An Application of High Performance Computing to Transmission Switching

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Overview of the Project

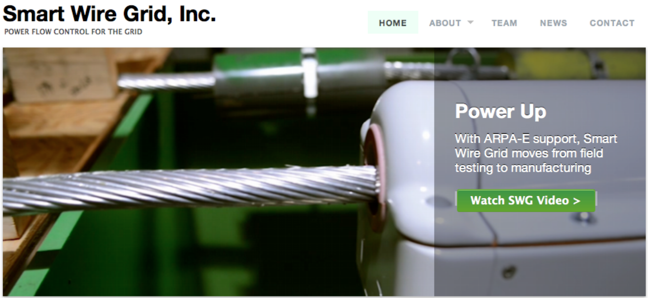
- Project funded by the US Department of Energy Advanced Research Project Agency - Energy (ARPA-E)
- Green Electricity Network Integration (GENI) program
- Team members:
  - Arizona State University
  - University of California at Berkeley
  - Texas A&M University
  - Collaborators (TVA, LLNL, ...)
- 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

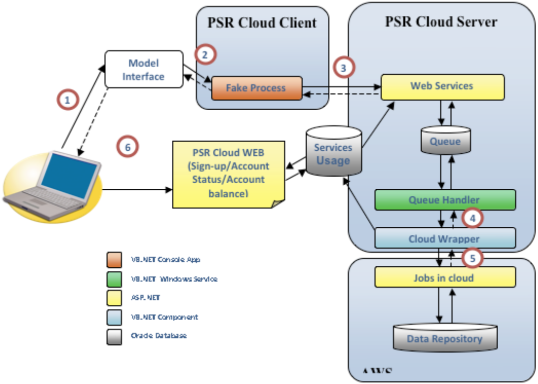
- FACTS devices can be used for controlling line characteristics
- The topology control problem can be easily modified to accommodate distributed FACTS control



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



MILP Formulation

$$(TXIP) : \min \sum_{g \in G} C_g p_g \tag{1}$$

$$P_g^- \leq p_g \leq P_g^+ \tag{2}$$

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

$$-z_k TC_k \leq f_k \leq z_k TC_k \tag{4}$$

$$-M_k(1 - z_k) \leq f_k - B_k(\theta_m - \theta_n) \leq M_k(1 - z_k) \tag{5}$$

$$p_g \geq 0, z_k \in \{0, 1\}$$

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

$$(TXLP) : \min \sum C_g p_g \quad (6)$$

$$p_g - P_g^+ \leq 0, (\mu_g^+) \quad (7)$$

$$-p_g + P_g^- \leq 0, (\mu_g^-) \quad (8)$$

$$-\sum_{k:F(k)=n} f_k + \sum_{k:T(k)=n} f_k + \sum_{g \in G_n} p_g - D_n = 0, (\rho_n) \quad (9)$$

$$-f_k - Z_k TC_k \leq 0, (\lambda_k^-) \quad (10)$$

$$f_k - Z_k TC_k \leq 0, (\lambda_k^+) \quad (11)$$

$$f_k - Z_k B_k(\theta_m - \theta_n) = 0, (\psi_k) \quad (12)$$

$$p_g \geq 0$$

Reformulation with Switching Decision Sensitivity

$$(TXNLP) : \min \sum C_g p_g \tag{13}$$

$$(7), (8), (9)$$

$$-f_k - s_k TC_k \leq 0, k \in \bar{K}, (\lambda_k^-) \tag{14}$$

$$f_k - s_k TC_k \leq 0, k \in \bar{K}, (\lambda_k^+) \tag{15}$$

$$-f_k - (1 - s_k) TC_k \leq 0, k \in \hat{K}, (\lambda_k^-) \tag{16}$$

$$f_k - (1 - s_k) TC_k \leq 0, k \in \hat{K}, (\lambda_k^+) \tag{17}$$

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

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

$$s_k = 0, (\gamma_k) \tag{20}$$

$$p_g \geq 0$$

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
- γ_k represents the sensitivity of switching a line
- Closed form solution for γ_k, generalizes result by (Fuller, 2012):

$$\gamma_k = TC_k((\lambda_k^+)^\star + (\lambda^-)^\star), k \in \bar{K} \quad (21)$$

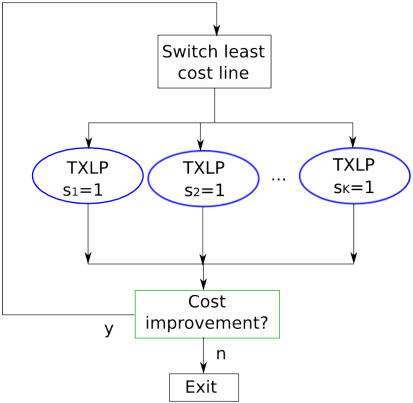
$$\gamma_k = f_k^\star(\rho_n^\star - \rho_m^\star), k \in \hat{K} \quad (22)$$

- 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 γ_k

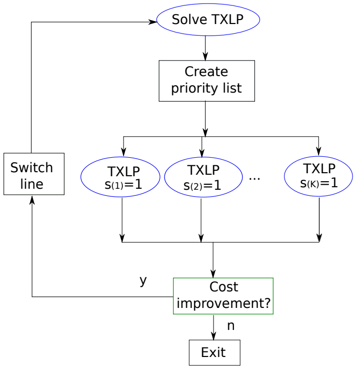
Solution Approaches

- 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 (γ_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

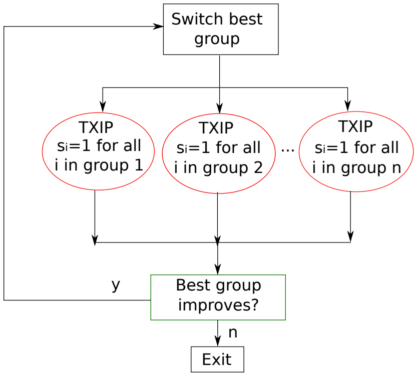
Parallel Implementation of Greedy Line Search (TX1)



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



MIP Heuristic (TX3)



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

System	Buses	Generators	Lines
IEEE 118	118	19	186
FERC PJM	13,867	1,011	18,824

Evolution of Iterations for IEEE 118

Iteration	TX1	Cost	TX2	Cost	TX3	Cost
1	L153	1924.5	L132	1930.6	L129 L132 L136	1778.3
2	L132	1795.9	L163	1797.5	L148 L153 L161 L162	1549.0
3	L136	1629.8	L133	1714.7		
4	L162	1607.9	L153	1683.0		
5	L37	1603.1	L151	1609.4		
6	L122	1600.3	L78	1600.6		
7	L14	1597.0	L85	1596.6		
8	L31	1595.9	L82	1596.1		
9	L19	1595.8	L96	1595.3		
10	L54	1595.6	L45	1595.32		
11	L60	1595.6	L48	1595.3		
12	L68	1595.6	L59	1595.3		

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 γ_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.

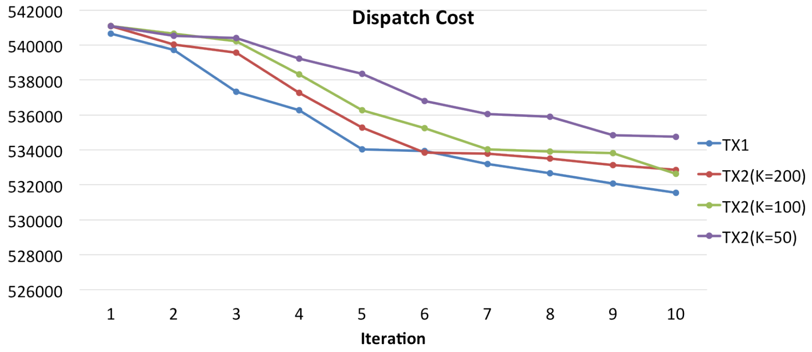
Evolution of Iterations for FERC PJM

Iteration	TX1	% cost impr.	TX2	% cost impr.
1	L17230	0.182	L2813	0.098
2	L2913	0.353	L1831	0.200
3	L8731	0.792	L11231	0.226
4	L12031	0.991	L103	0.441
5	L7031	1.404	L7482	0.605
6	L721	1.420	L2310	0.893
7	L293	1.556	L14823	1.030
8	L7981	1.652	L5567	1.059
9	L10002	1.762	L787	1.255
10	L8310	1.860	L8313	1.268

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 $\succ$ TX2 but TX1 runs much slower
- No common lines switched

Evolution of Costs for PJM



Financial Transmission Rights

- (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

Thank you

Questions?

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http://perso.uclouvain.be/anthony.papavasiliou/public_html/publications.html