Transmission Topology Optimization

CONGESTION RELIEF IN OPERATIONS AND OPERATIONS PLANNING

PREPARED BY

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THE Brattle GROUP

newgrid

SPP Southwest Power Pool

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

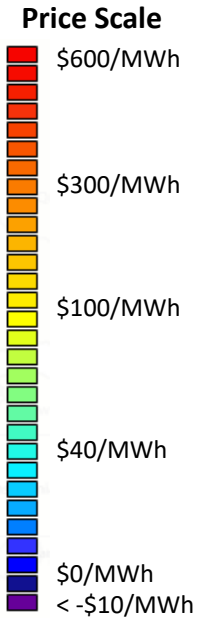
Current Congestion Management Impacts

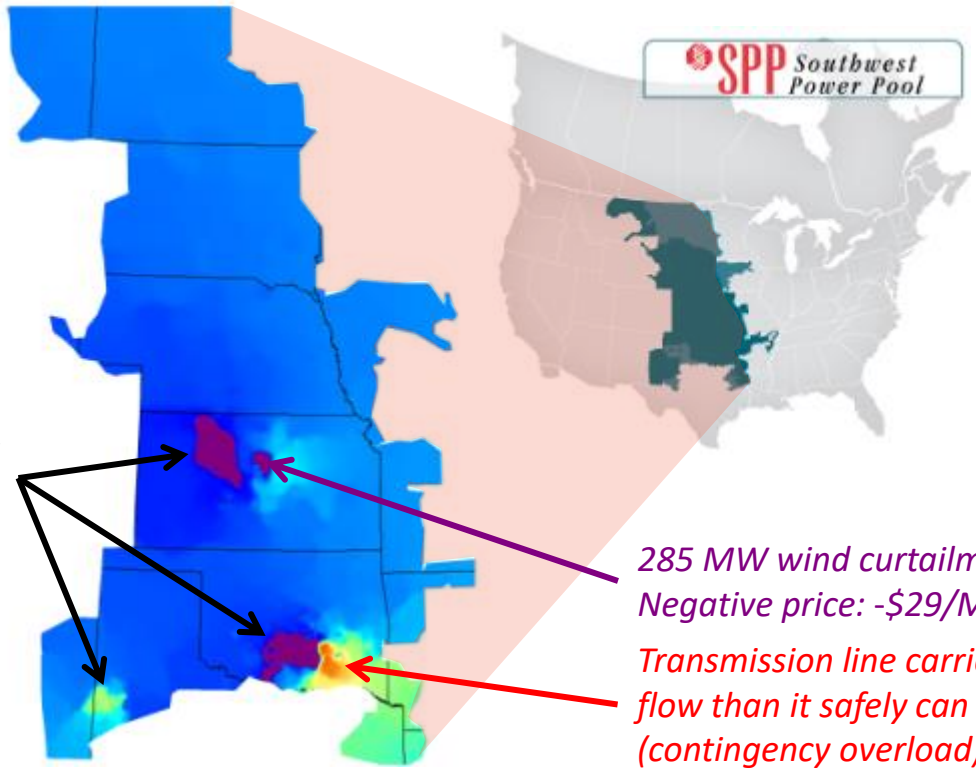
Congestion Impacts in SPP (2017)*

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

Example

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



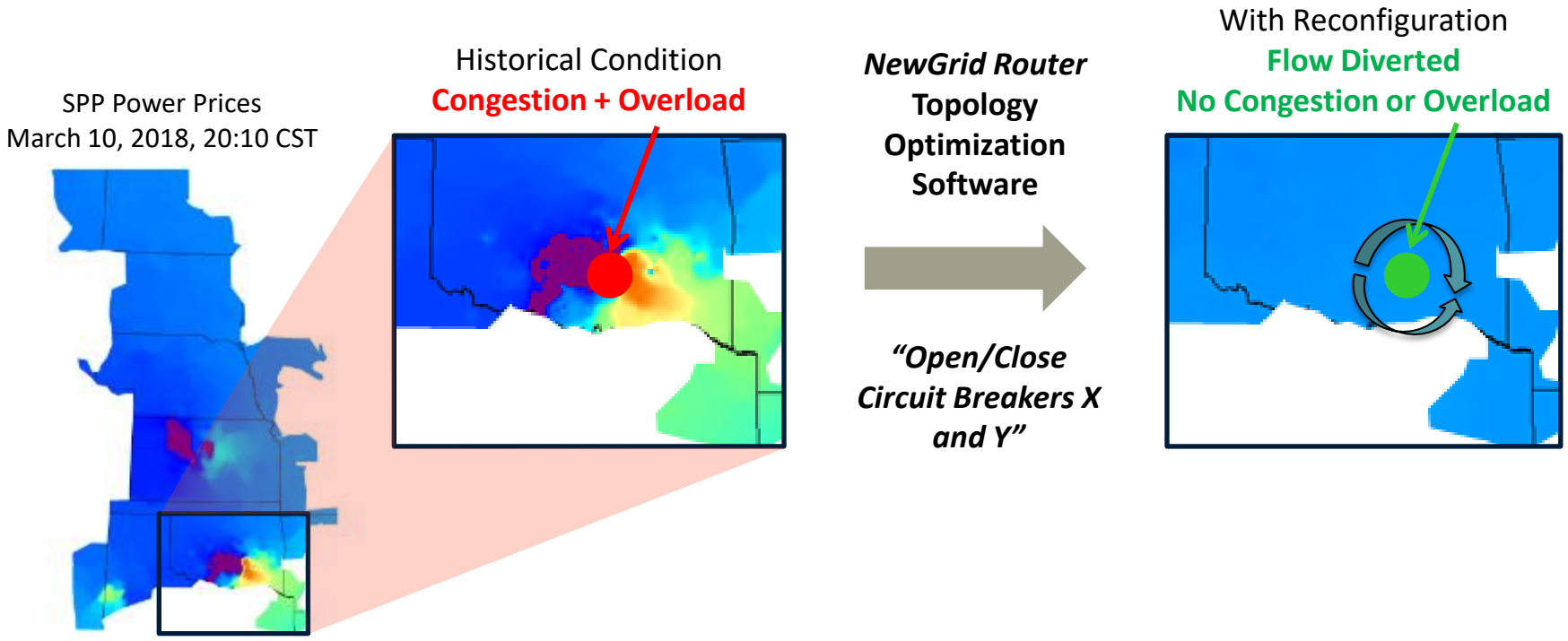


Sources:
Southwest Power Pool State of the Market 2017, published May 8, 2018.
Southwest Power Pool Marketplace Portal, https://marketplace.spp.org/.

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.



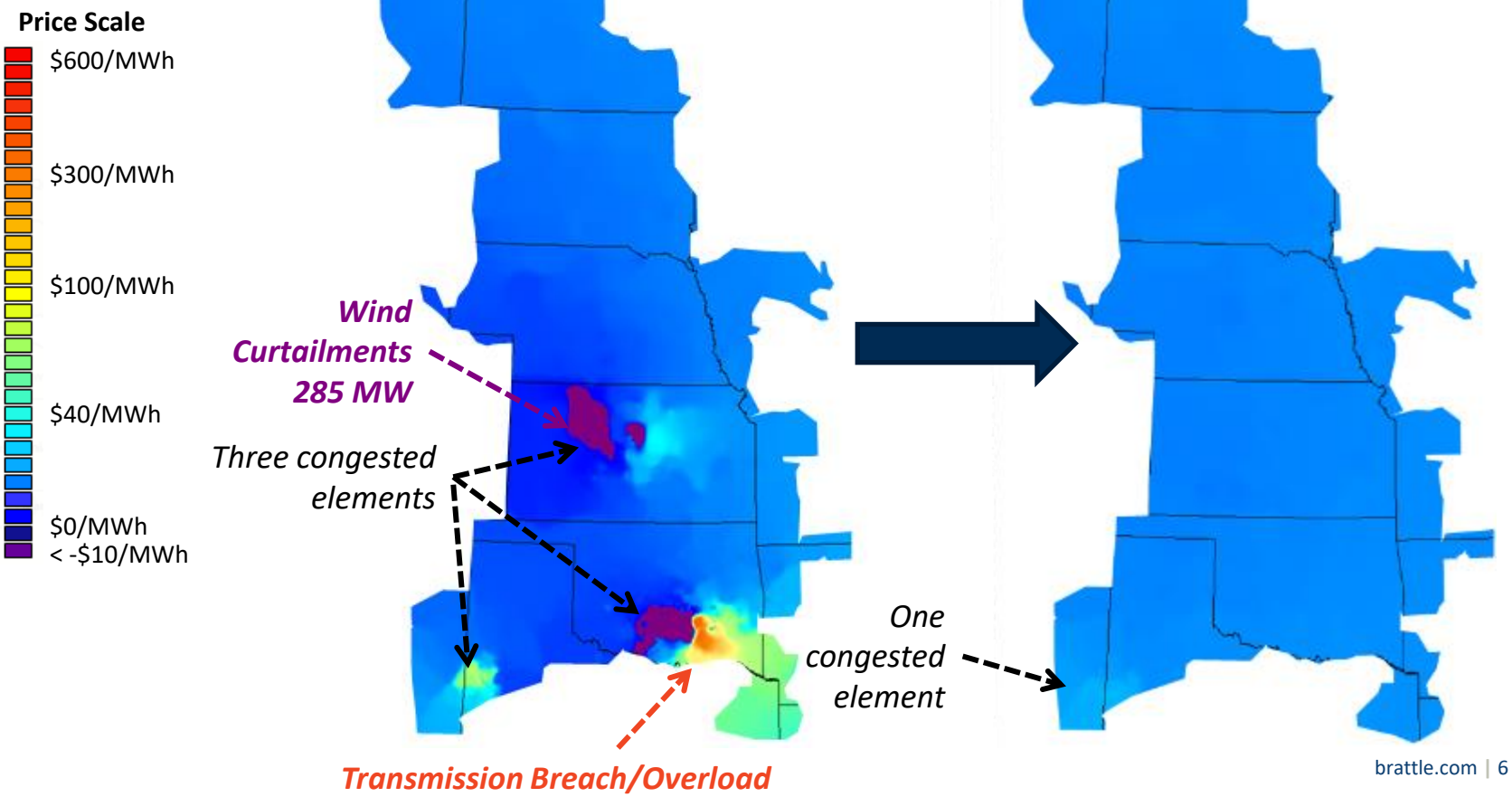
Case Study: Real Time Market, 3/10/18 8pm, 38% Wind Penetration

Congestion, Overload, Wind Curtailment Relief

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

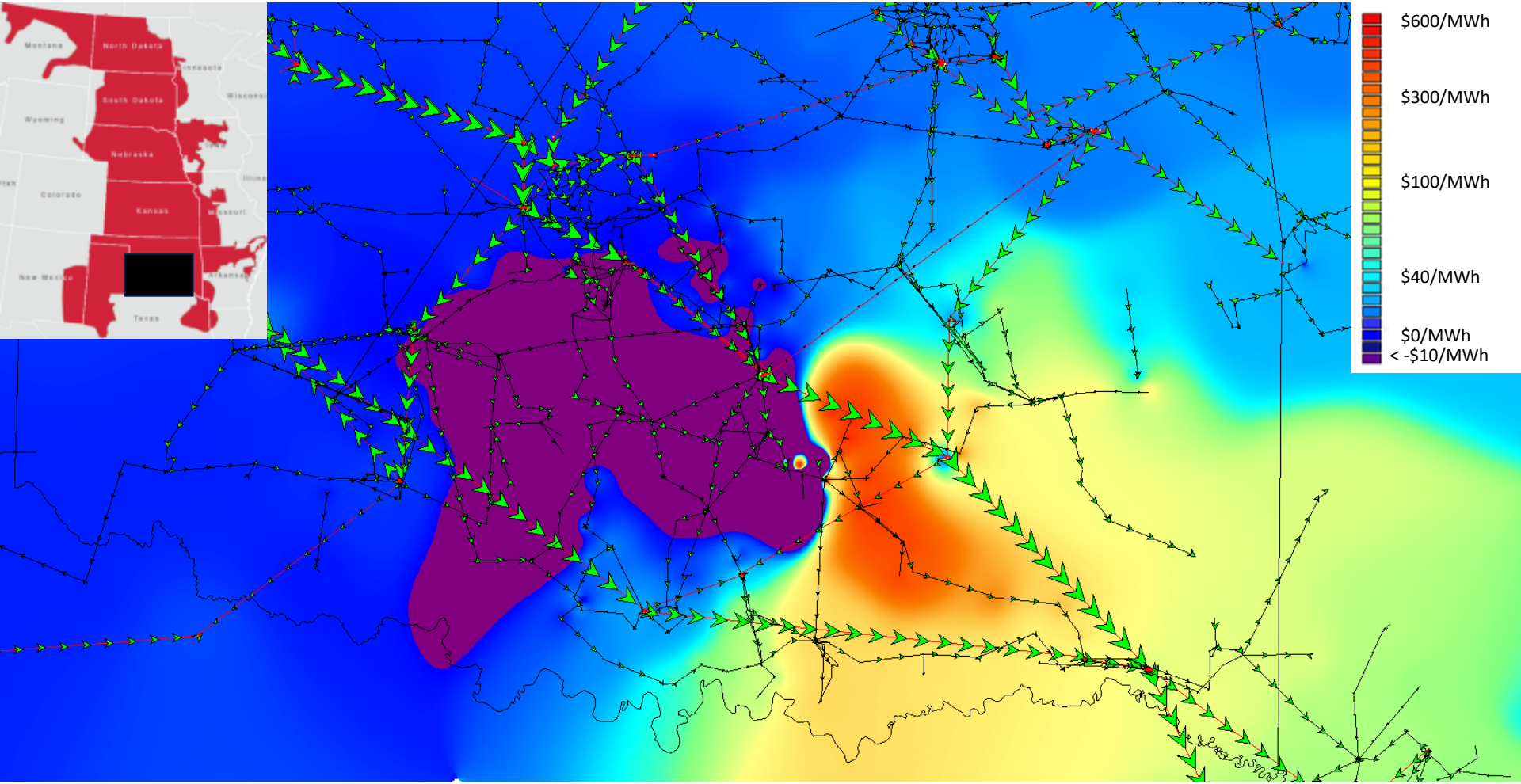
Historical Case
Binding constraints: 3
Shadow prices: **$174 – $984/MWh**
Breached constraints: **one**
Wind Curtailments: **285 MW**

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



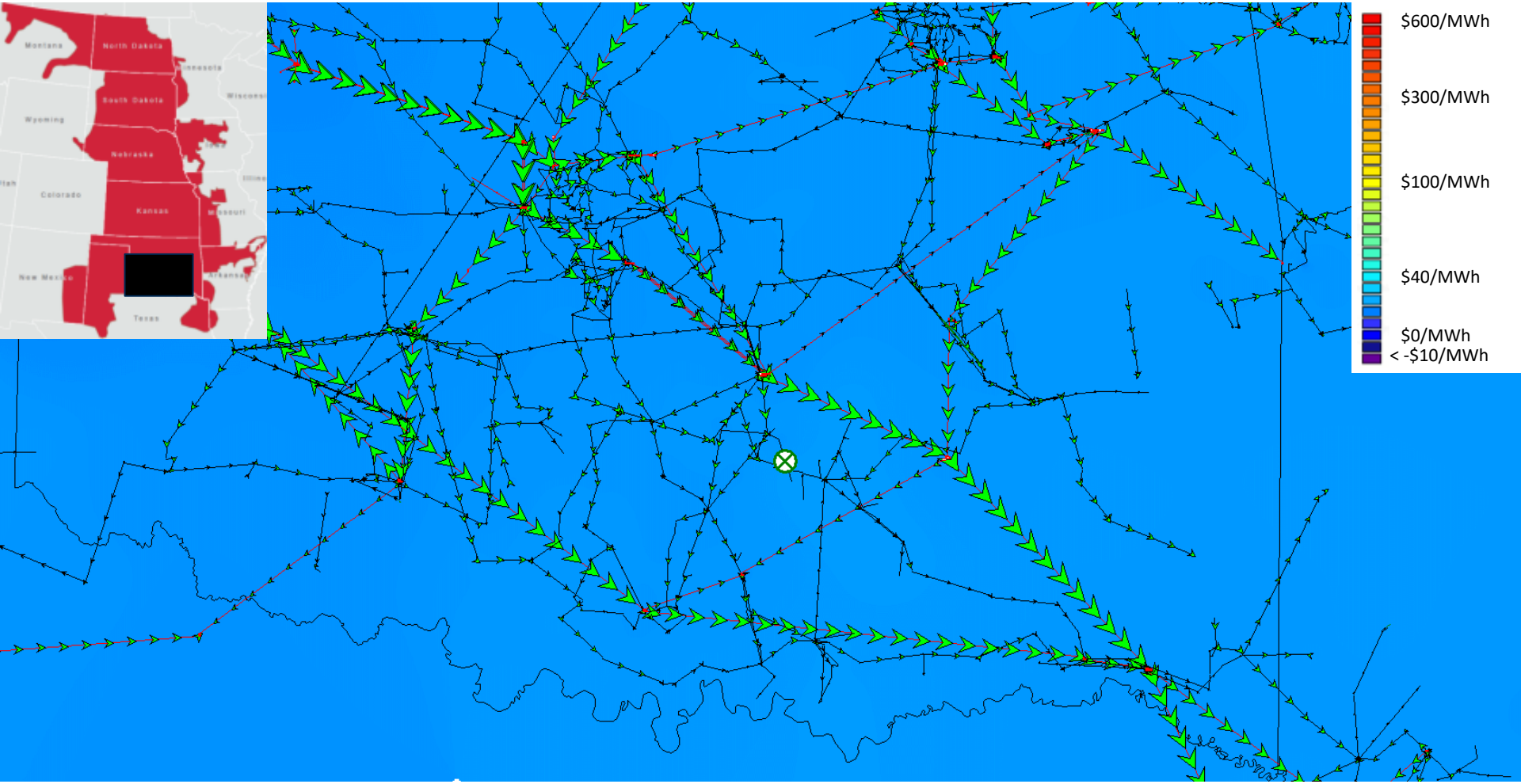
Case Study: Oklahoma, 3/10/18 8pm, 38% Wind Penetration

Historical Configuration: **Congestion, Breach**

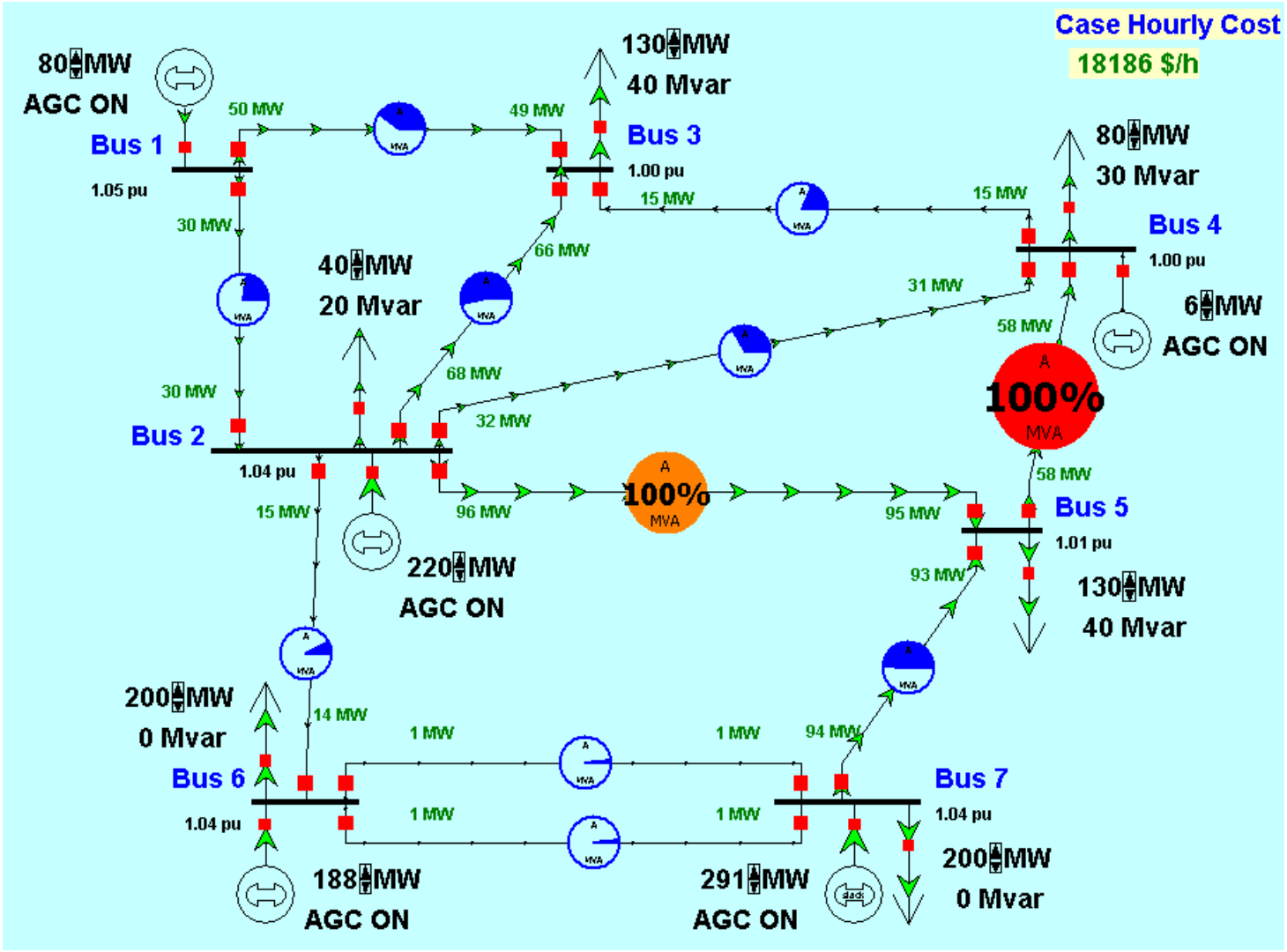


Case Study: Oklahoma, 3/10/18 8pm, 38% Wind Penetration

With Reconfiguration: **No Congestion**

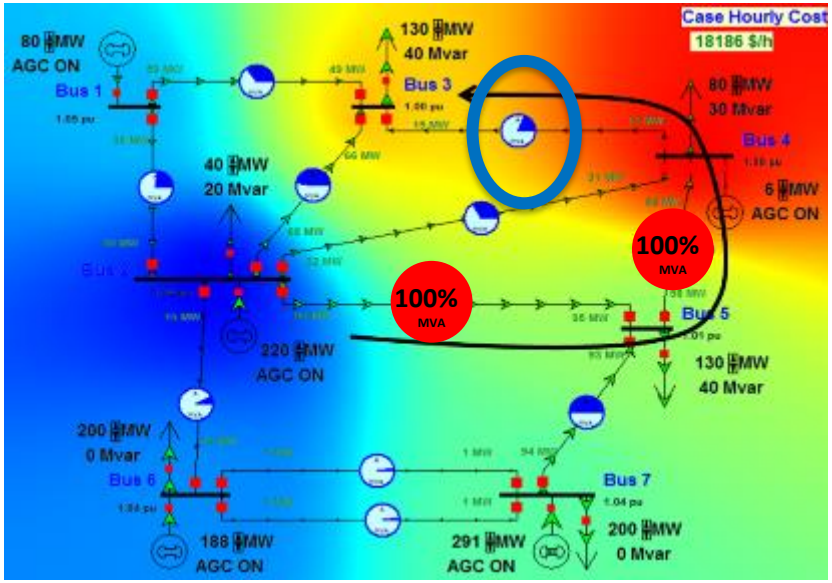


7-Bus Example: All Lines Closed



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

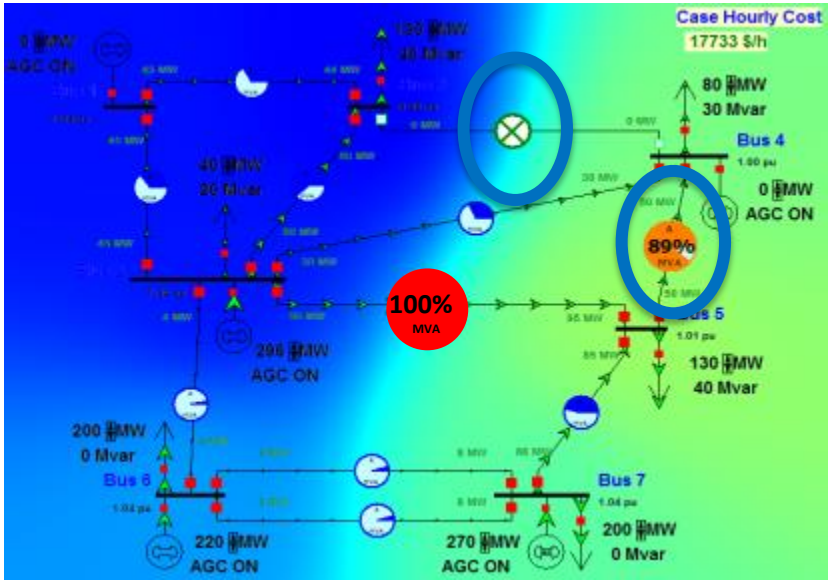
$40/MWh

$15/MWh

Hourly Cost

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

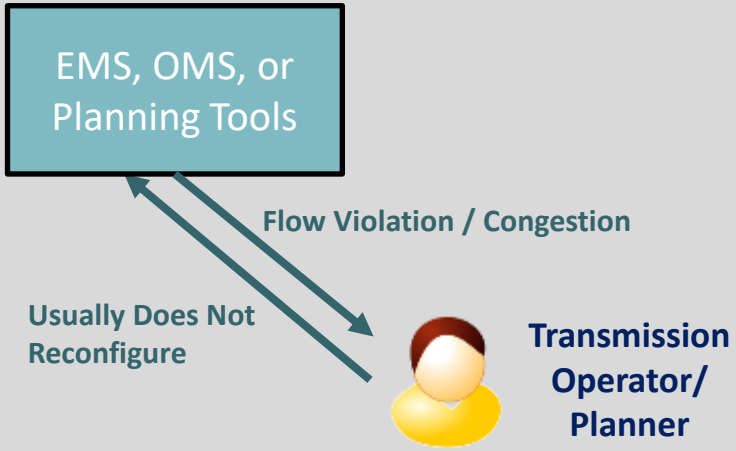
After: line 3-4 Opened



Reconfiguration Practice

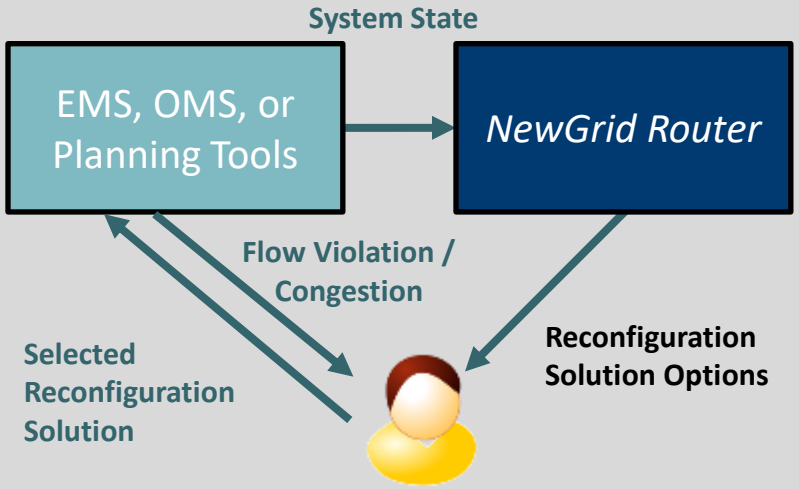
Traditional/Today

- 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

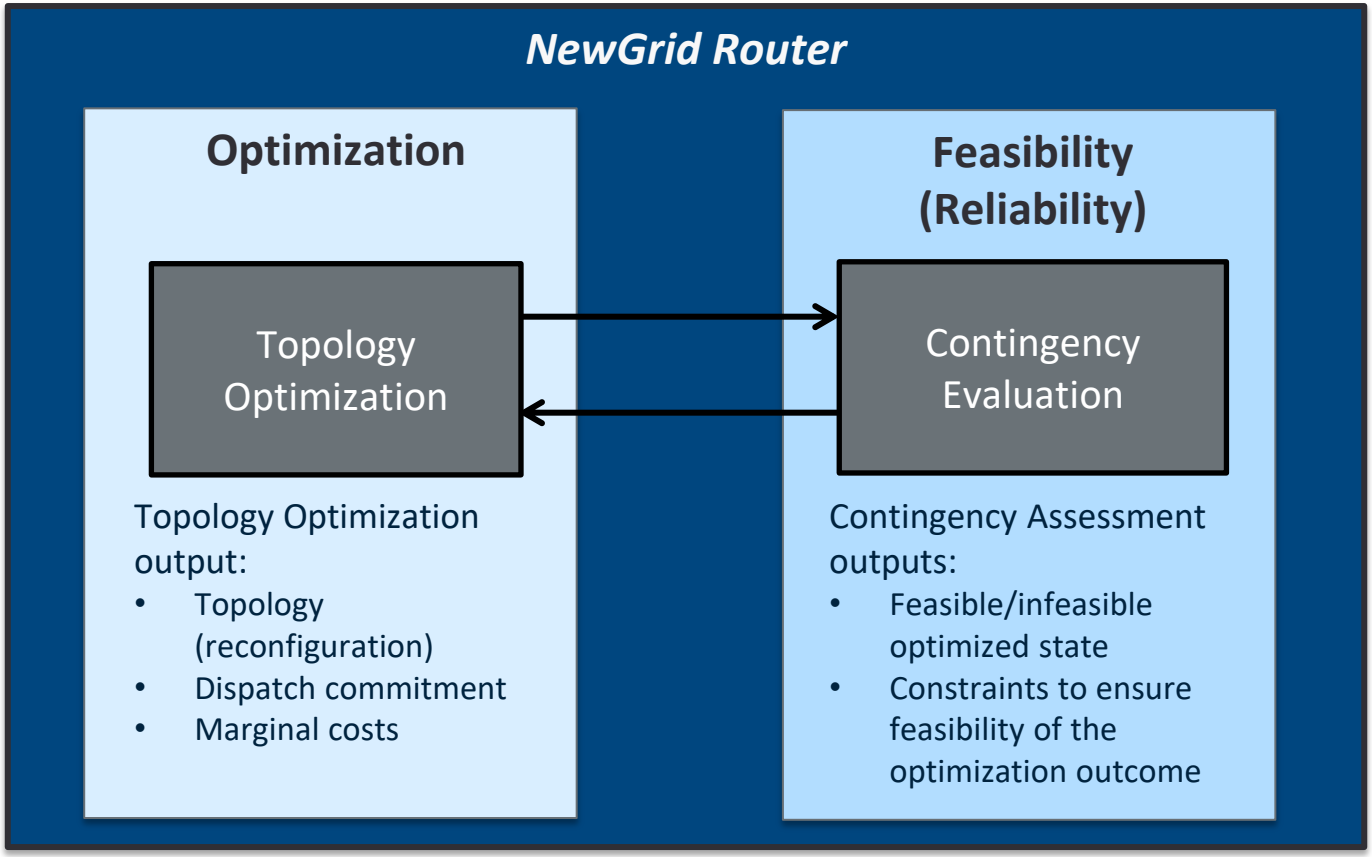


Transmission Topology Optimization Software

- 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.

Reconfigurations Meet N-1 Reliability Criteria

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).



SPP Transmission Topology Optimization Study

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

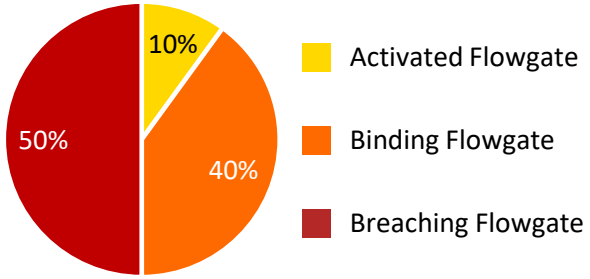
- Constraint Flow Relief:
  - SPP Operations selected a set of recent historical real-time snapshots of the SPP system in which a constraint of focus was binding or breached.
  - NewGrid Router identified a few reconfiguration options to relieve the focus constraints while:
    - Keeping the dispatch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

Constraints Analyzed

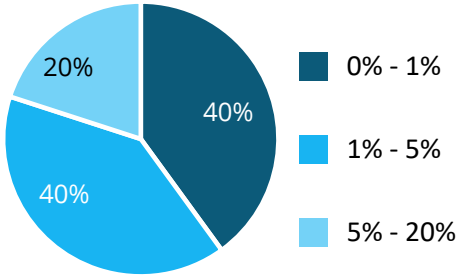
SPP selected 17 focus constraints on 20 cases to show a representative set of *complex* transmission system conditions.

- 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.

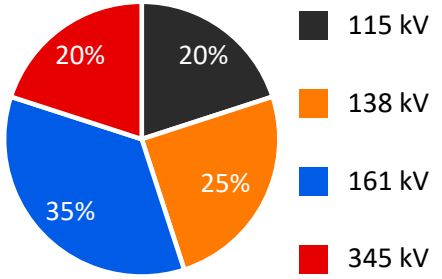
Focus Congestion Event Type



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



Focus Monitored Facility Nominal Voltage

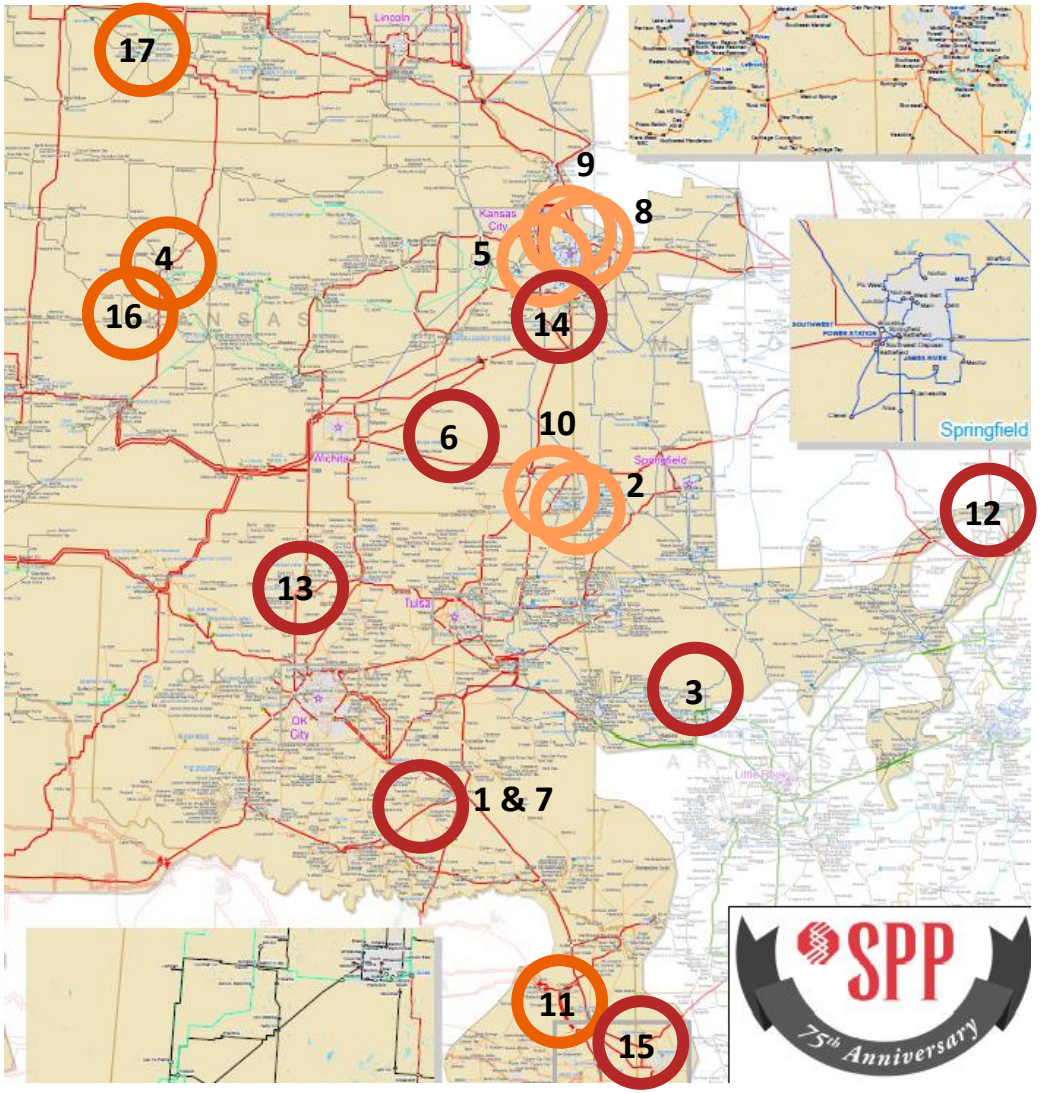


[1] For more details, see Kathryn Dial, *SPP Winter Peak 1/17/18*, presented at SPP ORWG Meeting, 4/4/18, [online] https://www.spp.org/Documents/56710/ORWG%20Meeting%20Materials%204-04-18.zip.

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

Study Inputs

Location of Constraints Analyzed



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 115 KV (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*

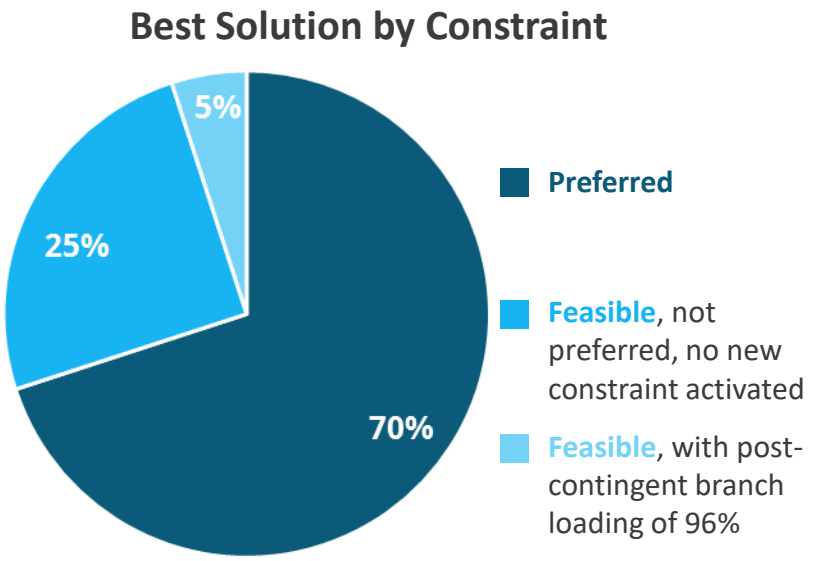
Lightly binding (shadow price $0-150/MW)

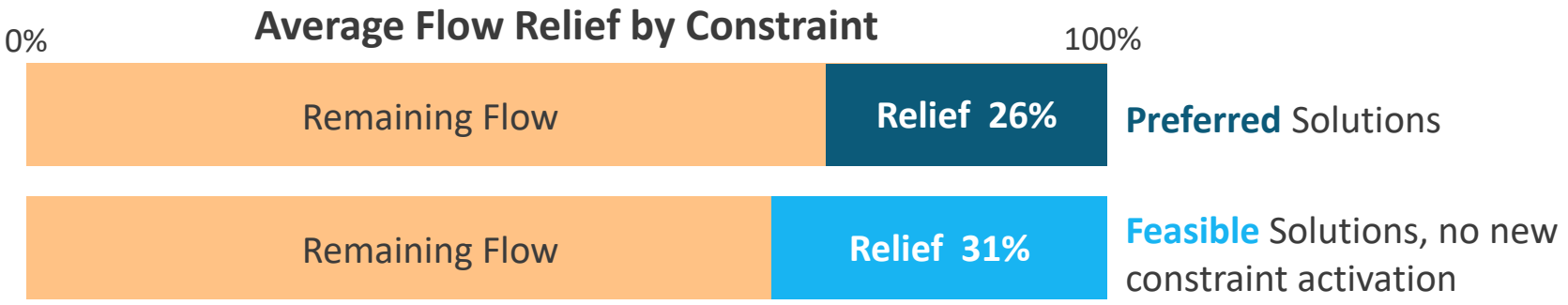
Heavily binding (shadow price $350-750/MW)

Breaching (shadow price $750/MW or above)

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

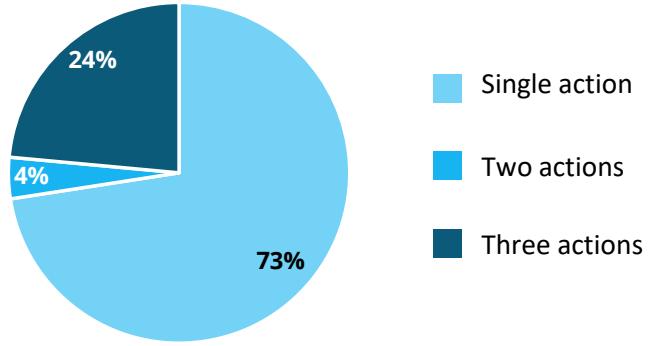




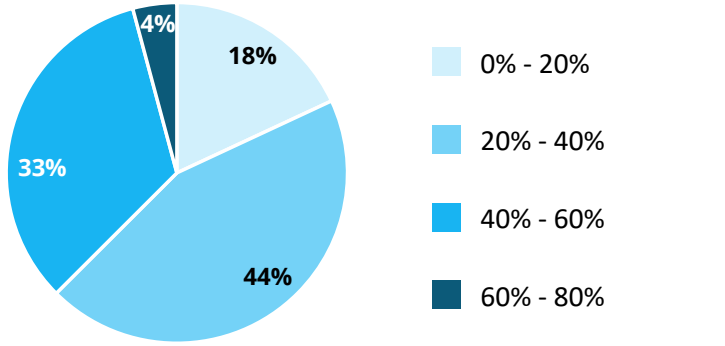
Feasible Solution Characteristics

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

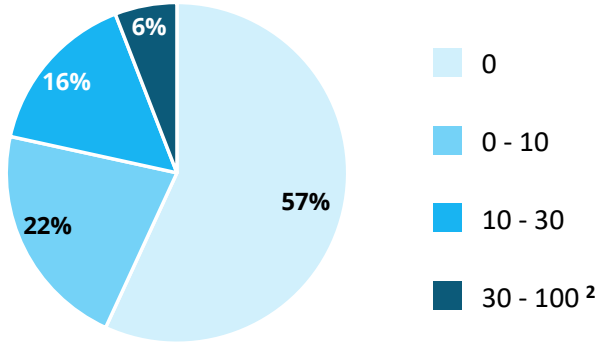
Number of Switching Actions



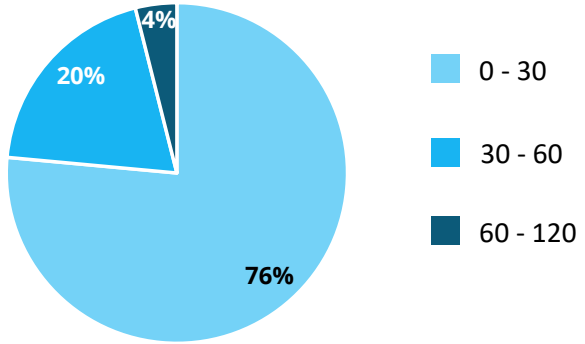
Flow on Opened Branches as % of Normal Rating



Load Radialized (MW)



Solution Search Times[1] (seconds)

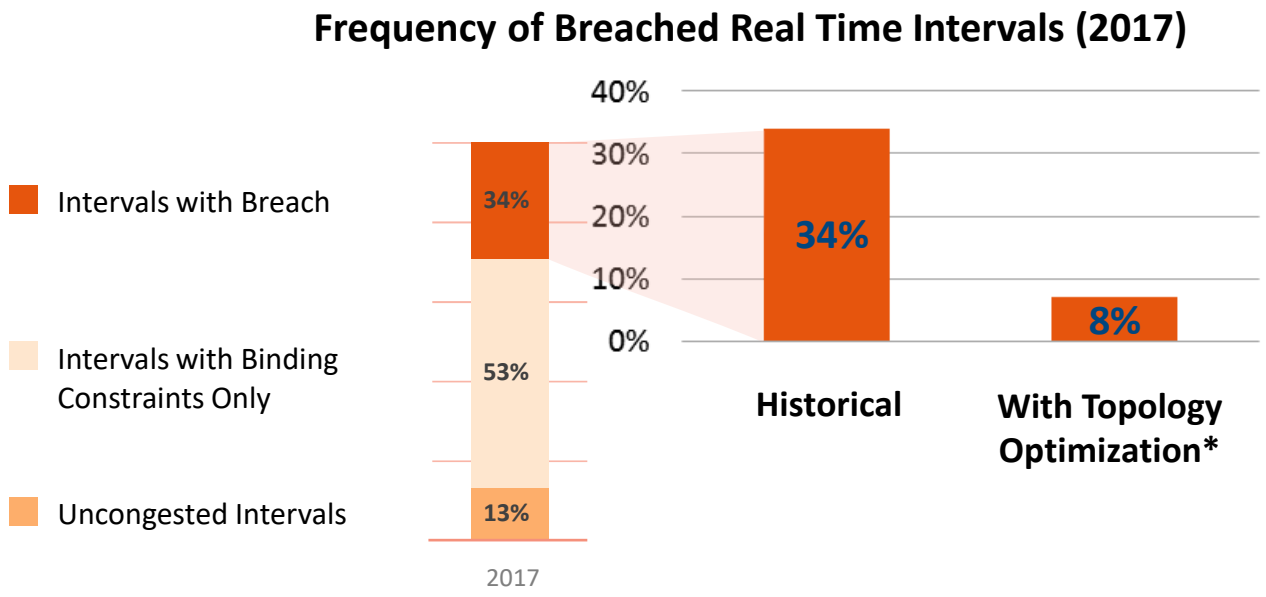


[1] Search performed on a commercial off-the-shelf server.
[2] Solutions with more than 30 MW load radialized were found before SPP indicated the preferred 30 MW threshold.

Reliability Benefits – 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.



Sources:
Historical: SPP State of the Market Report 2017.

* *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

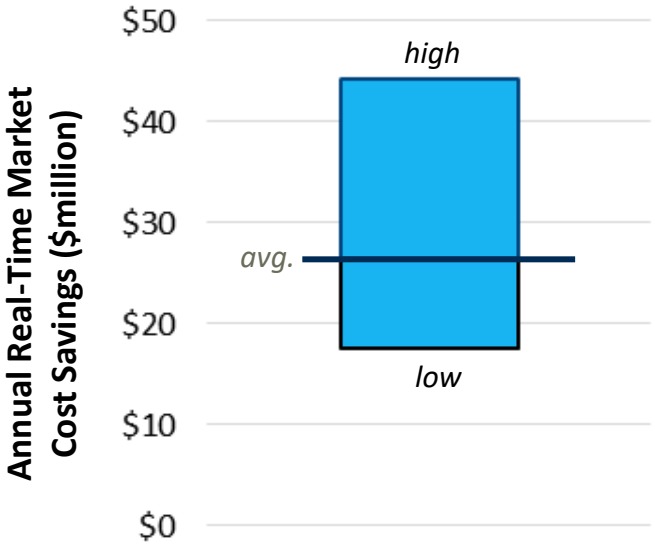
Constraint relief in the previous slides were based on the historical dispatch. We assessed real-time markets savings for four out of the twenty cases selected by SPP.

- 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.

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.

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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.

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

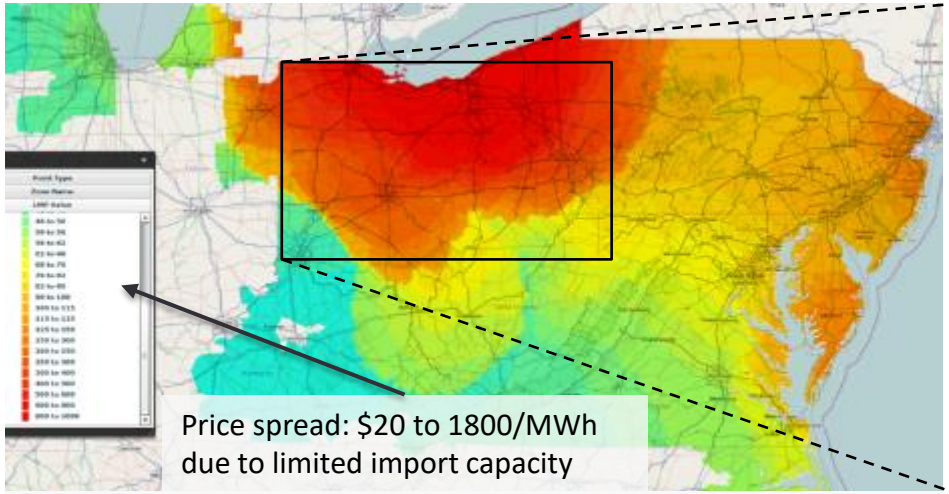
Objectives

- ✓ 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

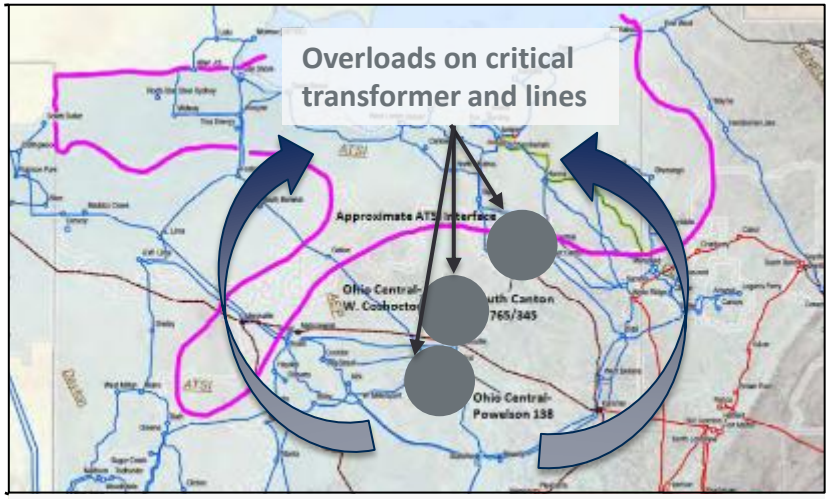
Appendix 1

Increased Grid Resiliance

- 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



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



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

Sources:
National Infrastructure Advisory Council (NIAC), *Critical Infrastructure Resilience Final Report and Recommendations*, 2009, pages 2-11.
http://www.pjm.com/~/media/committees-groups/committees/mrc/20130829/20130829-item-13-hot-weather-operations-presentation.ashx

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

[6] P. A. Ruiz, "Transmission topology optimization software: operations and market applications and case studies," presented at *ERCOT Emerging Technologies Working Group Meeting*, Austin, TX, Dec 2016. [Online] http://www.ercot.com/content/wcm/key_documents_lists/85542/05._Transmission_topology_control_--_ERCOT_ETWG_12616.pdf

[7] P. A. Ruiz, "Transmission topology optimization software: operations and market applications and case studies," *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," presented 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

References (II/II)

[11] J. Chang and P. A. Ruiz, "Transmission Topology Control – Applications to Outage Scheduling, Market Efficiency and Overload Relief," presented at *WIRES Summer Meeting*, Boston, MA, July 2015.

[12] P. Ruiz et al, "Topology Control Algorithms (TCA) – Simulations in PJM Day Ahead Market and Outage Coordination," pres. at *FERC Tech. Conf. Increasing Market Efficiency through Improved Software*, Docket AD10-12-006, Washington, DC, June 2015.

[13] E. A. Goldis, X. Li, M. C. Caramanis, A. M. Rudkevich, P. A. Ruiz, "AC-Based Topology Control Algorithms (TCA) – A PJM Historical Data Case Study," in *Proc. 48th Hawaii Int. Conf. System Science*, January 2015.

[14] P. A. Ruiz, X. Li, and B. Tsuchida, "Transmission Topology Control – Curtailment Reduction through System Reconfiguration," presented at *Utility Variable-Generation Integration Group Fall Technical Workshop*, San Antonio, TX, October 2014.

[15] P. A. Ruiz *et al*, "Transmission Topology Control for System Efficiency: Simulations on PJM Real Time Markets," presented at *2013 IEEE PES General Meeting*, Vancouver, Canada, July 2013.

[16] P. A. Ruiz, J. M. Foster, A. Rudkevich and M. C. Caramanis, "Tractable transmission topology control using sensitivity analysis," *IEEE Transactions on Power Systems*, vol. 27, no. 3, Aug 2012, pp. 1550 – 1559.

[17] P. A. Ruiz, A. Rudkevich, M. C. Caramanis, E. Goldis, E. Ntakou and C. R. Philbrick, "Reduced MIP formulation for transmission topology control," in *Proc. 50th Allerton Conf. on Communications, Control and Computing*, Monticello, IL, October 2012.

[18] J. M. Foster, P. A. Ruiz, A. Rudkevich and M. C. Caramanis, "Economic and corrective applications of tractable transmission topology control," in *Proc. 49th Allerton Conf. on Communications, Control and Computing*, Monticello, IL, September 2011.

[19] P. A. Ruiz, J. M. Foster, A. Rudkevich and M. C. Caramanis, "On fast transmission topology control heuristics," in *Proc. 2011 IEEE Power and Energy Soc. Gen. Meeting*, Detroit, MI, July 2011.

[20] R. O'Neill, R. Baldick, U. Helman, M. Rothkopf, and W. Stewart, "Dispatchable transmission in RTO markets," *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 171–179, Feb. 2005.

[21] E. B. Fisher, R. P. O'Neill, and M. C. Ferris, "Optimal transmission switching," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1346–1355, Aug. 2008.

[22] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1577–1586, Aug. 2009.

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