Advanced Grid Modeling, Simulation, and Computation

Building Research Collaborations: Electricity Systems

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August 28-29, 2013
Overview of Challenges in Grid Modeling

Computational Challenges in Grid Modeling

1. **Size:** $\sim 100k$ 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: $\approx 100k$ 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

\[ V = \sqrt{e^2 + h^2} \]
\[ e = |V| \cos x \]
\[ h = |V| \sin x \]
\[ x = \arctan \frac{e}{h} \]

- **AC Polar–Coordinates**
- **AC Cartesian–Coordinates**
- **AC Trigonometric Approximation**
- **DC Lossless**
- **DC Linear**

**ACTIVE POWER ONLY**

**LINEAR**

**NONLINEAR**

Voltage Magnitudes = 1
No Reactive Power Constraints

Voltage Magnitudes = 1
No Reactive Power Constraints

\[ \sin x = x \]
\[ \cos x = 1 \]
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 \(\sin(x) \approx x\) and \(\cos(x) \approx 1\) and \(U \approx 1\)

**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

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

<table>
<thead>
<tr>
<th></th>
<th>MINOTAUR</th>
<th>Bonmin</th>
<th>Baron</th>
<th>Couenne</th>
<th>MINLPBB</th>
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<tbody>
<tr>
<td>Objf</td>
<td>836.30</td>
<td>836.43</td>
<td>840.64</td>
<td>844.92</td>
<td>836.17</td>
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<tr>
<td>CPU</td>
<td>117.87</td>
<td>174.496</td>
<td>&gt; 10hrs</td>
<td>&gt; 10hrs</td>
<td>147.98</td>
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<tr>
<td>Nodes</td>
<td>204</td>
<td>61</td>
<td>363,358</td>
<td>932,400</td>
<td>129</td>
</tr>
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</table>

### 4-Day Data Set

<table>
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<th>MINOTAUR</th>
<th>Bonmin</th>
<th>Baron</th>
<th>Couenne</th>
<th>MINLPBB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objf</td>
<td>3344.81</td>
<td>3304.69</td>
<td>3304.69</td>
<td>Inf</td>
<td>3266.47</td>
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<tr>
<td>CPU</td>
<td>11.45</td>
<td>7522.89</td>
<td>&gt; 10hrs</td>
<td>&gt; 10hrs</td>
<td>26293.08</td>
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<tr>
<td>Nodes</td>
<td>1</td>
<td>9</td>
<td>17,875</td>
<td>88,454</td>
<td>3,062</td>
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### 7 Day Data Set

<table>
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<tr>
<th></th>
<th>MINOTAUR</th>
<th>Bonmin</th>
<th>Baron</th>
<th>Couenne</th>
<th>MINLPBB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objf</td>
<td>6178.37</td>
<td>Inf</td>
<td>5748.18</td>
<td>Inf</td>
<td>5726.0</td>
</tr>
<tr>
<td>CPU</td>
<td>168.38</td>
<td>&gt; 10hrs</td>
<td>&gt; 10hrs</td>
<td>&gt; 10hrs</td>
<td>&gt; 10hrs</td>
</tr>
<tr>
<td>Nodes</td>
<td>1</td>
<td>350</td>
<td>13,231</td>
<td>38,693</td>
<td>827</td>
</tr>
</tbody>
</table>

... tough problem, and not even the right one!
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 ...
Unit commitment with wind power ... min. expected cost

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

- \( x \) — here-and-now decisions
- \( z \) — 2nd-stage decisions
  
  ... random realizations of wind
- \( \omega \in \Omega \) random 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]

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

Modeling & Computational Challenges in Power Grid Systems

- **Size**: network, contingencies, and time-scales (ms to years)
- **Complexity**: nonlinear, mixed-integer → 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

⇒ scope for new models/math/algorithms!