Unit Commitment with Intermittent Wind Generation via Markovian Analysis with Transmission Capacity Constraints," in *Proceedings of the IEEE Power and Energy Society 2012 General Meeting*, San Diego, California, July 2012.
3. P. B. Luh, Y. Yu, B. Zhang, E. Litvinov, T. Zheng, F. Zhao, J. Zhao and C. Wang, "Grid Integration of Intermittent Wind Generation: a Markovian Approach," to appear in *IEEE Transactions on Smart Grid*.

Thank you!