Transmission Topology Optimization

CONGESTION RELIEF IN OPERATIONS AND OPERATIONS PLANNING

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Executive Summary

- Topology optimization software finds reconfigurations to route flows around congested or breached elements while meeting reliability standards.
- We evaluated the effectiveness of topology optimization to mitigate congested or breached constraints in 20 real-time SPP snapshots selected to provide a representative set of complex conditions.
- Key study findings:
  - 70% of constraints analyzed: single-action solutions on facilities below 345 kV led to 26% flow relief (average).
  - 95% of constraints analyzed: other solutions led to 31% relief, no new constraints.
- SPP created an Op. Guide based on this analysis (Tupelo overloads, OK).
- We estimate that topology optimization would enable:
  - Reduced frequency of breached intervals from 34% (current) to 8%.
  - Annual RT market efficiency gains of $18-44 million if used in RT Market Optimization.
  - Significantly reduced wind curtailments, full relief under some conditions.
Agenda

Background
Project Objectives
Operations Study Inputs
Reconfiguration Analysis Summary
Reliability and Market Benefits
Next Steps
Appendix

- Topology Optimization Applications
- References
Background
Current Congestion Management Impacts

Congestion Impacts in SPP (2017)*

Example

SPP Real Time Power Prices
March 10, 2018, 20:10 CST

<table>
<thead>
<tr>
<th>Price Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$600/MWh</td>
<td>Highest price</td>
</tr>
<tr>
<td>$400/MWh</td>
<td>High price</td>
</tr>
<tr>
<td>$300/MWh</td>
<td>Medium price</td>
</tr>
<tr>
<td>$100/MWh</td>
<td>Low price</td>
</tr>
<tr>
<td>$0/MWh</td>
<td>Lowest price</td>
</tr>
<tr>
<td>&lt; -$10/MWh</td>
<td>Negative price</td>
</tr>
</tbody>
</table>

Member Costs: $500 million
Reliability: breached constraints in the market happen in 34% of the RT market instances
Wind: 2.5% curtailments

285 MW wind curtailments
Negative price: -$29/MWh
Transmission line carries more flow than it safely can (contingency overload)

Sources:
Background

Topology Optimization Software

Software automatically finds reconfigurations to route flow around congested or overloaded elements (“Waze for the transmission grid”), complementing resource-based (re-dispatch) flow control.

Historical Condition

Congestion + Overload

With Reconfiguration

Flow Diverted

No Congestion or Overload

NewGrid Router

Topology Optimization Software

“Open/Close Circuit Breakers X and Y”
Case Study: Real Time Market, 3/10/18 8pm, 38% Wind Penetration
Congestion, Overload, Wind Curtailment Relief

SPP System Conditions
March 10, 2018, 20:10 CST

**Historical Case**
- Binding constraints: 3
- Shadow prices: $174 – $984/MWh
- Breached constraints: **one**
- Wind Curtailments: **285 MW**

**With Reconfigurations** (3 switching actions)
- Binding constraints: 1
- Shadow price: $15/MWh
- Breached constraints: **none** ✓
- Wind Curtailments: **0 MW** ✓

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**Price Scale**
- $600/MWh
- $300/MWh
- $100/MWh
- $40/MWh
- $0/MWh
- < -$10/MWh

**Wind Curtailments 285 MW**

**Three congested elements**

**Transmission Breach/Overload**

**One congested element**
Case Study: Oklahoma, 3/10/18 8pm, 38% Wind Penetration

**Historical Configuration:** Congestion, Breach
Case Study: Oklahoma, 3/10/18 8pm, 38% Wind Penetration
With Reconfiguration: No Congestion

$600/MWh
$300/MWh
$100/MWh
$40/MWh
$0/MWh
< -$10/MWh
Background

7-Bus Example: All Lines Closed
Background

7-Bus Example Results: Before and After

**Hourly Cost**
- All lines Closed: $18,186
- Line 3-4 Opened: $17,733
- **Savings:** $453 (2.5%)

### Generation

<table>
<thead>
<tr>
<th>Generation</th>
<th>All lines closed</th>
<th>Line 3-4 open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>80 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Bus 2</td>
<td>220 MW</td>
<td>296 MW</td>
</tr>
<tr>
<td>Bus 4</td>
<td>6 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Bus 6</td>
<td>188 MW</td>
<td>220 MW</td>
</tr>
<tr>
<td>Bus 7</td>
<td>291 MW</td>
<td>270 MW</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>785 MW</strong></td>
<td><strong>786 MW</strong></td>
</tr>
</tbody>
</table>
**Background**

**Reconfiguration Practice**

**Traditional/Today**
- Reconfigurations are employed on an ad-hoc basis
- Reconfigurations are identified based on staff experience (time-consuming process)
- The transmission grid flexibility is underutilized

**With Topology Optimization**
- Software identifies reconfiguration solution *options* to select
- Fast identification: 10 sec – 2 min
- Facilitate training of new operators
- Take full advantage of grid flexibility
- Achieve better outcomes

**Diagram**

- **System State**
  - Flow Violation / Congestion

- **EMS, OMS, or Planning Tools**
  - Usually Does Not Reconfigure
  - Transmission Operator/Planner

- **NewGrid Router**
  - Selected Reconfiguration Solution
  - Flow Violation / Congestion
  - Reconfiguration Solution Options
We developed topology control algorithms (TCA) for optimizing transmission network topology with DOE ARPA-E support.

- Designed to operate with existing systems and software (EMS, OMS, MMS).
- **Decision Support**: Multiple options proposed, impacts evaluated for each option.
- **Reliability**: Connectivity constraints (including max admissible load radialized), contingency constraints, voltage criteria.
- **Speed**: Meets solution times that align with operations timeframes.
- **High-Definition**: Handles operations (node-breaker, EMS) cases.
- **Reconfiguration Types**: Line switching (open/close), bus-tie and bypass breaker state.
- **Look-Ahead**: Optimization decisions with “topology continuity” constraints.
- **Market Optimization**: SCED and SCUC co-optimized with transmission configuration.

- With PJM staff, we tested and assessed the TCA impacts in a simulated environment replicating PJM market operations and outage coordination.
- With ERCOT staff, we performed assessments on operations planning cases.
- NewGrid has developed *NewGrid Router*, the first production-grade topology decision support software tool, based on the TCA technology.
As part of the reconfiguration search, *NewGrid Router* runs contingency analysis to ensure that the new configurations are feasible (e.g., do not cause new contingency violations).

**NewGrid Router**

**Optimization**
- Topology Optimization output:
  - Topology (reconfiguration)
  - Dispatch commitment
  - Marginal costs

**Feasibility (Reliability)**
- Contingency Assessment outputs:
  - Feasible/infeasible optimized state
  - Constraints to ensure feasibility of the optimization outcome
Study Objectives
SPP Transmission Topology Optimization Study

We evaluated the effectiveness and benefits of topology optimization in SPP Operations.

- Constraint Flow Relief:
  - SPP Operations selected a set of recent historical real-time snapshots of the SPP system in which a constraint of focus was binding or breached.
  - NewGrid Router identified a few reconfiguration options to relieve the focus constraints while:
    - Keeping the dispatch fixed (no production cost change),
    - Meeting reliability standards,
    - Not introducing new constraints.
  - SPP validated the feasibility and quantified relief impacts on the EMS.

- Market Savings Assessment:
  - For selected reconfiguration solutions, we evaluated their market impacts.
  - By scaling these results against historically observed congestion across SPP, we estimated the annual reliability and market impacts of using topology optimization.
SPP selected 17 focus constraints on 20 cases to show a representative set of complex transmission system conditions.

- Some of these cases are severe or extreme:
  - Winter load peak record, January 17, 2018: extreme congestion and breaches, post-contingency load shed plans, reconfigurations implemented by SPP Operations.¹
  - Wind peak record, Dec 4, 2017: 58.23% renewable penetration, 13,588 MW wind.²

- Topology optimization is expected to perform better under normal operating conditions since the system has more room to be optimized.

¹ For more details, see Kathryn Dial, SPP Winter Peak 1/17/18, presented at SPP ORWG Meeting, 4/4/18, [online] https://www.spp.org/Documents/56710/ORWG%20Meeting%20Materials%204-04-18.zip.
Focus Constraints

1. TUPELO TAP – TUPELO 138 KV (flo) PITTSBURG – VALLIANT 345 KV *
2. NEOSHO – RIVERTON 161 KV (flo) NEOSHO - BLACKBERRY 345 KV *
3. DARDANELLE DAM – CLARKSVILLE 161 KV (flo) ARKANSAS NUCLEAR ONE – FORT SMITH 500 KV
4. VINE – NORTH HAYS 115 KV (flo) POSTROCK – KNOLL 230 KV
5. EDWARDSVILLE 115/161 KV XFR (flo) 87TH STREET – CRAIG 345 KV
6. BUTLER – ALTOONA 138 KV (flo) CANEY RIVER – NEOSHO 345 KV
7. TUPELO TAP – TUPELO 138 KV (flo) SEMINOLE – PITTSBURG 345 KV
8. HAWTHORN 345/161 KV XF20 (flo) HAWTHORN 345/161 KV XF22 *
9. NASHUA 345/161 KV T1_HV (flo) NASHUA - HAWTHORN 345 KV *
10. JOPLIN - ORONOGO101 161 KV (flo) RIVERTON - ORONOGO 161 KV
11. WELSH - DIANA 345 KV [897] (flo) WESLH - DIANA 345 KV [896]
12. SIKESTON - IDALIA 161 KV (flo) SIKESTON - MINER 161 KV
13. WOODRING 345/138 KV XFR (flo) WOODRING - SOONER 345 KV
14. CENTENNIAL - PAOLA 161 KV (flo) WEST GARDNER - PLEASANTVILLE 161 KV
15. LONGWOOD - OAK 138 KV (flo) SOUTHWEST SHREVEPORT 345/138 KV XFR
16. NESS CITY - ALEXANDER 115KV (flo) BUCKNER - SPEARVILLE 345 KV
17. JOHN LAKE - JOHNSON 115 KV (flo) NORTH PLATTE – CROOKED CREEK 230 KV

* Constraint for which the market impacts were evaluated

- Lightly binding (shadow price $0-150/MW)
- Heavily binding (shadow price $350-750/MW)
- Breaching (shadow price $750/MW or above)
Reconfiguration Analysis Summary
Constraint Flow Relief

**Feasible** Solution:
- Meets pre- and post-contingency criteria, validated in the EMS

**Preferred** Solution by SPP, in addition to being feasible:
- Loading on any new constraints below 95%
- Comprises a single action below 345 kV
- Radializes less than 30 MW of load
- Provides at least 10% relief

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Average Flow Relief by Constraint

- Preferred Solutions
  - Relief 26%
  - Remaining Flow

- Feasible Solutions, no new constraint activation
  - Relief 31%
  - Remaining Flow

Best Solution by Constraint

- Preferred 70%
- Feasible, not preferred, no new constraint activated 25%
- Feasible, with post-contingent branch loading of 96% 5%
Most solutions comprised one action, were found within 30 seconds, radialized less than 10 MW of load, and opened lightly loaded branches.

1 Search performed on a commercial off-the-shelf server.
2 Solutions with more than 30 MW load radialized were found before SPP indicated the preferred 30 MW threshold.
Reliability and Market Benefits

Reliability Benefits – Breached Constraint Relief

Topology optimization can significantly reduce the frequency of breached constraints in the markets without incurring additional costs.

- Real-time system conditions differ from those planned day-ahead.
- Operators have limited means to manage some constraints in real time.

**Frequency of Breached Real Time Intervals (2017)**

<table>
<thead>
<tr>
<th></th>
<th>Intervals with Breach</th>
<th>Intervals with Binding Constraints Only</th>
<th>Uncongested Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical</td>
<td>34%</td>
<td>53%</td>
<td>13%</td>
</tr>
<tr>
<td>With Topology Optimization*</td>
<td>34%</td>
<td>8%</td>
<td>2017</td>
</tr>
</tbody>
</table>

**Sources:**

* We conservatively assume that the use of topology optimization in RT Operations could provide breach constraint relief in 75% of the observed breached constraints; in the study of the 20 selected historical constraints, 95% of them were relieved to well below their limit.
Constraint relief in the previous slides were based on the historical dispatch. We assessed real-time markets savings for four out of the twenty cases selected by SPP.

- We simulated the real-time market for four cases and evaluated the reduced congestion costs of applying reconfigurations to relieve constraints in those cases.
- Base case market results benchmarked against the historical market dispatch and shadow prices.
- Conservative assumptions:
  - We fixed the dispatch of 25-85 units (out of 200-250 market-dispatchable units) to the historical dispatch level so as to achieve market simulation results that meet the benchmark.
  - Because we removed many units as decision variables from the market, we are most likely underestimating the savings achievable by relieving bindings constraints.
Reliability and Market Benefits

Market Efficiency Benefits

Topology optimization would provide **annual Real Time Market savings of over $18-44 million** when used in market optimization.

- Based on the cases simulated, the real-time market cost savings provided by topology optimization is about 3% (+2%/-1%) of the initial *congestion rent* of the constraints relieved.

- We extrapolated the market savings based on the historical Real Time Market congestion rent ($1.2 billion in 2017), conservatively assuming that topology optimization can effectively provide relief for 75% of the constraints.*

* *In the study of the 20 selected historical constraints, 95% of them were relieved with topology optimization.*
Application in SPP and Next Step

- SPP has been testing the topology optimization software in operations planning and operations support, focused on reliability applications.
- The latent market efficiency benefits are very large, how could they be practically realized, while maintaining:
  - Transparency
  - Predictability
- **Idea for a next step**: Use topology optimization to mitigate the expected market congestion impacts of planned outages.
  - This would be done in conjunction with the reliability analyses that are performed in the existing outage coordination process.
  - No new process would be needed, only an expansion of the existing outage coordination process.
  - The congestion reduction benefits would likely be significant, since planned outages tend to drive a large fraction of the congestion costs.
Dr. Pablo A. Ruiz, a senior consultant at The Brattle Group, is an electrical engineer with over ten years of experience in electric power systems and markets analysis and research. He specializes in power operations, planning and market design under high levels of renewable penetration, modeling and analysis of electricity markets, and advanced technologies for the power grid. Dr. Ruiz is also an Associate Research Professor at Boston University, where he served as the Principal Investigator for the DOE ARPA-E Topology Control Algorithms project, leading a team of researchers from seven institutions in the development of transmission topology control technology. This technology is being used to develop decision support and simulation tools by NewGrid, Inc., a software company co-founded by Dr. Ruiz.

Dr. Ruiz has published articles in the IEEE Transactions on Power Systems and has presented papers at international conferences on topics related to renewables integration and uncertainty management, power flow analysis, operating reserve requirements and valuation, transmission system operations and expansion and unit commitment.

Prior to joining Brattle, Dr. Ruiz was an Associate Principal at Charles River Associates (CRA) and a Power Systems Engineer at AREVA T&D.

Dr. Ruiz holds a Ph.D. in Electrical and Computer Engineering from the University of Illinois at Urbana-Champaign.

The views expressed in this presentation are strictly those of the presenter(s) and do not necessarily state or reflect the views of The Brattle Group, Inc. or its clients.
Appendix Contents

Appendix 1: Topology Optimization Applications
Appendix 2: References
Appendix 1

Topology Optimization Applications

### Business Process
- Long-term planning
- Seasonal contingency planning
- Outage coordination
- Day-ahead market optimization
- Real-time market optimization
- Intra-day operations

### Objectives
- Adapt to emergency system conditions
- Increase grid resilience
- Avoid load shedding
- Enable conflicting outages
- Train new staff
- Increase transfer capability
- Relieve flow violations
- Minimize congestion costs
- Reduce wind curtailments
Appendix 1
Increased Grid Resilience

- Resilience: “ability to reduce the magnitude and/or duration of disruptive events.”
  - NewGrid Router identifies grid reconfigurations to:
    - Quickly adapt the grid to the disruptive event conditions
    - Minimize impacts by more quickly relieving overloads and consumer disconnections
    - Expedite recovery from events by providing more operational options.

- Case Study: 15-18 July, 2013 Extreme Heat Wave in PJM with Key Outages

Price spread: $20 to 1800/MWh due to limited import capacity

PJM Real Time Prices, 18/7/2013, 15:30 (pjm.com)

Overloads on critical transformer and lines

Fully relieve overloads by diverting flow around them, and increase import capacity to N Ohio

Sources:
References (I/II)


Appendix 2
References (II/II)


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