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Methods for Power System Expansion Planning Considering Reliability Criteria

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Outline

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- Power Grid R&D at Sandia (Operations, Management, and Evolution)
- Long-Term Grid Planning
- Transmission and Generation Expansion Problem (TGEP)
- Reliability Metrics

Grid Operations, Management and Evolution R&D at Sandia

- Long-Term Planning Under Uncertainty
  - Wind Farm Network Design
  - *N*-*k* Survivable Grid Design
- Advanced Predictive Models for Renewables Output
- Unit Commitment and Day-Ahead Scheduling

Power Grid Operations, Management and Evolution

- Electric power systems are extremely complex
  - sheer physical size
  - widely dispresed geographically
  - nation and international interconnections
  - flows follow physical laws not desired transportation routes
  - cannot be efficiently/effectively stored in large quantities
  - interdependence across large distances
- Primary emphasis on providing a reliable supply of electricity to customers
- Spare or redundant capacities (generation and transmission) inbuilt to ensure adequate and acceptable continuity of supply in the event of disruptions (scheduled or unscheduled)
- How much redundancy and at what cost?

Long-Term Power Grid Planning

- Long-term grid planning centers on two mathematical optimization models for cost minimization:
    - generation capacity expansion
    - transmission capacity expansion
- Generation expansion addresses the question of where and when to place new generation facilities (plants) and in what quantity
- Transmission expansion addresses the analogous question for high-voltage transmission corridors and lines, typically in the context of a transportation model or DC approximation of power flow.

Power Flow Overview

- Alternating Current (AC) Line Flow Equations:

$$P_k = V_m^2 G_k - V_m V_n (G_k \cos(\theta_m - \theta_n) + B_k \sin(\theta_m - \theta_n)), \ \forall\, k$$
$$Q_k = -V_m V_n (G_k \sin(\theta_m - \theta_n) - B_k \cos(\theta_m - \theta_n)) - B_k V_m^2, \ \forall\, k$$

- Non-convex constraints
- In practice, approximations of AC flow equations are used:
  - Linearized Direct Current (DC) Flow Equations:

$$B_k(\theta_n - \theta_m) - P_k = 0$$

  - Transportation (network flow) model

Nominal Transmission and Generation Expansion Problem

Minimize:

- Total Capacity (Generation and Transmission) Expansion Cost and
- Operation Cost

Subject to:

- Generation operating constraints
- Node balance constraints
- Line flow constraints

$$B_k(\theta_n - \theta_m) - P_k = 0$$

- Line capacity constraints

Reliability Metrics in Widespread Use

- Reserve Margins
  - Difference between available capacity and peak demand, normalized by peak demand
- Loss of Load Cost (LOLC)
  - Objective penalty ($/MW) for load shedding
- Loss of Load Expectation (LOLE)
  - Constraint on the amount of load shed (MWh) in expectation
- Loss of Load Probability (LOLP)
  - Demand must be satisfied with some probability $\alpha \in (0, 1)$
- *N*-*k* security requirement
  - Grid must be able to survive outage of up to *k* network elements (transmission line, transformer, generator) – while satisfying demand

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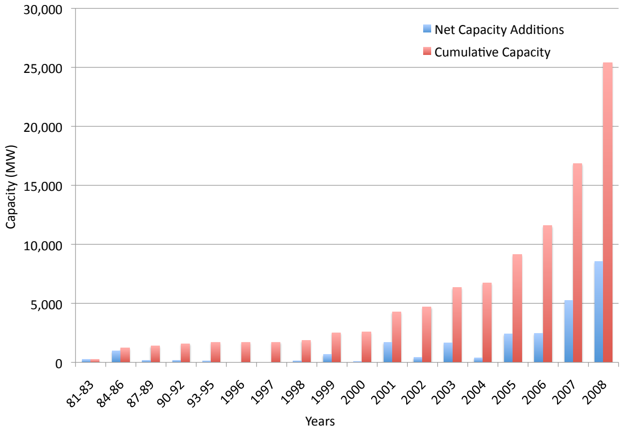
Section 2: Wind Farm Network Design (WFND)

- Overview
- WFND Formulation
- Solution Approaches
- Computational Results
- Ongoing Efforts

Motivation (1 of 2)

- Wind is the fastest growing source of electricity in U.S. (AWEA 2008)



Motivation (2 of 2)

- Much of the growth in renewable energy is a direct result of climate change concerns and increasing government support:
  - More than half the states passed Renewable Portfolio Standards
    - TX: 5,880MW (1%) by 2015, 10,000NW (2%) by 2025
    - CA: 30% by 2030
    - MI: 10% by 2015
  - American Recovery and Reinvestment Act of 2009
    - Production Tax Credit
    - Investment Tax Credit
- Wind is almost always the most cost-competitive renewable electricity source

Challenges

- Power system design models must now include wind-based generation
- Current models permit multiple types of generation (coal, natural gas, nuclear)
- Why can't we treat wind the same?
- Several important differences

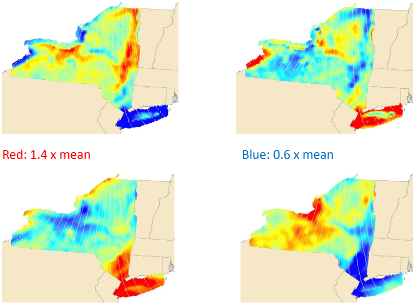
1. Spatial Variability of Wind Speed

- Wind speed varies over space
- Two coal generators at location A have the same capacity output and variability as two equivalent generators at location B
- Not true with wind!
- Can't separate capacity decisions from location decisions (integrated approach)

2. Temporal Variability

- At any given site, wind speed is also stochastic over time
- Because wind power can't be efficiently stored, fluctuations are a real challenge

Deviations from Mean by Time of Day

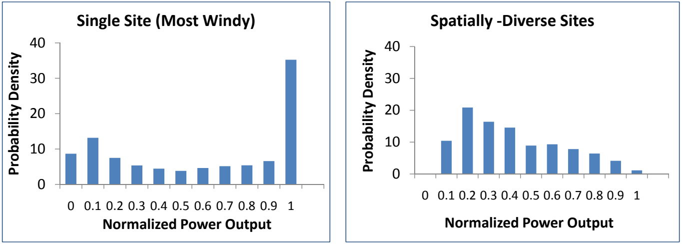


3. Co-Locating Production and Demand

- Conventional generators often located fairly close to load center (demand points)
  - Leads to reduced transmission costs
- Can't necessarily do this with wind
  - Best wind resources not necessarily near population centers
  - Transmission loss

4. Trade-off Between Transmission and Reliability

- More diverse network can mean greater reliability but higher transmission costs



Problem Overview

- How to design a network of wind farms to supply electricity across a large area, considering both system reliability and cost?
- All the challenges of designing traditional generation and transmission networks
- Additional challenges of spatial and temporal correlations of wind
- Current system planning studies focus on site-level optimization
  - selects sites based on average wind speed
  - neglects effect of spatio-temporal correlation across wind sites

Problem Statement (WFND)

- WFND is a two-stage stochastic program where first-stage decisions correspond to network design and second-stage decisions correspond to operating cost (OC) and loss-of-load-cost (LOLC)

$$\underbrace{\sum_{i\in\mathcal{N}} h_i z_i}_{\text{Gen. siting}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{g\in\mathcal{G}} c_i^g x_i^g}_{\text{Gen. capacity}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}:i<j} h_{ij} z_{ij}}_{\text{Trans. siting}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}:i<j}\sum_{t\in\mathcal{T}} c_{ij}^t x_{ij}^t}_{\text{Trans. capacity}} + \underbrace{\sigma\mathbb{E}_\omega\left[Q_{\mathbf{x}\omega}\right]}_{\text{Operating Cost \& LOLC}}$$

s.t.

fixed charges
$$\begin{cases} x_i^g \leqslant M_i^g z_i, & \forall\, g\in\mathcal{G},\ i\in\mathcal{N} \\ x_{ij}^t \leqslant M_{ij}^t z_{ij}, & \forall\, t\in\mathcal{T},\ i,j\in\mathcal{N},\ i<j \end{cases}$$

renewable portfolio standards
$$\left\{\ \sum_{i\in\mathcal{N}} \rho_i x_i^0 \geqslant \Delta_{RPS} \right.$$

variable integrality
$$\begin{cases} x_i^g \in \mathbb{Z}^+, & \forall\, g\in\mathcal{G},\ i\in\mathcal{N} \\ x_{ij}^t \in \mathbb{Z}^+, & \forall\, t\in\mathcal{T},\ i,j\in\mathcal{N},\ i<j \\ z_i \in \{0,1\}, & \forall\, i\in\mathcal{N} \\ z_{ij}\in\{0,1\}, & \forall\, i,j\in\mathcal{N},\ i<j \end{cases}$$

Recourse Function

$$Q_{\mathbf{x}\omega} = \min \quad \underbrace{\sum_{i\in\mathcal{N}}\sum_{g\in\mathcal{G}} n_i^g p_i^g}_{\text{Operating Cost}} + \underbrace{\sum_{i\in\mathcal{N}} l_i s_i}_{\text{LOLC}}$$

s.t.

production + flow in − flow out = demand − lost load

$$\left\{ \sum_{g\in\mathcal{G}} p_i^g + \sum_{j\in\mathcal{N}}\sum_{t\in\mathcal{T}} \left[\mathcal{L}(f_{ji}^t) - f_{ij}^t\right] = d_i(\omega) - s_i, \quad \forall\, i \in \mathcal{N} \right.$$

transmission line capacity limits

$$\left\{ f_{ij}^t \leqslant \kappa^t \cdot (e_{ij}^{t\omega} + x_{ij}^t), \ \forall\, t \in \mathcal{T},\ i,j \in \mathcal{N} \right.$$

generation capacity limits

$$\left\{ p_i^g \leqslant \kappa_i^{g\omega} \cdot (e_i^{g\omega} + x_i^g), \ \forall\, g \in \mathcal{G},\ i \in \mathcal{N} \right.$$

variable nonnegativity

$$\left\{ \begin{array}{c} f_{ij}^t \geqslant 0,\ \forall\, t \in \mathcal{T},\ i,j \in \mathcal{N} \\ s_i \geqslant 0,\ \forall\, i \in \mathcal{N} \\ p_i^g \geqslant 0,\ \forall\, g \in \mathcal{G},\ i \in \mathcal{N} \end{array} \right.$$

Stochastic Mixed-Integer Programming: The Algorithm Landscape

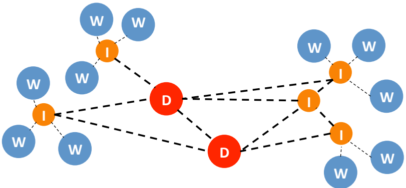
- The Extensive Form or Deterministic Equivalent
  - Write down the full variable and constraint set for all scenarios
  - Write down, either implicitly or explicitly, non-anticipativity constraints
  - Attempt to solve with a commercial MILP solver
    - Great if it works, but often doesn't due to memory or time limits
- Time-stage or "vertical" decomposition
  - Benders / L-shaped methods (including nested extensions)
  - Pros: Well-known, exact, easy for (some) 2-stage problems, parallelizable
  - Cons: Master problem bloating, slow convergence for (some) 2-stage problems, multi-stage difficulties
- Scenario-based or "horizontal" decomposition
  - Progressive hedging / Dual decomposition
  - Pros: Inherently multi-stage, parallelizable, leverages

WFND Solution Approach

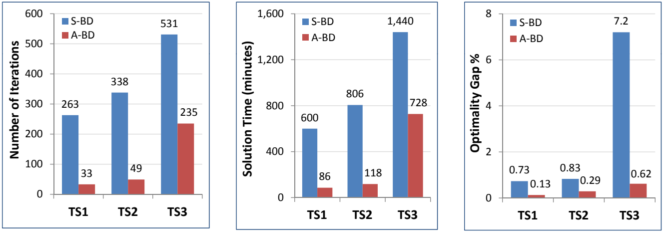
- Standard Benders Decomposition (S–BD)
  - performs poorly
- Accelerated Benders Decomposition (A–BD)
  - Necessary conditions
    - Network connectivity
    - Demand fulfillment – (I) area loads and (II) total system load
  - Knapsack constraints
  - Multi-cut generation

Computational Experiments

- 3 Test Systems (18-34 nodes, 25-38 arcs), 8784 scenarios
- Demand nodes represent five large meltropolitan areas in the West coast (hourly load data FERC 2004)
- Coincidental wind speed data from NREL's Western Wind Data Set (same period as load)
- Candidate wind sites randomly selected out of 32,043 candidate locations
- 24 hour runtime limit (AMD Opteron 8218, 1.5 GB RAM, CPLEX 11.0)



Computational Results



- Using S–BD, TS3 did not finish within the 24 hour runtime limit.
- Using S–BD a large number of iterations (long runtime) is required for convergence.

Ongoing Efforts

- Testing on CA's RETI data
- Testing with linearized DC transmission model with loss (important if transmission distance is large)
- Developing new algorithms to solve LOLP-constrained WFND problem
- Developing new models for the co-location of transmission interconnections

Section 3: Survivable Grid Design

- Grid Security Overview
- Identification of Severe Multiple Contingencies
- *N*-*k* Survivable Grid Design Problem

Power Grid Increasingly Complex and Vulnerable

Reliabable Grid Planning

R. Chen

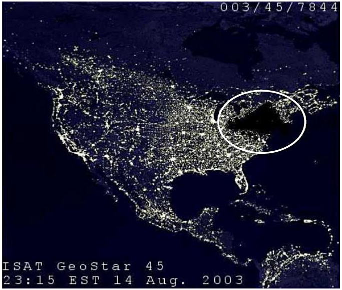
Overview

Wind Farm Network Design (WFND)

N-k Survivable Grid Design

Conclusion

Increase emphasis on grid security following 9/11 and 2003 blackout

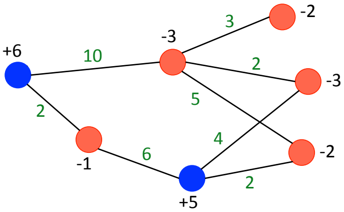


Northeast blackout started with three broken lines.

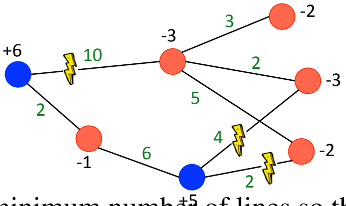
- Problem: current standard requires system to be resilient to only one failure (higher standards not enforceable)
- Goal: develop computational methods to
  - detect vulnerabilities of the power network
  - effectively augment the system to increase reliability/security

Grid Vulnerability As A Network Problem

- Given a graph G=(V,E) with weights on its vertices
  - positive for generation
  - negative for loads
- find a partition of V into two loosely connected regions with a significant load/generation mismatch



Mininum Cardinality Network Inhibition Problem (MC–NIP)



k =0, max-flow = 11

k =1, max-flow = 7

k =2, max-flow = 3

k =3, max-flow = 1

- Cut a minimum number of lines so that max-flow (min-cut) is below a specified bound.
- Shown to be NP-complete (Phillips 1991).
- The classical min-cut problem is a special version of network inhibition, where max-flow is set to zero.
- Can be formulated as Mixed Integer Linear Program (MILP) with |V|+|E| binary variables (Pinar et al. 2010).

MILP Formulation of MC–NIP

number of lines destroyed $\left\{ \min \quad \sum d_{ij} \right.$

subject to:

capacity of cut $\left\{ \sum_{(v_i,v_j)\in E} c_{ij}s_{ij} \leqslant D \right.$

cut identification constraints
$$\left\{ \begin{array}{rl} p_i - p_j - s_{ij} - d_{ij} \leqslant 0 & \forall (v_i,v_j) \in E \\ p_i - p_j + s_{ij} + d_{ij} \geqslant 0 & \forall (v_i,v_j) \in E \\ p_s = 0 & \\ p_t = 1 & \end{array} \right.$$

s-t partitioning variables $\left\{ p_i \in \{0,1\}, \forall\, i \in V \right.$

edge cut variables $\left\{ d_{ij} \in \{0,1\}, \quad \forall (v_i,v_j) \in E \right.$

min-cut identification variables $\left\{ s_{ij} \in \{0,1\}, \quad \forall (v_i,v_j) \in E \right.$

N-*k* Survivable Grid Design

- N-k survivable power grid must be able to withstand the loss of up to k lines
- Given failure budget k, the number of failure contingencies is $T = \binom{N}{1} + \cdots + \binom{N}{k-1} + \binom{N}{k}$, where N is the number of network components.
- T extremely large for moderate size N and $k \geqslant 2$

N-k Survivable Grid Design Problem (NK–SGD)

$$\min_{\mathbf{f},\mathbf{p},\mathbf{q},\mathbf{x}} \quad \underbrace{\sum_{(i,j)\in\mathcal{A}:i<j} c_{ij}x_{ij}}_{\text{capacity expansion cost}} + \underbrace{M\sum_{s=1}^{T}\sum_{i\in\mathcal{N}} q_i^s}_{\text{load shedding penalty}}$$

s.t.

flow balance $\left\{ -p_i^s + \sum_{j:(i,j)\in\mathcal{A}} f_{ij}^s - \sum_{j:(j,i)\in\mathcal{A}} f_{ji}^s - q_i^s = b_i \quad \forall i \in \mathcal{N}, s = 1\cdots \right.$

flow capacity $\left\{ \begin{array}{l} 0 \leqslant f_{ij}^s \leqslant u_{ij}x_{ij} \quad \forall (i,j) \in \mathcal{A}^{-s} : i < j, s = 1\cdots, T \\ 0 \leqslant f_{ij}^s \leqslant 0 \quad \forall (i,j) \in \mathcal{A}^s, s = 1\cdots, T \end{array} \right.$

generation capacity $\left\{ 0 \leqslant p_i^s \leqslant u_i \quad \forall i \in \mathcal{N}, s = 1\cdots, T \right.$

$$q_i^s \geqslant 0 \quad \forall i \in \mathcal{N}, s = 1\cdots, T$$

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in \mathcal{A} : i < j$$

Observations

- *NK–SGD* is an extremely large MILP even for moderate N and k
  - For $N = 1000$ and $k = 2$, there are over $500,000$ failure contingencies
- Small instances solvable directly using commercial MILP solver
- Moderate instances extremely hard to solve (long runtime and large memory usage)

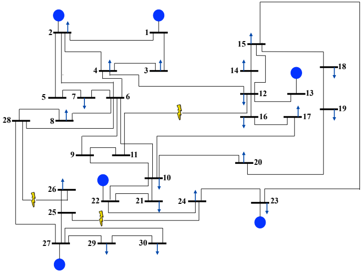
NK–SGD Solution Approach 1

- *L*-Shaped Method/Benders Decomposition
  - First-stage/master problem – network design decisions
  - Second-stage/subproblem – network flow problems (one for each failure contingency)
- For moderate size instances up to 100x faster than direct approach using commercial MILP solver
  - e.g. $N \in [50, 200]$ and $k \leqslant 2$
- For larger instances, this approach still not tractable as the nmber of possible contingencies is prohibitively large

NK–SGD Solution Approach 2

- *L*-Shaped Method/Benders Decomposition not appropriate for larger *NK–SGD* problems
- Delayed Contigency Generation Algorithm (DCGA) for solving large instances
  - Master-slave decomposition algorithm
  - Failure contingency generation embedded within decomposition algorithm
    - MC–NIP used to generate failure contingencies
    - New failure contingency added to scenario list
    - Solve minimum cost flow problem to generate optimality (separation) cut

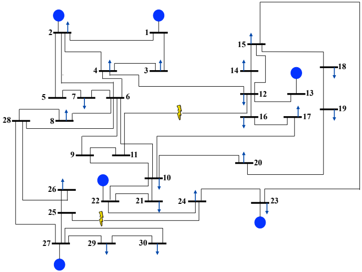
Computational Experiment: IEEE 30-Bus System *N*-1



IEEE 30-Bus System

- Three candidate lines identified
- The most severe failure can cause a blackout with 372 MW loss (out of a total of 1655 MW)
- Current system can be augmented to meet *N*-1 security criteria with the addition of three new lines

Computational Experiment: IEEE 30-Bus System *N*-2



IEEE 30-Bus System

- 632 failure contingencies identified (out of 7503 possible contingencies)
- The most severe failure can cause a blackout with 408 MW loss (out of a total of 1655 MW)
- Current system can be augmented to meet *N*-2 security criteria with the addition of 20 new lines

Computational Results

IEEE Test Systems	*K*	*N*	*# of possible contingencies*	*Full MIP (sec.)*	*Benders Decomposition (sec.)*	*Delayed Contingency Generation (sec.)*
30	1	82	82	0	0	0
118	1	358	358	20	4	4
179	1	444	444	33	11	19
30	2	123	7,503	81,722	36	3
118	2	537	143,916	x	2,865	40
179	2	666	221,445	x	9,974	85

- DCG more than 100x faster than standard Benders Decomposition approach

Ongoing Efforts

- Testing on larger IEEE Systems using DCGA
- Extension to DC power flow model

Section 4: Conclusion

- Summary
- Acknowledgements
- Questions?

Summary

- Stochastic mixed-integer programs are a natural modeling paradigm for solving many core grid operations and planning problems

- Solver technologies capable of solving realistic instances are emerging
  - But many challenges remain, both in terms of research and deployment
- Sandia is developing algorithms (and corresponding software) to address what we view as the challenges (or at least challenges we can effectively address!)
  - Frameworks to support rapid modeling and solver prototyping
  - Scalable parallelization of decomposition strategies
  - Rigorous quantification of uncertainty bounds on solution costs
  - Open-source solutions

Related Work

- Generation expansion
  - Bloom 1983, Gorenstin et al. 1993, Malcolm and Zenios 1994
- Transmission expansion
  - De la Torre et al. 1999, Oliveira et al. 2005, Shrestha et al. 2004
- Integrated transmission and generation expansion
  - Jirutitijaroen and Singh 2008, McCusker and Hobbs 2003
- Wind system expansion
  - Milligan and Factor 2000, Oh and Short 2009
- Network Vulnerability and Survivability
  - Bienstock and Verma 2010, Pinar, Meza, Donde, and Lesieutre 2010, Smith, Lim and Sudargho 2007

Questions?

Why An Integrated Planning Approach?

- Wind and transmission are almost always built by separate organizations.
- Chicken-and-egg problem:
  - Wind developers not building if they can't access transmission
  - Transmission co. not building if no electrons flowing on wires
- Public agencies identifying resource in need of transmission
  - Incentives for transmission companies to build
  - If transmission is built, the wind developers will come
- Public agencies are engaging in centralized planning processes to determine the best location for this infrastructure (e.g. ERCOT's CREZ program, CA's RETI program)

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