An Application of High Performance Computing to Transmission Switching

Anthony Papavasiliou ¹  Shmuel S. Oren ²  Zhu Yang ²
Kory Hedman ³  Pranav Balasubramanian ³

¹Catholic University of Louvain
²University of California at Berkeley
³Arizona State University

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Overview of the Project

- Project funded by the US Department of Energy Advanced Research Project Agency - Energy (ARPA-E)
- Green Electricity Network Integration (GENI) program
- Team members:
  - Arizona State University
  - University of California at Berkeley
  - Texas A&M University
  - Collaborators (TVA, LLNL, ...)
- 3-year $5-M project
- Scope:
  - Economic-based and corrective-based topology control
  - Adaptive protection systems
  - Risk-based circuit breaker monitoring
  - Communication systems for topology control
Topology Control (a.k.a. Transmission Switching)

- Transmission network analog of unit commitment
- **Redundancy** in transmission network design can result in cost improvements from switching lines
  - Under certain loading conditions certain lines may increase cost of operations
  - Under different loading conditions the same lines may be necessary for satisfying demand
- Computationally challenging problem
  - Systematical approach to unit commitment in system operations, not so for topology control
  - **Research objective**: Demonstrate that high performance computing can support integration of topology control in operations
FACTS Devices

- FACTS devices can be used for controlling line characteristics
- The topology control problem can be easily modified to accommodate distributed FACTS control
Relevant Literature

- **Topology control**
  - (Fisher, 2008): First formal treatment as large-scale optimization
  - (Hedman, 2010): Benders decomposition algorithm
  - (Fuller, 2012): Heuristics inspired by LMP difference of candidate lines

- **Parallel computing in power system operations**
  - (Monticelli, 1987): security constrained optimal power flow with corrective rescheduling
  - (Pereira, 1990): reliability evaluation, simulation and hydrothermal planning
  - (Kim, 1997): decentralized optimal power flow
  - (Bakirtzis, 2003), (Biskas, 2005): parallel implementation of optimal power flow in PVM
PSR Cloud: Industry Practice in Hydrothermal Scheduling
(TXIP) : \( \min \sum_{g \in G} C_g p_g \) \hspace{1cm} (1)

\( P^-_g \leq p_g \leq P^+_g \) \hspace{1cm} (2)

\(- \sum_{k: F(k) = n} f_k + \sum_{k: T(k) = n} f_k + \sum_{g \in G_n} p_g - D_n = 0 \) \hspace{1cm} (3)

\(- z_k TC_k \leq f_k \leq z_k TC_k \) \hspace{1cm} (4)

\(- M_k (1 - z_k) \leq f_k - B_k (\theta_m - \theta_n) \leq M_k (1 - z_k) \) \hspace{1cm} (5)

\( p_g \geq 0, z_k \in \{0, 1\} \)
Notation and Assumptions

- Linearized, lossless representation of Kirchoff voltage / current laws
- Load shedding permitted
- Big-M formulation for switching action
- $z_k$ is a transmission switching variable
  - $z_k = 1$ implies Kirchoff's laws and thermal limits limits are respected (line is on)
  - $z_k = 0$ implies $f_k = 0$ and Kirchoff's laws non-binding, (line is off)
- Susceptance $B_k$ used instead of PTDF since PTDFs depend on switching actions
- $K = \bar{K} \cup \hat{K}$, where $\bar{K}$ are lines out of service and $\hat{K}$ are lines in service
Reformulation with Fixed Switching Decisions

\[(TXLP) : \min \sum C_g p_g \] (6)
\[p_g - P_g^+ \leq 0, (\mu_g^+) \] (7)
\[-p_g + P_g^- \leq 0, (\mu_g^-) \] (8)
\[- \sum f_k + \sum f_k + \sum p_g - D_n = 0, (\rho_n) \] (9)
\[-f_k - Z_k TC_k \leq 0, (\lambda_k^-) \] (10)
\[f_k - Z_k TC_k \leq 0, (\lambda_k^+) \] (11)
\[f_k - Z_k B_k (\theta_m - \theta_n) = 0, (\psi_k) \] (12)
\[p_g \geq 0 \]
Reformulation with Switching Decision Sensitivity

\[(TXNLP) : \min \sum C_g p_g \quad (13)\]

\[(7), (8), (9)\]

\[-f_k - s_k TC_k \leq 0, k \in \bar{K}, (\lambda^-) \quad (14)\]

\[f_k - s_k TC_k \leq 0, k \in \bar{K}, (\lambda^+) \quad (15)\]

\[-f_k - (1 - s_k) TC_k \leq 0, k \in \hat{K}, (\lambda^-) \quad (16)\]

\[f_k - (1 - s_k) TC_k \leq 0, k \in \hat{K}, (\lambda^+) \quad (17)\]

\[f_k - s_k B_k(\theta_m - \theta_n) = 0, k = (m, n) \in \bar{K}, (\psi_k) \quad (18)\]

\[f_k - (1 - s_k) B_k(\theta_m - \theta_n) = 0, k = (m, n) \in \hat{K}, (\psi_k) \quad (19)\]

\[s_k = 0, (\gamma_k) \quad (20)\]

\[p_g \geq 0\]
Sensitivity Interpretation

- \( s_k \) represents a switching action
  - \( s_k = 1 \) switches the state (from on to off and from off to on)
  - \( s_k = 0 \) keeps line in existing state
- \( \gamma_k \) represents the sensitivity of switching a line
- Closed form solution for \( \gamma_k \), generalizes result by (Fuller, 2012):
  \[
  \gamma_k = TC_k((\lambda^+_k)^* + (\lambda^-_k)^*), k \in \bar{K}
  \]
  \[
  \gamma_k = f_k^*(\rho_n^* - \rho_m^*), k \in \hat{K}
  \]

- Starred variables are optimal primal and dual variables of (TXLP), not (TXNLP). They can be computed easily.
- According to sensitivity interpretation, most promising candidate for switching is line with most negative \( \gamma_k \)
Solution Approaches

- **Greedy line selection**
  - Find line whose switch causes greatest cost improvement
  - Repeat until no improvement can be found

- **Greedy line selection with priority listing**
  - Find line with greatest (most negative) sensitivity ($\gamma_k$) on cost
  - Repeat until no improvement can be found

- **MIP heuristic**
  - Solve smaller instances of (TXIP) with fewer candidate lines
  - Repeat until no improvement can be found
Parallel Implementation of Greedy Line Search (TX1)

Switch least cost line

TXLP $s_1 = 1$

TXLP $s_2 = 1$

... 

TXLP $s_k = 1$

Cost improvement?

y

n

Exit

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Parallel Implementation of Greedy Line Search with Priority Listing (TX2)

- Solve TXLP
- Create priority list
- Switch line
  - TXLP $s(1)=1$
  - TXLP $s(2)=1$
  - $\ldots$
  - TXLP $s(K)=1$
- Cost improvement?
- Exit

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MIP Heuristic (TX3)

Switch best group

TXIP \( s_i = 1 \) for all i in group 1

TXIP \( s_i = 1 \) for all i in group 2

TXIP \( s_i = 1 \) for all i in group n

Best group improves?

Exit

\( y \)
Running Times

- CPLEX 12.4 Java Callable Library
- MPI used for parallelization
- Implementation on Lawrence Livermore National Laboratory
  - Hosts Sequoia, 3rd largest supercomputer worldwide
  - 8 CPUs per node, 2.4 GHz and 10GB per node

<table>
<thead>
<tr>
<th>System</th>
<th>Buses</th>
<th>Generators</th>
<th>Lines</th>
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<tbody>
<tr>
<td>IEEE 118</td>
<td>118</td>
<td>19</td>
<td>186</td>
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<tr>
<td>FERC PJM</td>
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<td>1,011</td>
<td>18,824</td>
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</table>
Evolution of Iterations for IEEE 118

<table>
<thead>
<tr>
<th>Iteration</th>
<th>TX1</th>
<th>Cost</th>
<th>TX2</th>
<th>Cost</th>
<th>TX3</th>
<th>Cost</th>
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<td>1603.1</td>
<td>L151</td>
<td>1609.4</td>
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<td>L122</td>
<td>1600.3</td>
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<td>L59</td>
<td>1595.3</td>
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</tr>
</tbody>
</table>
Results for IEEE 118

- Full MIP ($1537.4) \succ TX3 ($1549.0) \succ TX2 ($1595.3) \succ TX1 ($1595.6)
- TX2 outperforms TX1 although TX1 checks all lines in each iteration. This supports the advantage of quantifying $\gamma_k$.
- Control actions:
  - L132, L153 switched by all lines
  - L136, L162 switched by both TX1 and TX3
  - Full MIP: 32 lines switched
- Elapsed time (3 processors in parallel):
  - Full MIP (0.5% MIP gap): 34 sec.
  - TX1: 1,314 sec.
  - TX2: 300 sec.
  - TX3: 17 sec.
## Evolution of Iterations for FERC PJM

<table>
<thead>
<tr>
<th>Iteration</th>
<th>TX1</th>
<th>% cost impr.</th>
<th>TX2</th>
<th>% cost impr.</th>
</tr>
</thead>
<tbody>
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<td>L8313</td>
<td>1.268</td>
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</table>
Results for FERC PJM

- TXLP takes up to an hour using CPLEX default settings
- TXIP is intractable even when a subset of lines are considered
- 10 iterations were performed due to running time constraints
- Both algorithms result in less than 2% cost reduction
- TX1 ≻ TX2 but TX1 runs much slower
- No common lines switched
Evolution of Costs for PJM

Dispatch Cost

- TX1
- TX2(K=200)
- TX2(K=100)
- TX2(K=50)

Iteration

1  2  3  4  5  6  7  8  9  10

542000  540000  538000  536000  534000  532000  530000  528000  526000

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(Hogan, 1992) proposed financial transmission rights (FTRs) as an instrument for hedging locational prices of electricity. This proposal was adopted in most US markets in order to overcome the conundrum of contract paths.

FTR revenue adequacy relies on the assumption that transmission network topology does not change.

Topology control
- violates the assumptions required for revenue adequacy,
- and creates winners and losers,
- but it creates an overall benefit for the system.

Can a new market mechanism be designed that hedges LMP differences in a system with transmission switching?
Conclusions

- **Benefits of parallelization:** For an industrial scale problem, each LP DCOPF can take up to an hour to solve. Parallelization enables us to make more trial switches in the same amount of time.

- **Careful trials make a difference:** We have derived a sensitivity result for switching trial lines. The effectiveness is demonstrated in the IEEE 118 bus system. This can help in industrial scale systems, since we can save on computation time by checking fewer lines.
Perspectives

- Extensions of the model
  - Using FACTS to control line impedance
  - Expansion of model for transmission expansion planning

- Warm-starting the linear programming solver when solving a sequence of TXLP

- Development of market mechanisms for hedging LMP differences in a regime with topology control
Questions?

Contact: anthony.papavasiliou@uclouvain.be