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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newgrid THE Brattle GROUP SPP Southwest Power Pool

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

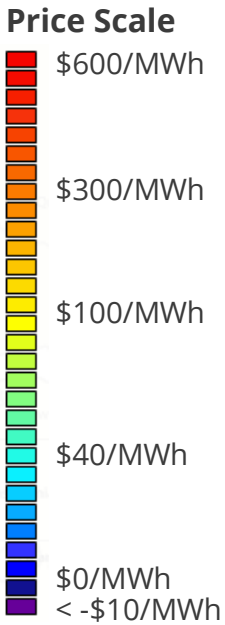
Congestion Management and its Impacts

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



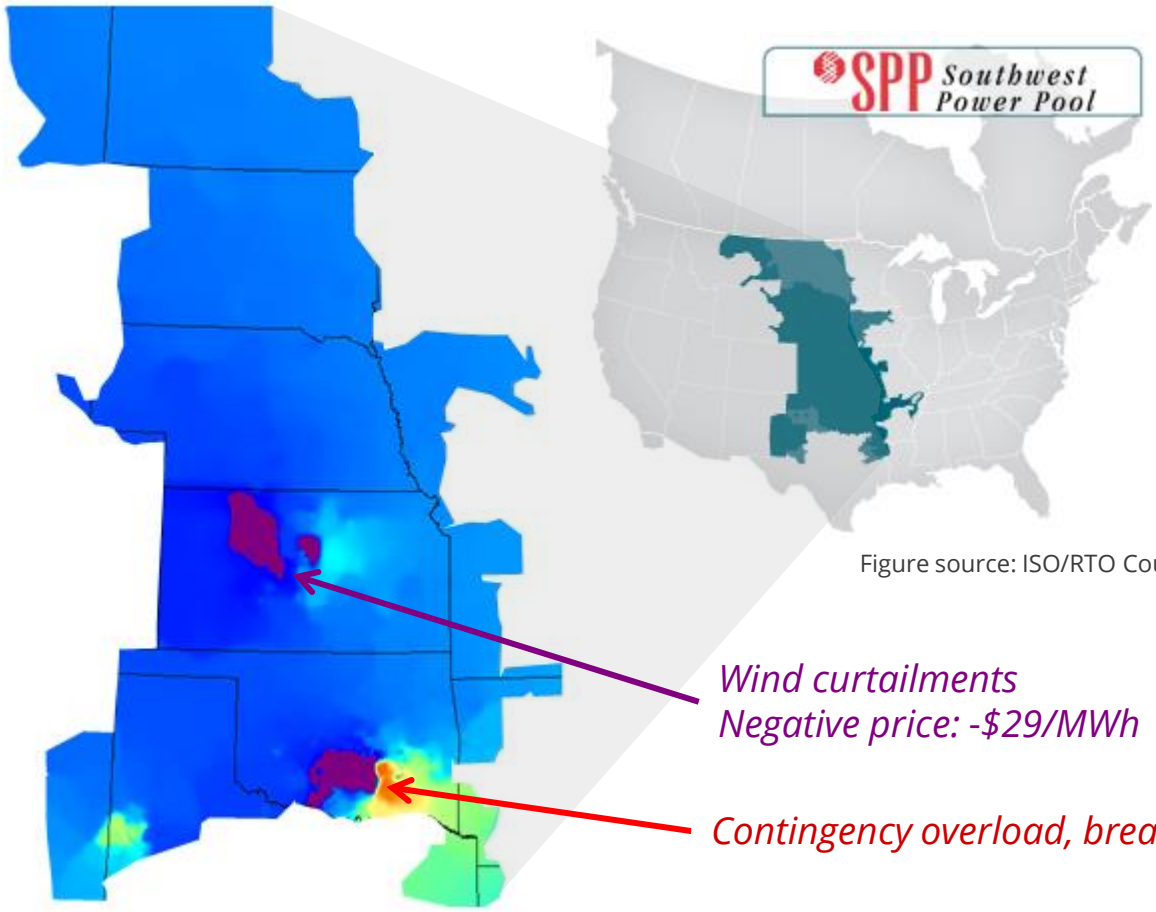


Figure source: ISO/RTO Council

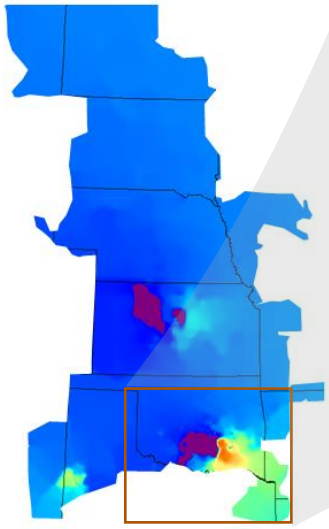
* Source: Southwest Power Pool State of the Market 2017, published May 8, 2018.

Background

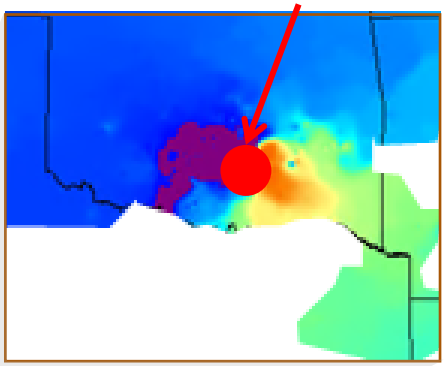
Transmission Topology Optimization Software

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

Power Prices
March 10, 2018, 20:10 CST



Historical Condition
Congestion + Breach

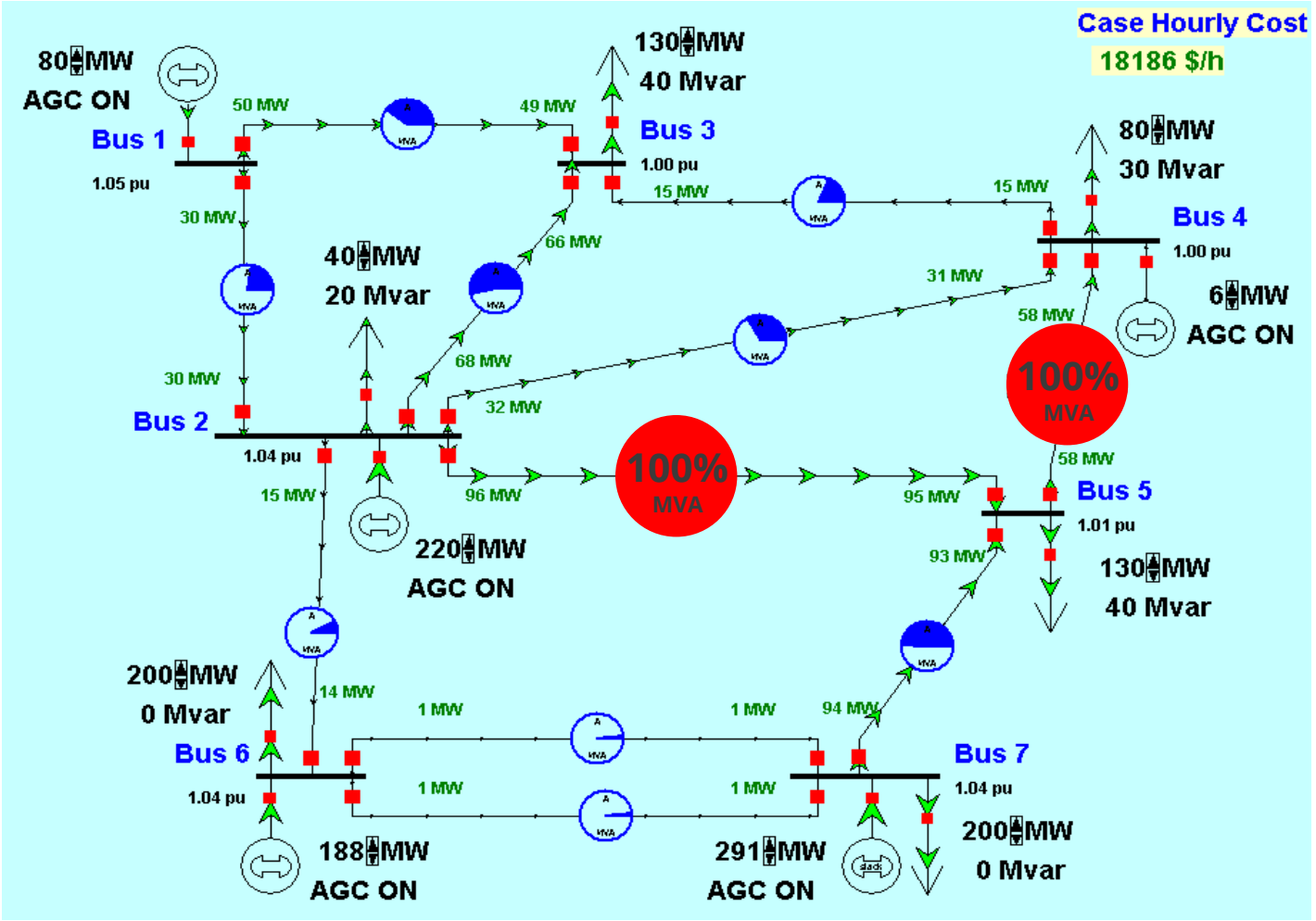


NewGrid Router

“Open Circuit Breakers X and Y”

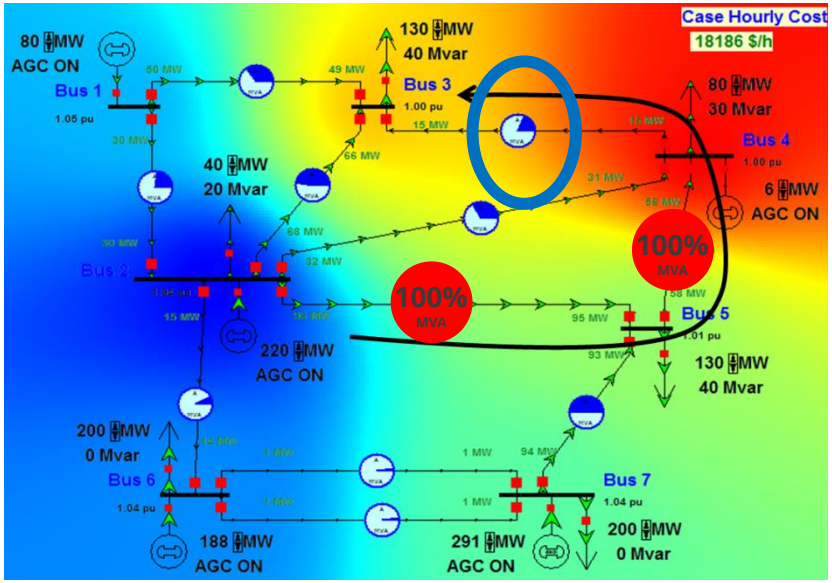
With Reconfiguration
Flow Diverted
No Congestion or Overload

7-bus Example: All Lines Closed



7-bus Example Results: Before and After

Before: all lines Closed



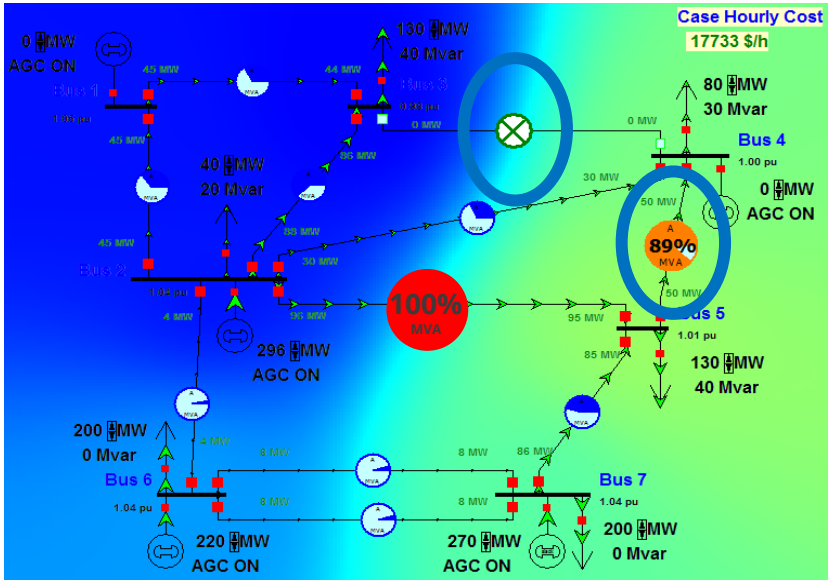
Generation	All lines closed	Line 3-4 open
Bus 1	80 MW	0 MW
Bus 2	220 MW	296 MW
Bus 4	6 MW	0 MW
Bus 6	188 MW	220 MW
Bus 7	291 MW	270 MW
Total	785 MW	786 MW

$40/MWh

$15/MWh

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

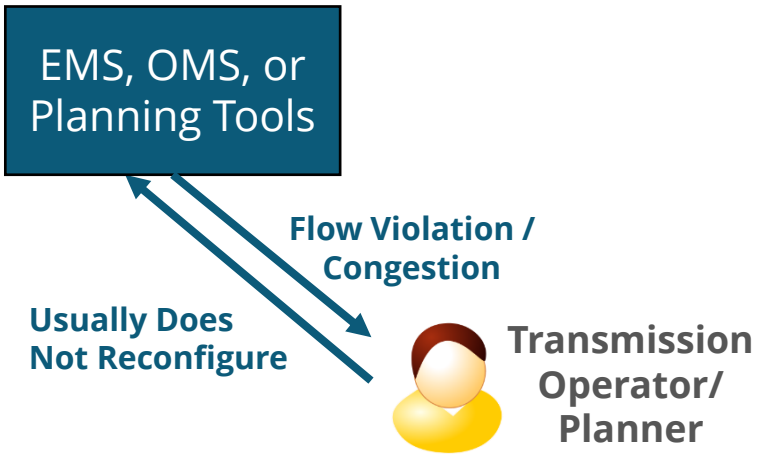
After: line 3-4 Opened



Reconfiguration Practice

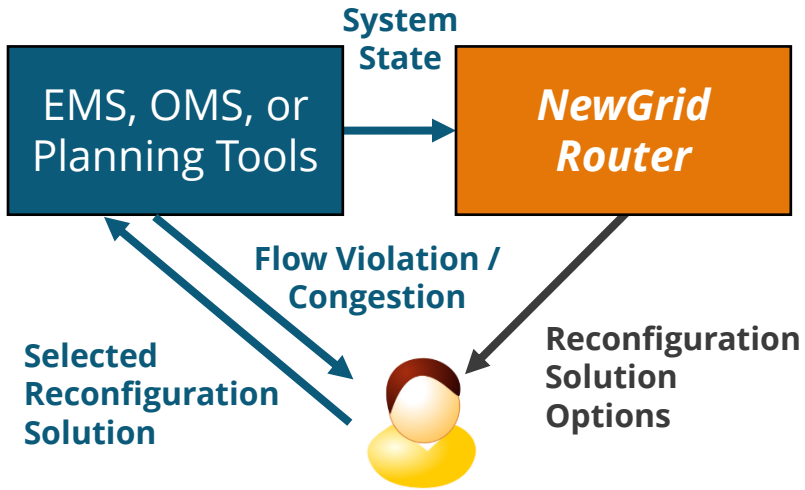
Traditional/Today

- 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

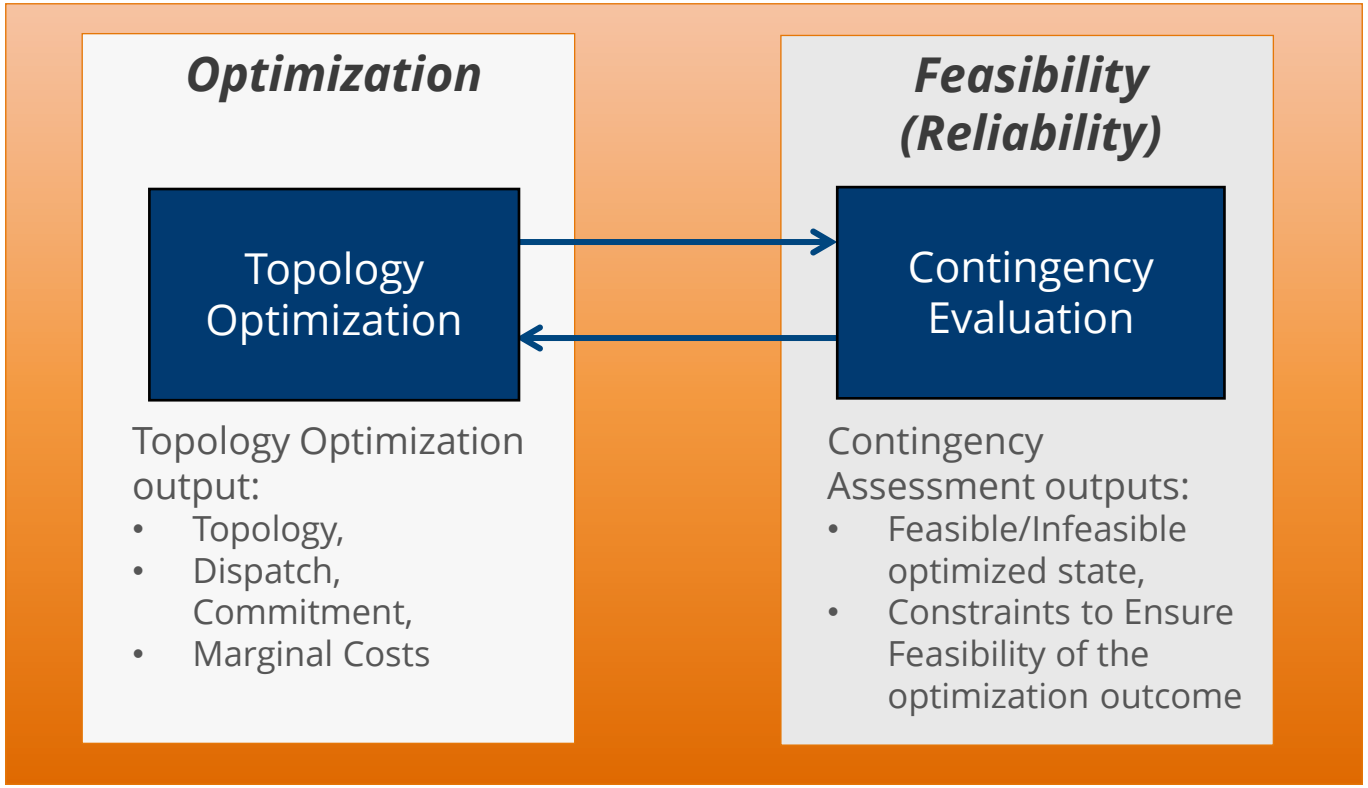


Topology Optimization Software

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



Project Objectives

We evaluated the effectiveness of topology optimization in SPP for three different applications.

- *Track 1* – Operations and Operations Planning.
  - Outage Coordination: development of Op. Guides.
  - 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.

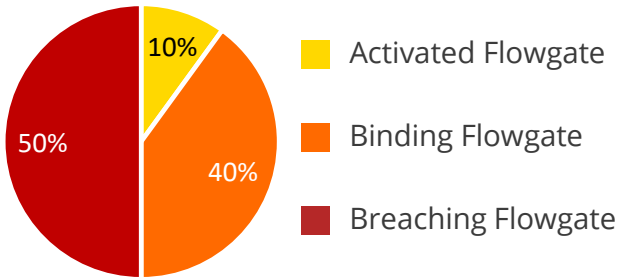
- Constraint Flow Relief:
  - SPP Operations selected a set of recent historical real-time snapshots of the SPP system in which a constraint of focus was binding or breaching.
  - NewGrid Router identified a few reconfiguration options to relieve the focus constraints while:
    - Keeping the dispatch 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.

Focus Constraints Statistics

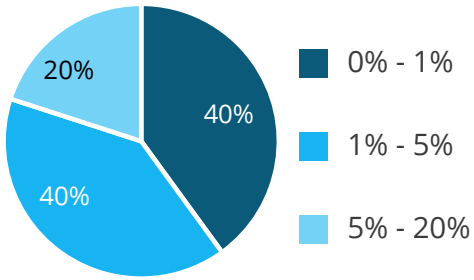
SPP selected 17 focus constraints on 20 cases to show a representative set of complex transmission system conditions.

- 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.

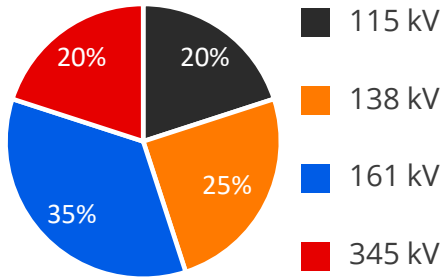
Focus Congestion Event Type



Focus Constraint Real-Time Binding Frequency (April 2017-2018)



Focus Monitored Facility Nominal Voltage



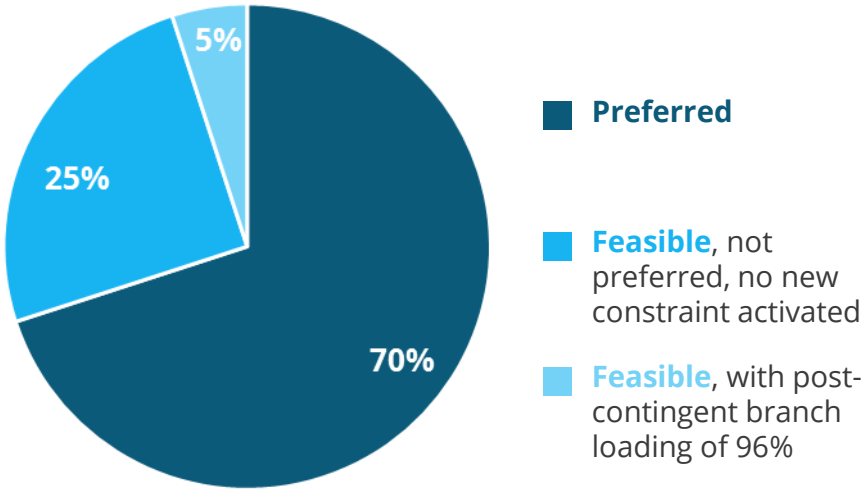
[1] For more details, see Kathryn Dial, *SPP Winter Peak 1/17/18*, presented at SPP ORWG Meeting, 4/4/18, [online] https://www.spp.org/Documents/56710/ORWG%20Meeting%20Materials%204-04-18.zip.

[2] https://www.spp.org/about-us/newsroom/spp-sets-wind-and-renewable-penetration-records/

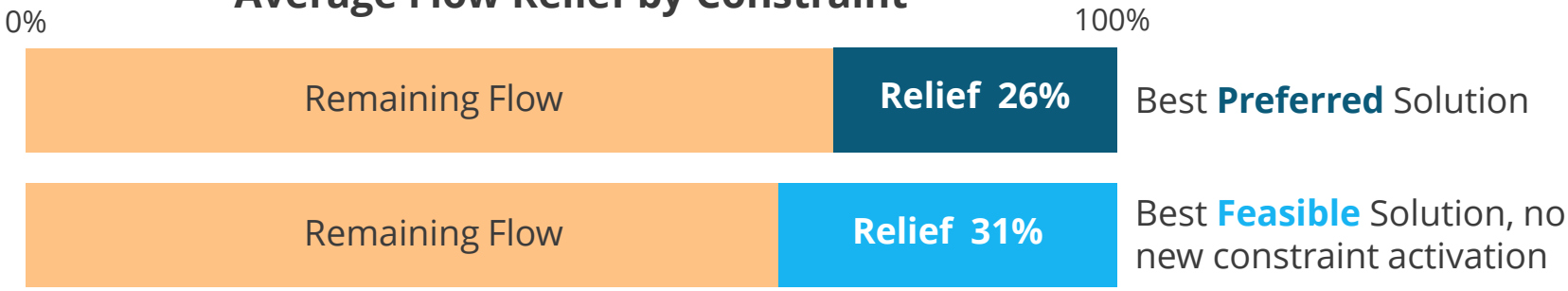
Solution Validation, Flow Relief Performance

- **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

Best Solution by Constraint



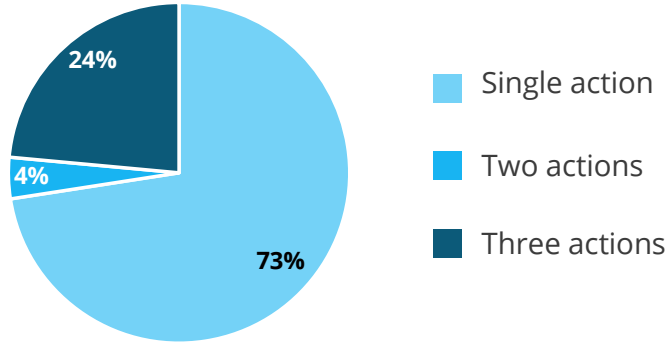
Average Flow Relief by Constraint



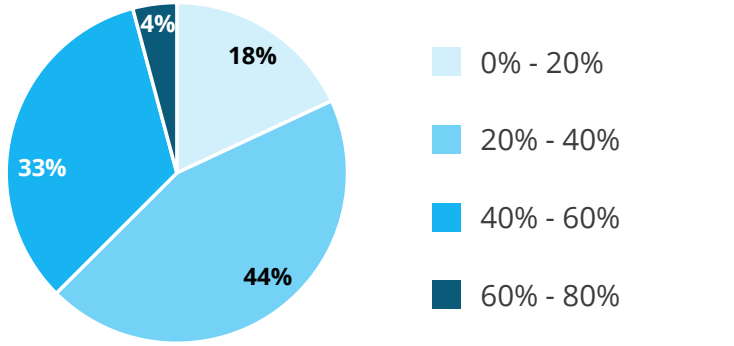
Feasible Solution Characteristics

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

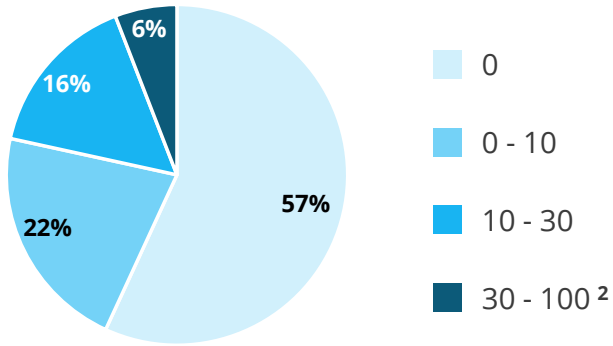
Number of Switching Actions



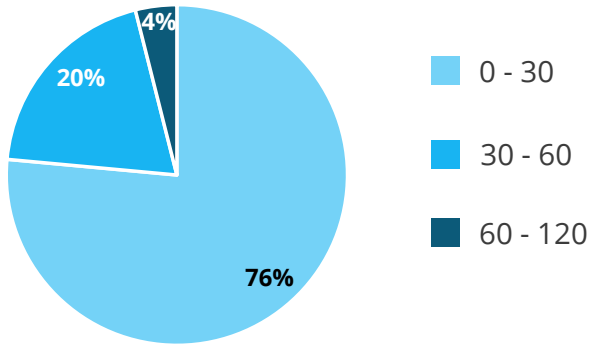
Flow on Opened Branches as % of Normal Rating



Load Radialized (MW)



Solution Search Times¹ (seconds)

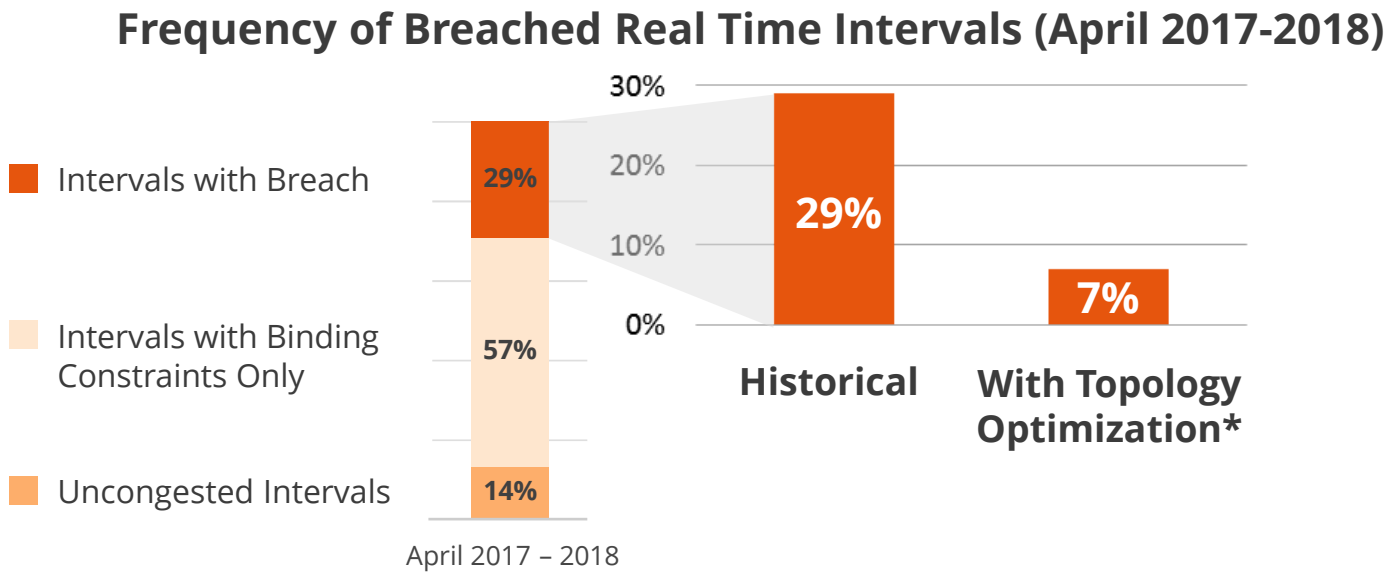


¹ Search performed on a commercial off-the-shelf server.
² Solutions with more than 30 MW load radialized were found before SPP indicated the preferred 30 MW threshold.

Reliability 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.



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.*

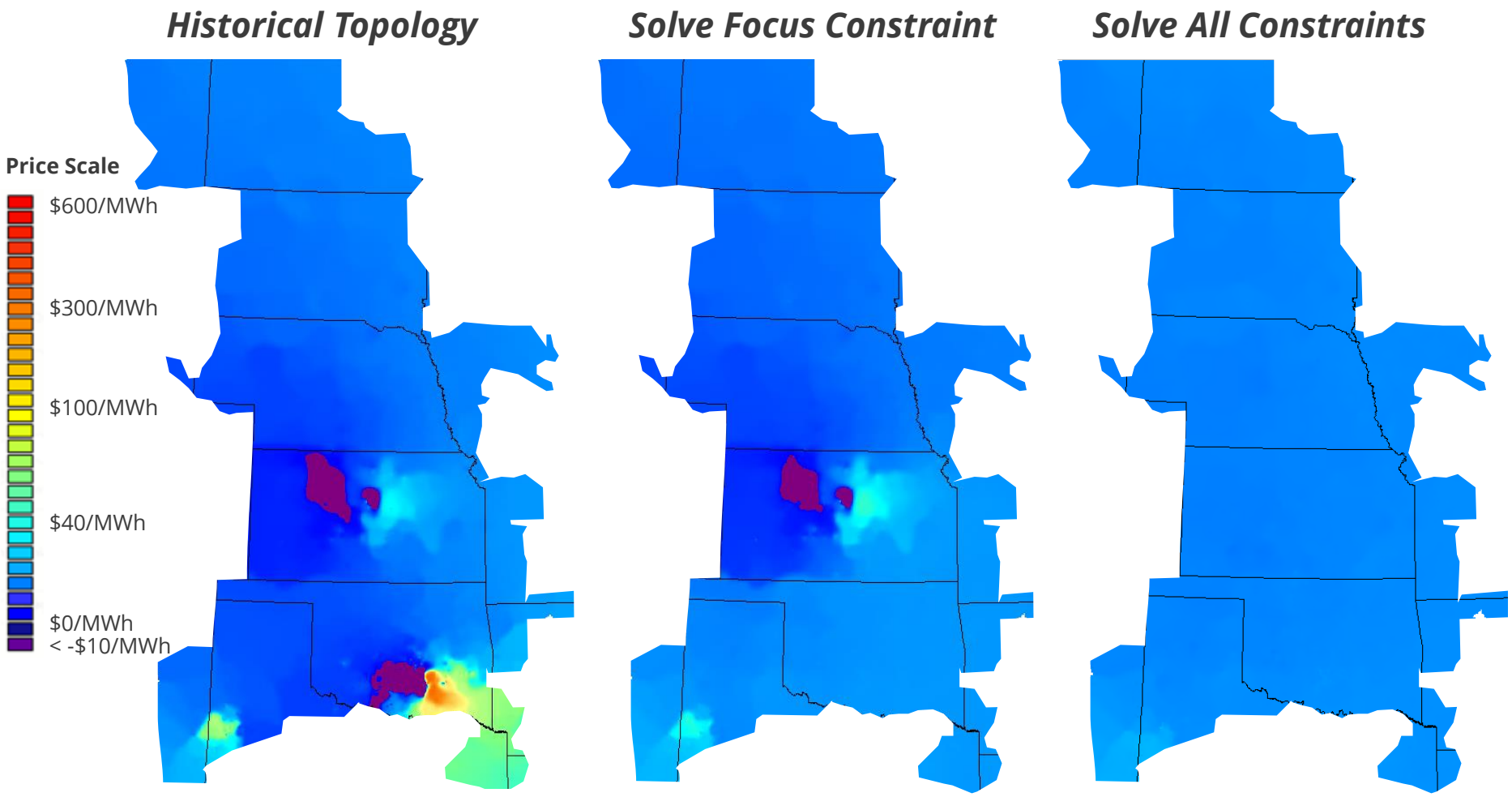
Market Simulation Methodology

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.

Price Contours w/ Reconfigurations Example

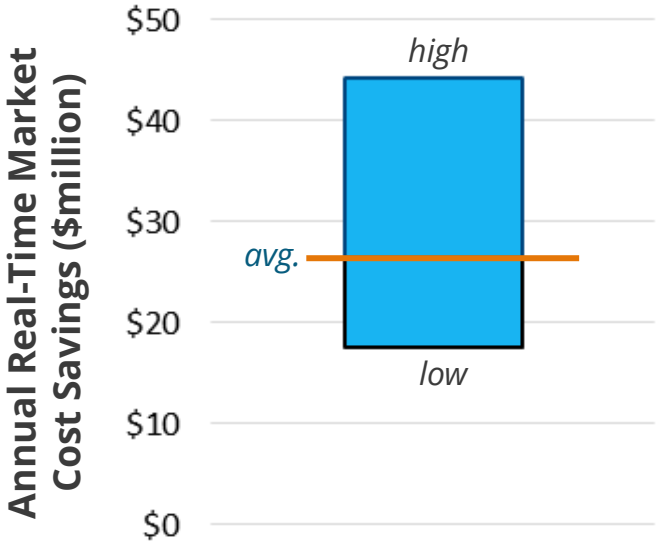
03/10/2018 20:10, TUPLOTP4 – TUPELO2 138 kV (flo) PITTSB9 – VALLIANT 345 kV



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.*

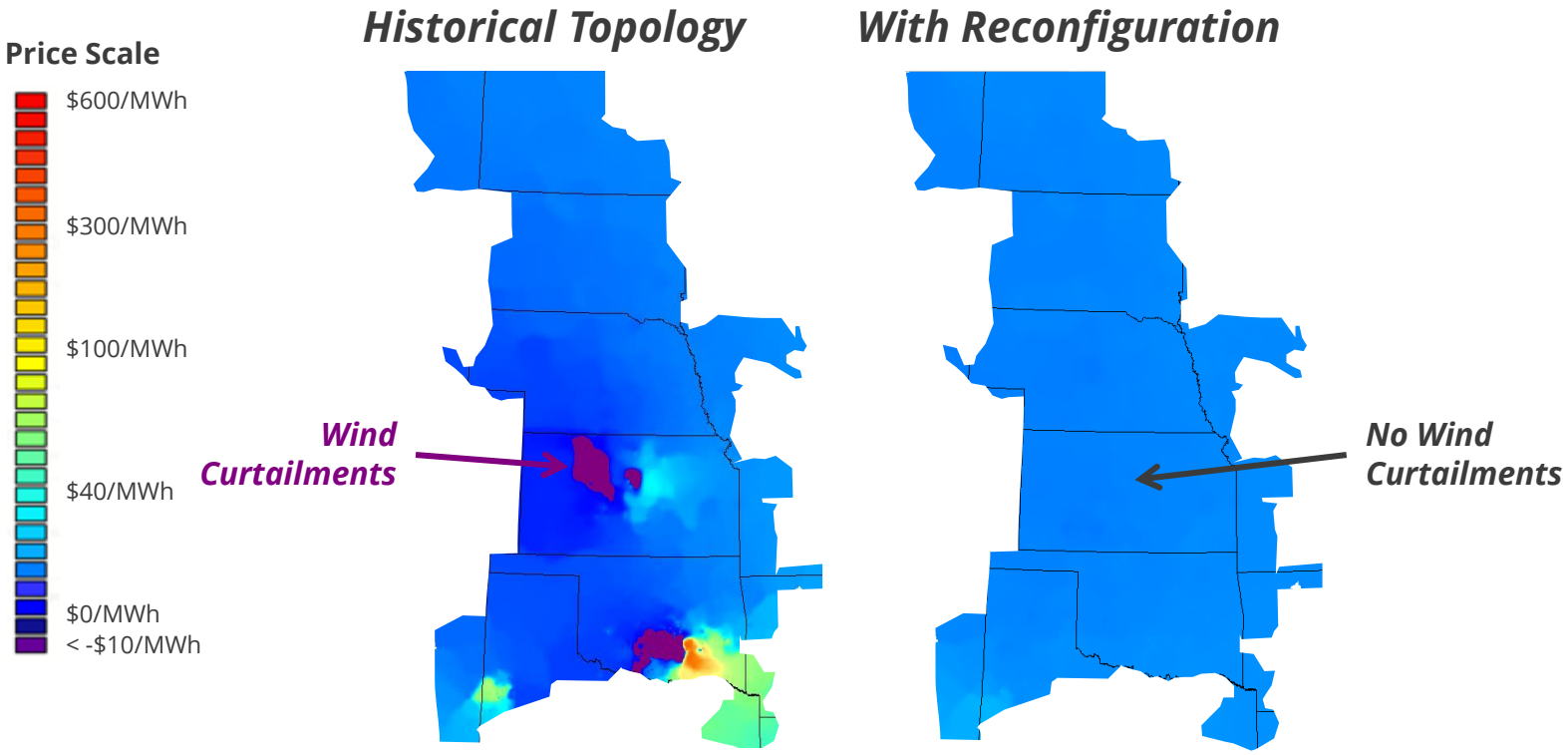


* *In the study of the 20 selected historical constraints, 95% of them were relieved with topology optimization.*

Reduced Wind Curtailments

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

Avoiding Consequential Load Loss in 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.

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

Avoiding Consequential Load Loss in Planning

We found corrective reconfigurations that *relieve the violations without load shedding* and without causing other violations.

Case Study Type	Flow on Violated Branch		Avoided Load Loss	No. of Actions	No. of New Constraints			Radialized Load
	Initial [% of Rating]	With Solution [% of Rating]	[MW]		>95% flow	>100% flow	<0.9 pu volt	[MW]
P6 Event	**129%**	**86%**	243	2	1	0	0	65
P7 Event	**107%**	**94%**	55	2	0	0	0	0
Extreme Event	**113%**	**97%**	151	1	0	0	0	0

* 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).
  - 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 CAPs based on reconfigurations fully avoid load shedding for the severe events selected by SPP.

Contact

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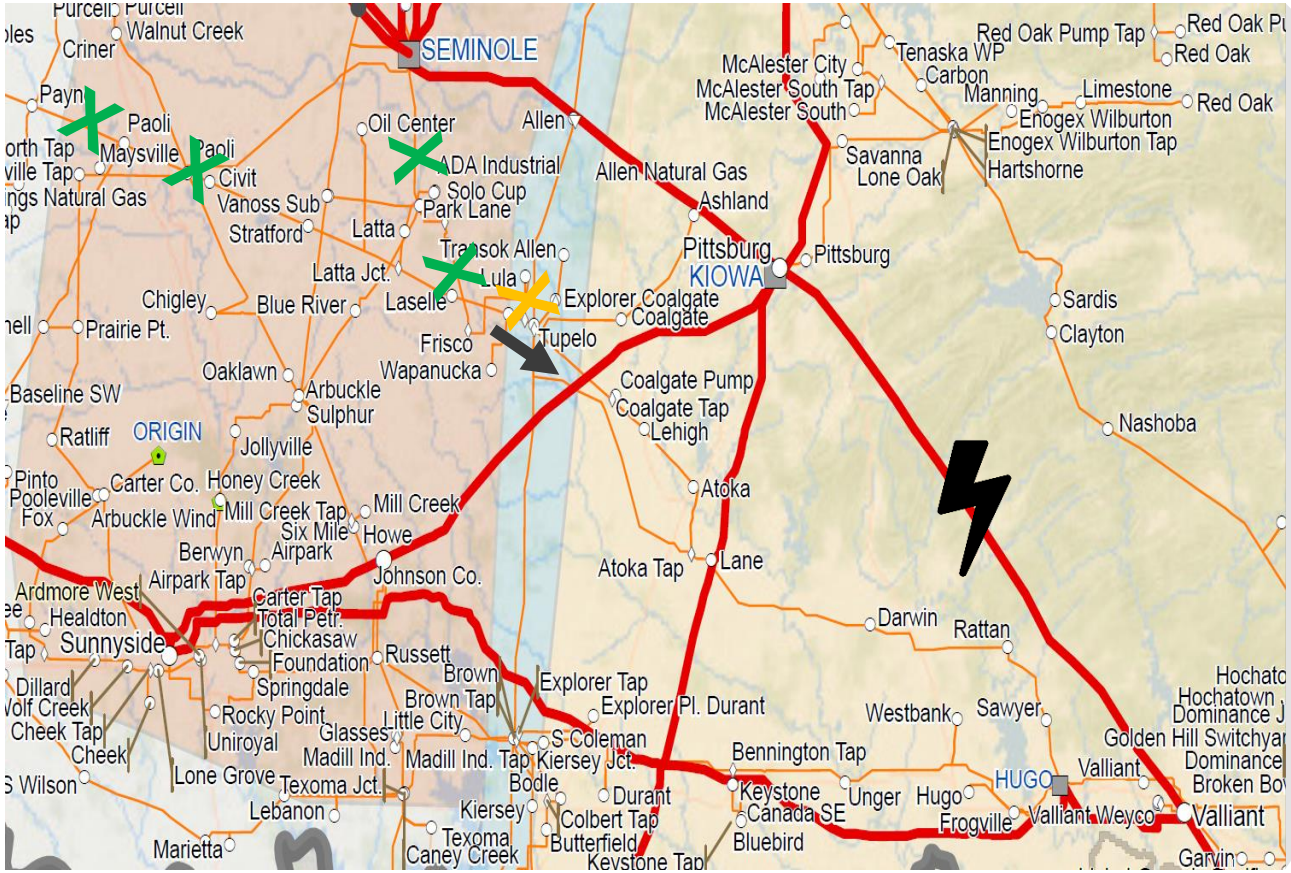
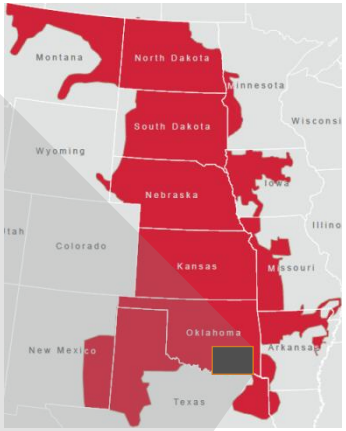
Highlighted Example Historical Snapshot

- 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

Single-Action Solutions





Contingency

Constraint

X Feasible, Single-Action Solution

X Single-Action Solution w/ post-contingency voltage violation/s

Other Constraints and Their Solutions

- 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)

[1] P. A. Ruiz *et al*, "Transmission topology optimization: performance and benefit assessment in SPP Operations and Operations Planning," presented at *SPP Operating Reliability Working Group Meeting*, Little Rock, AR, May 2018. [Online] https://www.spp.org/Documents/57991/ORWG%20Meeting%20Materials%205-30-18.zip

[2] P. A. Ruiz, "Power Flow Control Through Topology Optimization Software: Applications and Case Studies," presented at IEEE PES Transmission & Distribution Conference and Expo, Denver, CO, April 2018.

[3] P. A. Ruiz, "Transmission topology optimization: operations and market applications and case studies," presented at *ERCOT Demand Side Working Group Meeting*, Austin, TX, Nov 2017. [Online] http://ercot.com/content/wcm/key_documents_lists/127739/PRuiz_ERCOT_DSWG_FINAL.pdf

[4] National Grid Electricity Transmission Network Innovation Allowance Annual Summary 2016/2017, Jul 2017, page 14. [Online]https://www.nationalgrid.com/sites/default/files/documents/National%20Grid%20Electricity%20Transmission%20NIA%20Annual%20Summary%202016-17.pdf

[5] National Grid, Network Innovation Allowance Closedown Report, Transmission Network Topology Optimisation, project NIA_NGET0169, Jul 2017. [Online] http://www.smarternetworks.org/project/nia_nget0169/documents

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[7] P. A. Ruiz, "Transmission topology optimization software: operations and market applications and case studies," presented at *SPP Technology Expo*, Little Rock, AR, Nov 2016. [Online] https://www.spp.org/Documents/45058/Tech Expo 11 14 16 Agenda & 20Presentations.zip

[8] P. A. Ruiz *et al*, "Transmission topology optimization: simulation of impacts in PJM day-ahead markets," at *FERC Tech Conf on Increasing Market Efficiency through Improved Software*, Docket AD10-12-007, Washington, DC, June 2016.

[9] P. A. Ruiz, E. A. Goldis, A. M. Rudkevich, M. C. Caramanis, C. R. Philbrick, and J. M. Foster, "Security-constrained transmission topology control MILP formulation using sensitivity factors," *IEEE Trans on Power Systems*, vol. 32, no. 2, Mar 2017, pp. 1597 – 1605.

[10] E. A. Goldis, P. A. Ruiz, M. C. Caramanis, X. Li, C. R. Philbrick, A. M. Rudkevich, "Shift factor-based SCOPF topology control MIP formulations with substation configurations," *IEEE Trans. on Power Systems*, vol. 32, no. 2, Mar 2017, pp. 1179 – 1190.

Appendix 2

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