Data-Driven Do-Not-Exceed Limits

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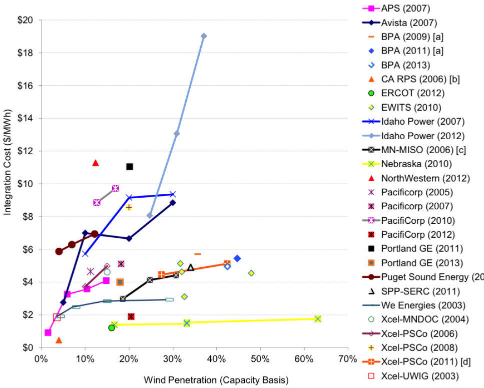
Outline

Wind Integration Status

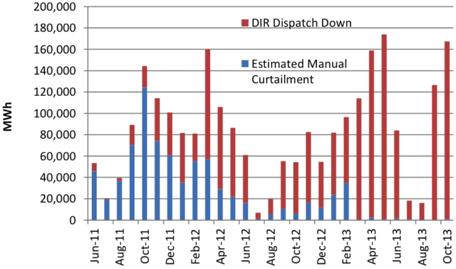
- Wind penetration in U.S.: 1.5% (2008) $\rightarrow$ 4.5% (2013) $\cdots \rightarrow$ 20% (2030)
- Wind integration costs
  - Non-dispatchable
- Have to improve wind dispatchability through better scheduling !



Wind Integration Cost (Source: EERE 2013)

Wind Dispatchability

- Traditionally a non-dispatchable resource
  - Curtailment occurs due to congestions or security reasons
  - Curtailment is implemented in an ex post fashion, endangering system reliability
- Proactive approaches to improve wind dispatchability
  - Dispatchable Intermittent Resource (DIR) protocol (MISO)



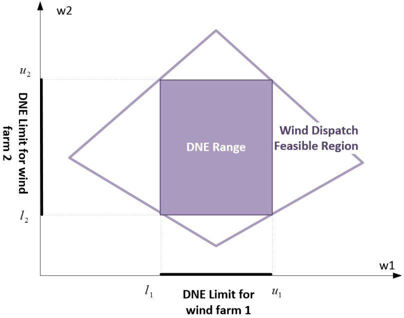
  - Do-Not-Exceed (DNE) Limits (ISO New England)

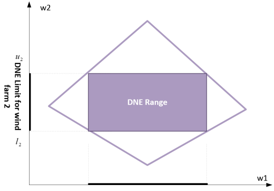
A Variable Resource Dispatch Framework – DNE Limits

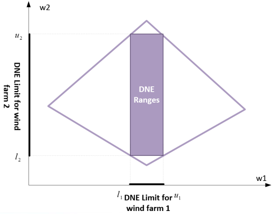
- Proposed by ISO New England [Zhao, Zheng, and Litvnov (2015)]
- DNE procedure
  1. Determine the ***dispatch base point*** based on hours-ahead wind forecasting
  2. Calculate the ***maximal ranges*** of power output for each wind farm, based on security analysis with reserve levels given by the dispatch base point
  3. Wind farms follow these ranges as a dispatch guidance
- Benefits
  - A dispatch framework for variable resources
  - DNE limits are simple for execution

DNE Limits Selection

- Allocation of dispatch ranges in the dispatchable regions
- Maximize the weighted circumference of the ***box***
- LMPs are used to weight the ranges [Zhao, Zheng, and Litvnov, 15']
  - A market perspective: $\sum_{i \in N} LMP_i \times (u_i - l_i)$
- Which wind farm should get larger limits? what other criteria for range determination?

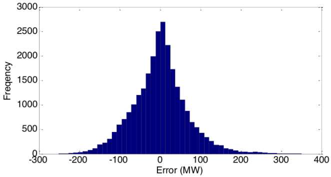




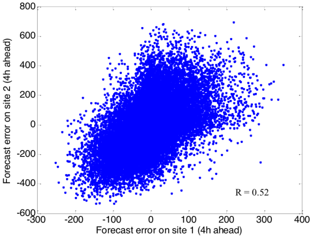


Discrepancy Between Forecast and Dispatch

- Actual wind power dispatched could deviate from base point because of
  - Point forecast
  - Forecasting errors
  - Forecasting bias
  - Curtailments due to congestions or security reasons
- Deviations maybe correlated

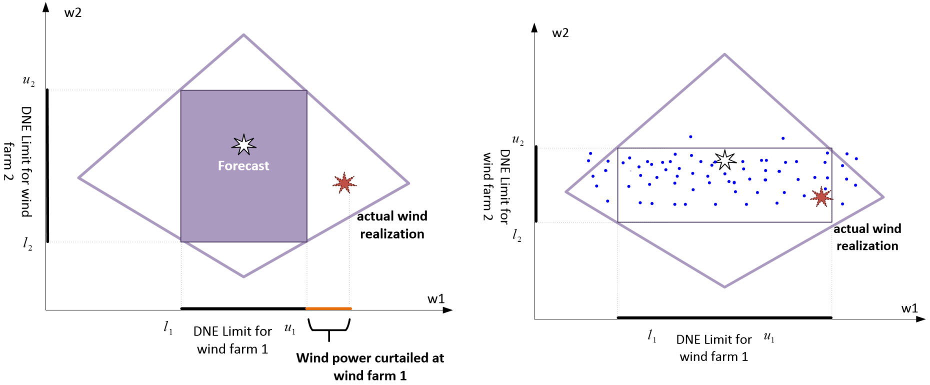


Source: NREL



DNE Limits Under Uncertainties

- Original DNE limits might not be effective in capturing the uncertainties
- Can we design DNE limits in another way to reduce curtailments?



A Data-Driven Dispatch Range Determination

1. Using data to understand uncertainties
   - Data
     - Wind power forecasting from each wind farm
     - Observed wind power dispatch from each wind farm
   - Statistic features: mean, variance, covariance
   - Possible distribution functions
2. Determinate wind dispatch ranges considering the uncertainties

Goal of the Data-Driven DNE Limits

Maximize the probability that wind realization is within the DNE limits

$$\max_{\ell,u} \mathbb{P}\{\ell \leq \tilde{w} \leq u\}$$
$$s.t.\ \ell + (1-v)u \in \mathcal{D} \quad \forall v \in [0,1]^n$$

$\mathcal{D} := \{w \in \mathbb{R}_+^n : \exists p \in \mathbb{R}_+^q\ s.t.\ Ap + Bw \leq c\}$, called ***wind dispatchbility set***

p : conventional generation dispatch; ***recourse variables***.

Characterizing Uncertainties

- Perfect information
  - Statistic models
- Limited information
  - Moments approximation [Scarf (1958), Vandenberghe et al. (2007)]
    - $\mathcal{P}_1 := \{\xi \in \mathbb{R}^n : \mathbb{E}[\xi] = \mu; \mathbb{E}[\xi\xi^\top] = \delta\}$
    - $\mathcal{P}_2 := \{\xi \in \mathbb{R}^n : (\mathbb{E}[\xi] - \mu)^\top \Lambda^{-1}(\mathbb{E}[\xi] - \mu) \leq \gamma_1; \mathbb{E}[(\xi - \mu)(\xi - \mu)^\top] \leq \gamma_2\}$
  - Density function approximation [Pardo (2006), Jiang and Guan (2015)]
    - A family of distribution functions that is not "far" from a reference distribution function
  - Sample average approximation [Shapiro (2003), Shapiro and Nemirovski (2005)]
    - True distribution is replaced by the empirical one

Introduction to Data-Driven Approaches

- A typical data-driven approach
  1. Design an uncertainty set: all probability distributions that satisfy the definition, e.g., $\mathcal{P}_1$ and $\mathcal{P}_2$
  2. Distributionally-robust optimization (a worst-case point of view)

$$\max_{\ell,u} \inf_{p\in\mathcal{P}} \mathbb{P}\{\ell \leq \xi \leq u\}$$

- Disadvantages
  - Non-convex reformulations/approximations
  - Overly conservative

Sample Average Approximation

- Actual wind power dispatched at wind farm i in the next time period

$$\tilde{w} = w^* + \tilde{e},$$

$w^* \in \mathbb{R}^n_+$: the base point; $\tilde{e} \in \mathbb{R}^n$: error vector

- Replace the real probability by $|S|$ samples (observations)$w^j = w^* + e^j$:

$$\mathbb{P}\{(\tilde{w} = w|_{w^*+e^j})\} = \frac{1}{|S|} \quad j \in S$$

- Approximate the probability:

$$\mathbb{P}\{\ell \leq \tilde{w} \leq u\} = \frac{\sum_{j \in S} \mathbb{1}\{\ell \leq w^j \leq u\}}{|S|}$$

where $\mathbb{1}(\ell \leq w^j \leq u) = \begin{cases} 1 & \text{if } \ell \leq w^j \leq u \\ 0 & \text{otherwise} \end{cases}$

Sample Average Approximation-Continued

- SAA reformulation

$$\max_{\ell,u} : \mathbb{P}(\ell \leq \tilde{w} \leq u)$$

$$\Downarrow$$

$$\max : \sum_{j} z_j$$

$$\text{s.t. } \ell - (1 - z^j) * M \leq w^j \leq u + (1 - z^j) * M \quad \forall j \in S$$

- Strong valid inequalities for SAA based on the ***mixing set*** results [Luedtke, Ahmed & Nemhauser (2010)] [Günlük & Pochet (2001)] etc.
- A mixed-integer linear programming (MILP) problem that can be readily solved by commercial solvers

Solution Approach: Delayed Constraint and Column Generation

- Master problem: SAA formulation + ***necessary*** dispatchability set constraints

$$\max : \sum_j z_j$$

$$\text{s.t. } \ell - (1 - z^j) * M \le w^j \le u + (1 - z^j) * M \quad \forall j \in S$$

$$\ell, u \in \mathbb{R}^n_+, z^j \in \{0, 1\} \ \forall j \in S$$

$$Ap^k + B(\ell + (1 - v^k)u) \le c \quad k = 1, 2, \ldots\ldots$$

k is the iteration number. [1]

- Subproblem: Identify the most violated dispatchability constraints

$$\max_{v \in [0,1]^n} \min_{s \in \mathbb{R}^n_+} \bar{1}^\top s$$

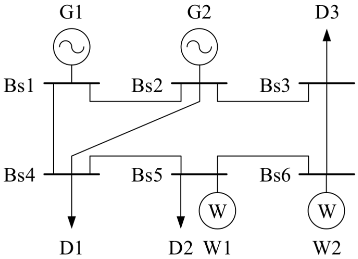
$$s.t.\ Ap + B(\ell^k + (1 - v)u^k) - s \le c$$

  - Observation: maximal violations always achieved by "corner" points of the "box"
  - Solution: dualize the inner problem and convert it to a MILP problem

[1] Solving Two-stage Robust Optimization Problems Using a Column-and-Constraint Generation Method, B Zeng, L Zhao, Operations Research Letters 41 (5), 457-461

Case Study: 6-Bus System

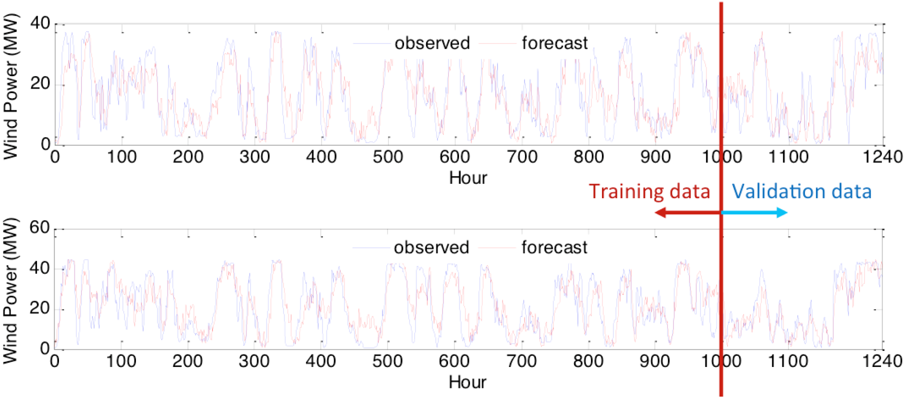
- Configuration
  - 6 bus, 7 lines
  - 2 thermal generators (250MW*2)
  - 2 wind farms (100MW*2)
  - System loads: 266MW-434MW
- Wind data (Eastern Wind Dataset by NREL [1])
  - Wind farm #1: site 3902 (W89.18, N41.68)
  - Wind farm #2: site 3945 (W88.55, N40.49)
- Comparison
  - Proposed method (D-DNE)
  - Original method (LMP-weighted DNE)



[1] Available: http://www.nrel.gov/electricity/transmission/data_resources.html

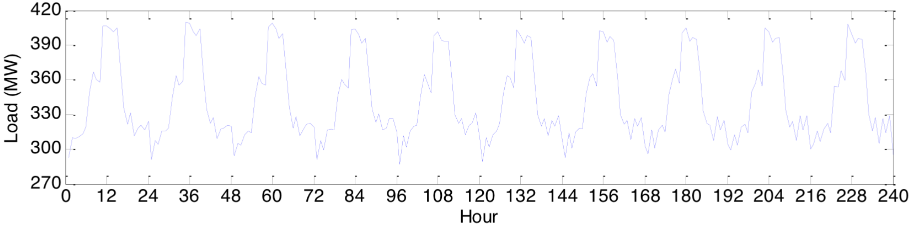
Case Study: A 6-Bus System

- Wind profiles (1240 hours, for training and validation)



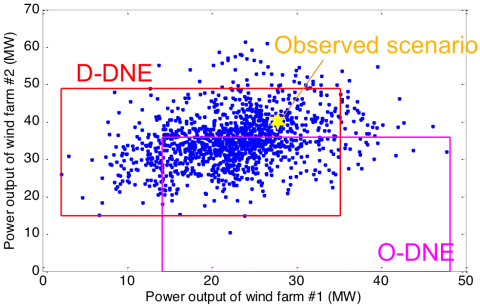
Case Study: 6-Bus System

- Load profile



DNE Limits Comparison: Single Snapshot (t=240)

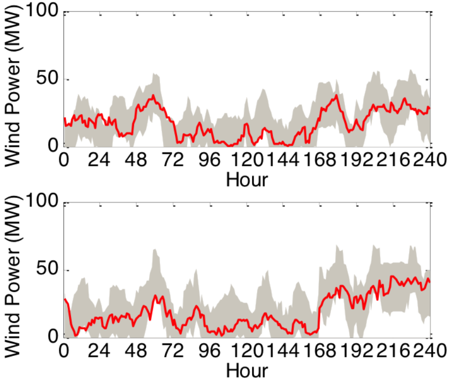
- D-DNE:
  - Actual wind realization lies in the D-DNE box
  - No wind curtailment
- O-DNE
  - Wind realization lies outside of the O-DNE box
  - Wind curtailment occurs in wind farm #2



DNE Comparison: Multiple Snapshots

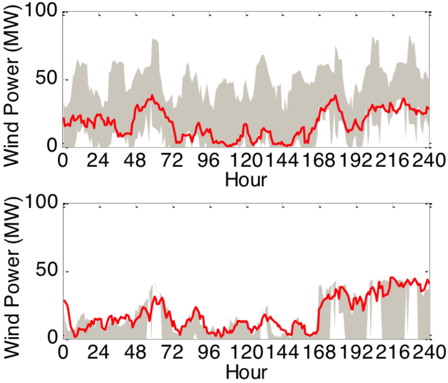
D-DNE

87.9% wind realizations are covered



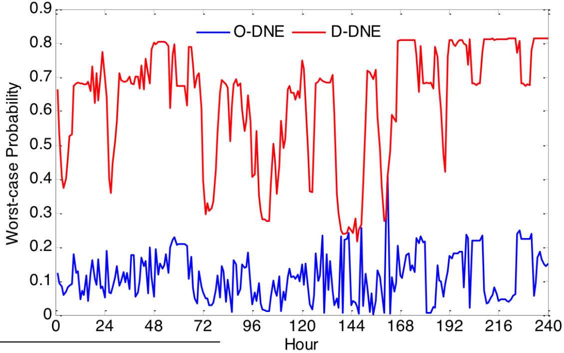
O-DNE

37.5% wind realizations are covered



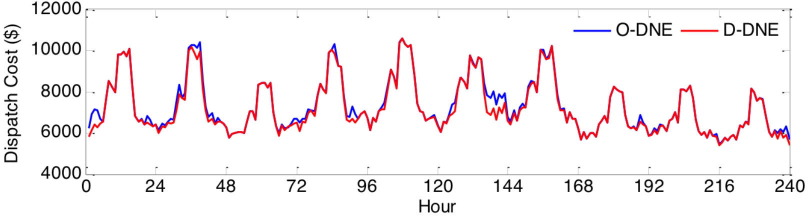
Wind Curtailment Probability Under Worst-Case Probability

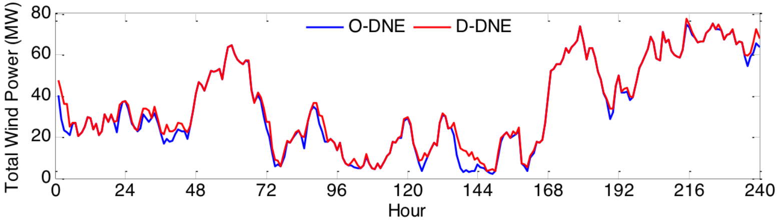
- Goal: To see how robust our DNE limits are in the worst-case “scenario”
- Measurement: The probability of “coverage” under the worst case scenario (probability)
- Approach: A lower bound on the probability given incomplete distribution information, i.e., only the first two moments as in $\mathcal{P}_1$ [1]



[1] B. P. Van Parys, P. J. Goulart, and D. Kuhn, ”Generalized Gauss inequalities via semidefinite programming,” Mathematical Programming, 2015.

Economic Benefits

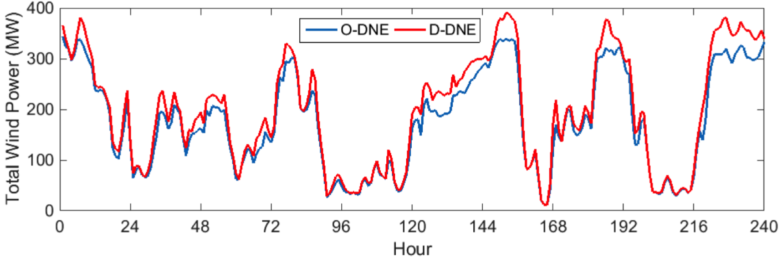




- D-DNE accommodates more wind power and incurs less dispatch cost

Algorithm Scalability: IEEE 118-Bus System

- Configuration
  - 118 bus, 186 lines, 76 conventional generators, 10 wind farms
  - Wind data: from 10 sites in Eastern Wind Dataset by NREL
- Total simulation time: 388s (240 runs)



Strengthened Formulation

6-Bus System (2 wind farms)

MP Iter.	Original Formulation			Strengthened Formulation		
	Root gap (%)	# nodes	Time (s)	Root gap (%)	# nodes	Time (s)
#1	97.8	7	0.73	42.7	0	0.26
#2	97.8	0	0.74	5.5	0	0.37
Term.	Optimal			Optimal		

IEEE 118-Bus System (10 wind farms)

MP Iter.	Original Formulation			Strengthened Formulation		
	Root gap (%)	# nodes	Time (s)	Root gap (%)	# nodes	Time (s)
#1	92.8	>1.4 M	>7200	75.1	0	1.01
#2	-	-	-	19.2	0	1.55
Term.	Time limit exceeded			Optimal		

- Computation efficiency is significantly improved
  - Exploit the structure of SAA
  - Only a few data points are dominant

Summary

- Data-Driven Do-Not-Exceed Limits
  - DNE limits considering uncertainties
  - Data-driven, requiring little knowledge
  - Computational efficiency and scalability
  - Improved wind utilization
- Possible future research
  - Multi time period
  - Resource redispatch

Thank you!

Comments?