Transmission Topology Optimization

Applications to Enhance System Reliability and Resilience and to Increase Market and Planning Efficiency in Southwest Power Pool

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Executive Summary

- Topology optimization software finds reconfigurations to divert flow 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 solution led to 26% flow relief (average).
  - 95% of constraints analyzed: feasible solution 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 29% (current) to 7%.
  - Annual RT market efficiency gains of $18-44 million if used in RT Market Optimization.
  - Significantly reduced wind curtailments, full relief under some conditions.

- We also evaluated the effectiveness of topology optimization in long-term planning to develop Corrective Action Plans for multiple outage events.
  - Alternative plans based on reconfigurations avoid load shedding for the events analyzed.
Agenda

- Background
- Project Objectives
- Operations Study Inputs
- Reconfiguration Analysis Summary
- Reliability and Market Benefits
- Development of Corrective Action Plans in Long-Term Planning
- Conclusions
- Appendix
  - Highlighted Case Study
  - References
Background

Congestion Management and its Impacts

Congestion Impacts in SPP (2017)*

- Member Costs: $500 million
- Reliability: breached constraints 34% of the time
- Wind: 2.5% curtailments

Example:

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

Price Scale

$600/MWh

$300/MWh

$100/MWh

$40/MWh

$0/MWh

< -$10/MWh

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

7-bus Example: All Lines Closed
### 7-bus Example Results: Before and After

#### Before: all lines Closed

- **Bus 1**
  - All lines closed: 80 MW
  - Line 3-4 open: 0 MW
- **Bus 2**
  - All lines closed: 220 MW
  - Line 3-4 open: 296 MW
- **Bus 4**
  - All lines closed: 6 MW
  - Line 3-4 open: 0 MW
- **Bus 6**
  - All lines closed: 188 MW
  - Line 3-4 open: 220 MW
- **Bus 7**
  - All lines closed: 291 MW
  - Line 3-4 open: 270 MW

**Total**

- All lines closed: 785 MW
- Line 3-4 open: 786 MW

#### After: line 3-4 Opened

- **Hourly Cost**
  - All lines closed: **$18,186**
  - Line 3-4 Opened: **$17,733**

**Savings:** **$453 (2.5%)**
Reconfiguration Practice

**Traditional/Today**
- Employed on an ad-hoc basis
- Reconfigurations are identified based on staff experience
- Reconfiguration development is a time-consuming process
- The transmission grid flexibility is underutilized

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

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**EMS, OMS, or Planning Tools**

- Usually Does Not Reconfigure
- Transmission Operator/Planner

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**NewGrid Router**

- System State
- Flow Violation / Congestion
- Selected Reconfiguration Solution
- Reconfiguration Solution Options
Background

Topology Optimization Software

Topology optimization software automatically identifies reconfiguration options.

- With DOE ARPA-E support, developed topology control algorithms (TCA) for optimizing transmission network topology.
  - Designed to operate with existing systems and software (EMS, OMS, MMS).
  - Decision Support: Multiple options proposed, impacts evaluated for each option.
  - Reliability: Connectivity, contingency constraints, voltage criteria met.
  - 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.
Topology Optimization Architecture

**Optimization**

Topology Optimization output:
- Topology,
- Dispatch,
- Commitment,
- Marginal Costs

**Feasibility (Reliability)**

Contingency Evaluation

Contingency Assessment outputs:
- Feasible/Infeasible optimized state,
- Constraints to Ensure Feasibility of the optimization outcome
We evaluated the effectiveness of topology optimization in SPP for three different applications.

- **Track 1** – Operations and Operations Planning.
  - Real-Time: mitigation of complex congestion/breaches, e.g., resulting from forced outages or other unforeseen system conditions.

- **Track 2** – Long-Term Planning.
  - Development of Corrective Action Plans for multiple contingency event violations.

- **Track 3** – Prevention and Mitigation of Ice Buildup during Ice Storms
  - Increase resistive heating on selected critical lines.

**In this presentation we focus on Track 1 – Operations and Operations Planning, and summarize the findings of Track 2 – Long-Term Planning.**
Operations and Operations Planning
Objectives & High-Level Methodology

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 breaching.
  - 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 relief impacts on the EMS.

■ Market Savings Assessment:
  - For selected reconfiguration solutions, we evaluated their market impacts.
  - By scaling these results against congestion and breach events historically observed 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.

- These cases are not representative of normal operating conditions, they were selected to test the capabilities of topology optimization.

- 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.
Reconfiguration Analysis Summary
Solution Validation, Flow Relief Performance

- **Feasible** Solution
  - Pre- and post-contingency branch flow and bus voltage criteria validated in the EMS

- **Preferred** Solution by SPP, in addition:
  - Does not activate new constraints (i.e., does not increase loading to over 95%)
  - Comprises a single-action below 345 kV
  - Radializes less than 30 MW of load
  - Provides at least 10% relief

Average Flow Relief by Constraint

<table>
<thead>
<tr>
<th>Remaining Flow</th>
<th>Relief</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26%</td>
</tr>
<tr>
<td>Best Preferred</td>
<td>Solution</td>
</tr>
<tr>
<td></td>
<td>31%</td>
</tr>
<tr>
<td>Best Feasible</td>
<td>Solution, no new constraint activation</td>
</tr>
</tbody>
</table>

Best Solution by Constraint

- **Preferred**
- **Feasible**, not preferred, no new constraint activated
- **Feasible**, with post-contingent branch loading of 96%
Reconfiguration Analysis Summary

Feasible Solution Characteristics

Most solutions comprised one action, were found within 30 s, radialized less than 10 MW of load, and opened lightly loaded branches.

- **Number of Switching Actions**:
  - Single action: 73%
  - Two actions: 24%
  - Three actions: 4%

- **Flow on Opened Branches as % of Normal Rating**:
  - 0% - 20%: 44%
  - 20% - 40%: 33%
  - 40% - 60%: 18%
  - 60% - 80%: 4%

- **Load Radialized (MW)**:
  - 0: 57%
  - 0 - 10: 22%
  - 10 - 30: 6%
  - 30 - 100: 16%

- **Solution Search Times¹ (seconds)**:
  - 0 - 30: 76%
  - 30 - 60: 20%
  - 60 - 120: 4%

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 – Breach Constraint Relief

Topology optimization can significantly reduce the frequency of breached constraints 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 (April 2017-2018)**

- Intervals with Breach: 29%
- Intervals with Binding Constraints Only: 57%
- Uncongested Intervals: 14%

**Historical**

| Intervals with Breach | 29% |
| Intervals with Binding Constraints Only | 57% |
| Uncongested Intervals | 14% |

**With Topology Optimization***

| Intervals with Breach | 7% |

Source
2017 – 2018: Brattle and NewGrid analysis of historical binding and constraint data provided by SPP.

* 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

Price Contours w/ Reconfigurations Example

03/10/2018 20:10, TUPLOTP4 – TUPELO2 138 kV (flo) PITTSB9 – VALLIANT 345 kV

Historical Topology

Solve Focus Constraint

Solve All Constraints

Price Scale

$600/MWh

$300/MWh

$100/MWh

$40/MWh

$0/MWh

< -$10/MWh
Reliability and Market Benefits

Market Efficiency Benefits

Topology optimization would provide annual market savings of over $18-44 million when used in Real Time 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, 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.
Based on representative case studies, the use of topology optimization would significantly reduce wind curtailments.

- Mar 10th 2018 example: Full curtailment relief (38% wind penetration).

- Dec 4th 2017 wind peak case: 12% relief on the most severe constraint.
Long-Term Planning
NERC allows load shedding as part of the Corrective Action Plan (CAP) for specified planning events that involve multiple transmission outages which would otherwise result in NERC TPL-001-4 violations.*

SPP identified three severe multiple-contingency events whose CAPs rely on load shedding (re-dispatch is ineffective):

- **P6 Event**: multiple contingency – two overlapping single contingencies.
- **P7 Event**: multiple contingency – loss of a common structure.
- **Extreme Event**: loss of a transmission corridor, of an entire substation or power plant, or of multiple elements due to a regional event.

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* NERC Standard TPL-001-4 — Transmission System Planning Performance Requirements.
We found corrective reconfigurations that relieve the violations without load shedding and without causing other violations.

<table>
<thead>
<tr>
<th>Case Study Type</th>
<th>Flow on Violated Branch</th>
<th>Avoided Load Loss</th>
<th>No. of Actions</th>
<th>No. of New Constraints</th>
<th>Radialized Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>P6 Event</td>
<td>129%</td>
<td>86%</td>
<td>243</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>P7 Event</td>
<td>107%</td>
<td>94%</td>
<td>55</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Extreme Event</td>
<td>113%</td>
<td>97%</td>
<td>151</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

* NERC Standard TPL-001-4 — Transmission System Planning Performance Requirements.
Conclusions

- 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 solution led to 26% flow relief (average).
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- SPP created an Op. Guide based on this analysis (Tupelo overloads, OK).

- We estimate that topology optimization would enable:
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  - Annual RT market efficiency gains of $18-44 million if used in RT market optimization.
  - Significantly reduced wind curtailments, full relief under some conditions.

- We also evaluated the effectiveness of topology optimization in long-term planning, to develop Corrective Action Plans for multiple outage events.
  - Alternative CAPs based on reconfigurations fully avoid load shedding for the severe events selected by SPP.
Contact

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+1.217.766.7602
Case Date: 03/10/2018 IE 20:10
- SPP Balancing Authority load: 27,098 MW
- SPP wind generation: 10,470 MW (38% instantaneous wind penetration)

Focus Constraint: TEMP29_23044
- TUPLOTP4 – TUPELO2 138 kV (flo) PITTSB9 – VALLIANT 345 kV
- Initial flow: 101% (144.5 MVA) – constraint breached
- Shadow price: $984/MWh

Other Binding Constraints:
- SMOSUMMULCIR: SMKHL – SUMM 230 kV (flo) MULGRE2 - CIRC 230 kV
  - Shadow price: $182/MWh
  - Initial flow: 334 MVA
- SUNXFRSUNAMO: SUNDOWN 230/115 (flo) AMOCO_SW - SUNDOWN2 230
  - Shadow price: $174/MWh
  - Initial flow: 140 MVA
Contingency Constraint

Feasible, Single-Action Solution

Single-Action Solution w/ post-contingency voltage violation/s
On 03/10/2018 IE 20:10, two other constraints were also binding.

**SMOSUMMULCIR: SMKHL – SUMM 230 kV (flo) MULGRE2 - CIRC 230 kV**
- Shadow price (historical market): $182/MWh
- Solution: Open SMOKYHL6 - KNOLL1 1 230 kV (flow: 24.4% A rating)
  - Constraint flow: 60.4%
  - No adverse effects on other constraints, no load radialized

**SUNXFRSUNAMO: SUNDOWN 230/115 kV (flo) AMOCO - SUNDOWN 230 kV**
- Shadow price (historical market): $174/MWh
- Solution 1: Open LR_LEVEL2 - SUNDOWN 115 kV (flow: 24.3% A rating)
  - Constraint flow: 71.6%
  - Increase in flow on two new constraints over 95%
    - AMOCO – SUNDOWN 230 kV (flo) TOLK - YOAKUM 230 kV
    - WOLFFORT – TERRY_CO 115 kV (flo) AMOCO – SUNDOWN 230 kV
  - Load radialized: 7.6 MW
Appendix 2

References (I/II)


Appendix 2

References (II/II)


