Advanced Grid Modeling, Simulation, and Computation

Building Research Collaborations: Electricity Systems

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Overview of Challenges in Grid Modeling

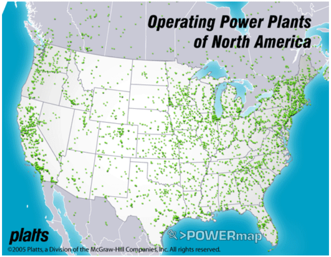
Computational Challenges in Grid Modeling

1. **Size:** $\simeq$ 100k lines ... "most complex machine ever built"
2. **Complexity:** nonlinear, hierarchical, and discrete decisions
3. **Uncertainty:** demand and supply (renewable) uncertainties

... many applications combine all three challenges

Missing from this talk:

- Big data (Session # 2)
- Real-time decisions
- Cyber-security (Session # 1)



... all involve modeling and computation

Outline

1. Size of Power Grid
2. Complexity of Power Grid
3. Modeling Uncertainty within Simulations & Design
4. Exascale Revolution
5. Summary and Discussion

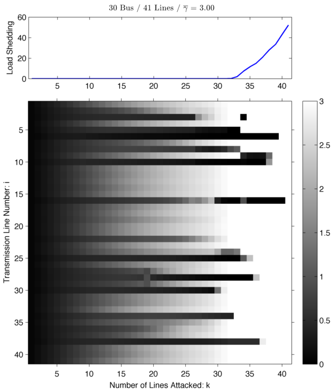
Challenge: Contingency Analysis [Steve Wright, Wisconsin]

Large power grid: $\simeq$ 100k lines; time-scales from ms to years

N-k contingency analysis $\Rightarrow$ combinatorial explosion

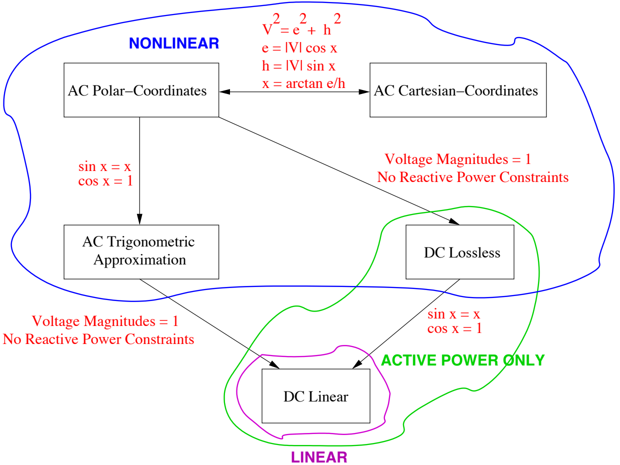
- Vulnerability of grid to disruption
- Combinatorial explosion: "N choose k" scenarios
- New: Bilevel optimization
  - Nonlinear AC power flow
  - Find collection of lines that produce maximum disruption
  - "Attacker" decreases line admittance to disrupt network
  - System operator adjusts demands & generation

80% lines not vulnerable



... more in Mahantesh's talk

Complexity of Power Grid: Nonlinearities



- Operation & Design: optimal power flow, transmission switching, network expansion
- Challenge: interaction of nonlinearities & discrete decisions

Complexity of Power Grid: Discrete Decisions

- Given existing power grid network and demand forecast
- Design expanded network for secure transmission

Traditional Approach. Simplify nonlinear (AC) power flow model:

$$F(U_k, U_l, \theta_k, \theta_l) := b_{kl} U_k U_l \sin(\theta_k - \theta_l) + g_{kl} U_k^2 - g_{kl} U_k U_l \cos(\theta_k - \theta_l)$$

by setting $\sin(x) \simeq x$ and $\cos(x) \simeq 1$ and $U \simeq 1$

Nonlinear Optimization Approach. Work with nonlinear model

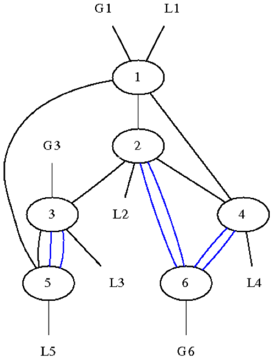
- $-M(1 - z_{k,l}) \leq f_{k,l} - F(U_k, U_l, \theta_k, \theta_l) \leq M(1 - z_{k,l})$
- $z_{k,l} \in \{0, 1\}$ switches lines on/off; $M > 0$ constant

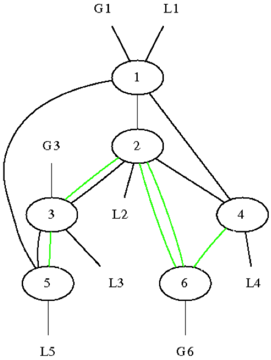
Questions.

Can we solve the nonlinear models? Does it matter?

Power-Grid Transmission Network Expansion

Expansion Results for linear vs. nonlinear power flow models





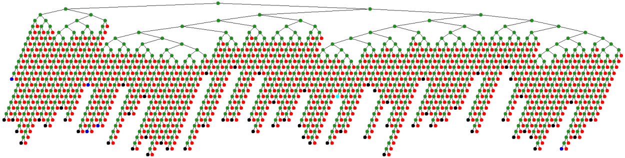
- Solve realistic AC power flow expansion models on desktop
- Significant difference between DC and AC solution
- Linearized DC model not feasible in AC power flow
- DC approximation not valid when topology changes

MIP Optimization Challenges

1. Combinatorial Explosion: generate huge search trees
   - Each node in tree is nonlinearly-constrained optimization
   - Must take uncertainty into account
   - Search tiny proportion of tree only
2. Nonconvexities $\Rightarrow$ multimodal & global optimization

MINOTAUR

It's only half bull

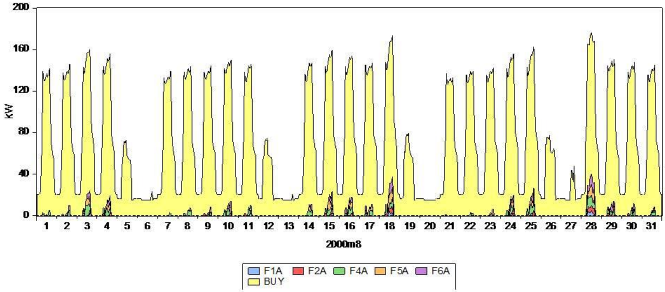


Argonne's Minotaur solver for mixed-integer nonlinear optimization

Co-Generation for Commercial Buildings

Goal: Net-zero energy buildings by 2020 ⇒ 60% reduction of CO_2

- Co-generation units: fuel-cell, solar panel, wind, storage unit.
- Which units to buy to minimize energy and purchase cost? Binary variables model type of equipment & size (discrete).
- Ramping for fuel-cell & storage unit ⇒ nonlinearities.
- Optimal hourly operation of units ⇒ on/off constraints.



Pruitt, Newman, Braun (Colorado School of Mines & NREL)

Co-Generation for Commercial Buildings

1-Day Data Set

	MINOTAUR BnB	MINOTAUR QPD	Bonmin	Baron	Couenne	MINLPBB
Objf	836.30	968.73	836.43	840.64	844.92	836.17
CPU	117.87	2.59	174.496	> 10hrs	> 10hrs	147.98
Nodes	204	5	61	363,358	932,400	129

4-Day Data Set

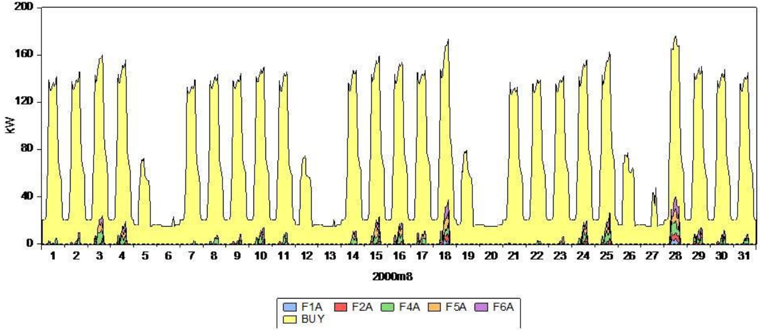
	MINOTAUR BnB	MINOTAUR QPD	Bonmin	Baron	Couenne	MINLPBB
Objf	3344.81	3344.81	3304.69	3304.69	Inf	3266.47
CPU	11.45	23.87	7522.89	> 10hrs	> 10hrs	26293.08
Nodes	1	1	9	17,875	88,454	3,062

7 Day Data Set

	MINOTAUR BnB	MINOTAUR QPD	Bonmin	Baron	Couenne	MINLPBB
Objf	6178.37	6178.37	Inf	5748.18	Inf	5726.0
CPU	168.38	54.55	> 10hrs	> 10hrs	> 10hrs	> 10hrs
Nodes	1	3	350	13,231	38,693	827

... tough problem, and not even the right one!

Challenge: Bilevel MINLP under Uncertainty



We solved the wrong problem badly!

- Should run on 10-year data set not 7-day data
- Demand & prices are uncertain ⇒ model the uncertainty

⇒ multi-scale, complex, mixed-integer problem

Extends to transmission expansion planning ...

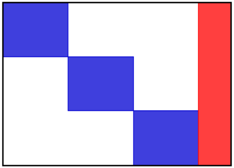
Uncertainty & Stochastic Optimization [Cosmin Petra]

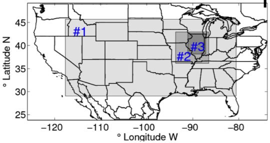
Unit commitment with wind power ... min. expected cost

$$\underset{x}{\text{minimize}} \quad f(x) + \mathbb{E}_\omega \left(\min_z \; h(x, z; \omega) \text{ s.t. } g(x, z; \omega) \geq 0 \right)$$
$$\text{subject to } c(x) \geq 0$$

- x — here-and-now decisions
- z — 2nd-stage decisions

  ... random realizations of wind
- $\omega \in \Omega$ random parameters





Realistic wind scenarios

- Weather Research Forecasting (WRF)
- Real-time grid-nested 24h simulation
- $|\Omega| = 30$ samples of WRF

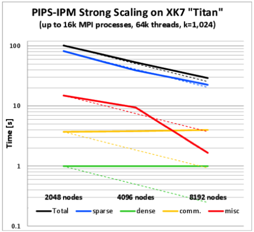
Stochastic Unit Commitment [Cosmin Petra]

PIPS - scalable framework for stochastic optimization problems

- Parallel distributed implementations of interior-point (IPM)
- Block-angular linear systems suitable to parallelization
- Schur complement-based decomposition of linear algebra
- Parallelization bottlenecks: dense linear algebra (first stage)
- Dense matrices can go on GPUs, multicores, or be distributed.

PIPS-IPM ported to IBM BG/P and BG/Q, Cray XE6, XK7 & XC30

- 32k scenarios
- 4 billion variables and constraints
- 128K cores on BG/P and 64K cores on XK7



... more from Victor

The Exascale Revolution [John Shalf, LBNL]

Systems	2009	2015 +1/-0	2018 +1/-0
System peak	**2 Peta**	**100-300 Peta**	**1 Exa**
Power	**6 MW**	**~15 MW**	**~20 MW**
System memory	0.3 PB	5 PB	64 PB (+)
Node performance	125 GF	0.5 TF or 7 TF	1-2 or 10TF
Node memory BW	25 GB/s	1-2TB/s	2-4TB/s
Node concurrency	12	O(100)	O(1k) or 10k
Total Node Interconnect BW	3.5 GB/s	100-200 GB/s 10:1 vs memory bandwidth 2:1 alternative	200-400GB/s (1:4 or 1:8 from memory BW)
System size (nodes)	18,700	50,000 or 500,000	O(100,000) or O(1M)
Total concurrency	225,000	O(100,000,000) *O(10)-O(50) to hide latency	O(billion) * O(10) to O(100) for latency hiding
Storage	15 PB	150 PB	500-1000 PB (>10x system memory is min)
IO	0.2 TB	10 TB/s	60 TB/s (how long to drain the machine)
MTTI	days	O(1day)	O(1 day)Slide 51

Summary and Discussion

Modeling & Computational Challenges in Power Grid Systems

- Size: network, contingencies, and time-scales (ms to years)
- Complexity: nonlinear, mixed-integer $\Rightarrow$ nonconvex
  - Hierarchical decision problem (leader-follower)
  - multiscale models and multi-model approximations
- Uncertainty: demand, supply, status, ...
  - Decision-making under uncertainty
  - Take “all” scenarios into account
  - Quantify cost of uncertainty
- Exascale revolution ... will affect all compute systems

... many problems beyond our solvers

$\Rightarrow$ scope for new models/math/algorithms!