Transmission Topology Optimization

PRESENTED BY

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THE Brattle GROUP

Agenda

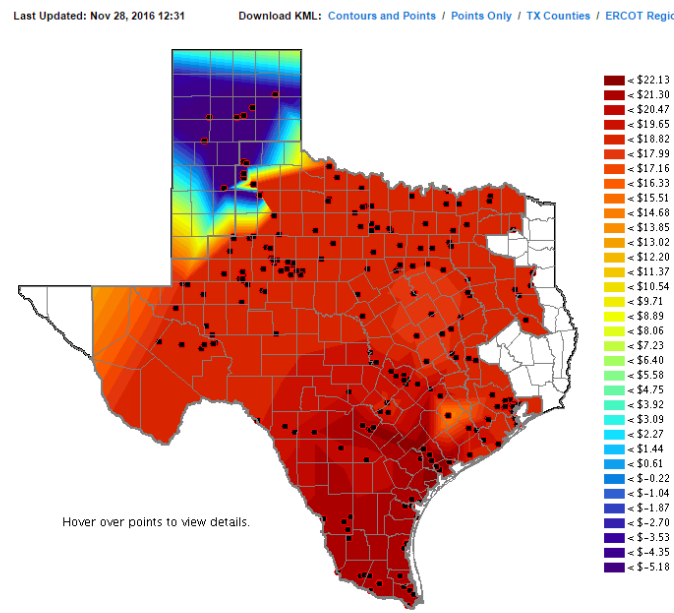
Topology Optimization Summary

- At any given time, few transmission lines or transformers are congested.
- Usually there are transmission topology reconfigurations (line switching, bus splitting) that can reliably route power around the congested facilities.
- Today, operators use reconfigurations to manage some challenges, identifying them based on their experience and knowledge of the system.
- Topology control algorithms (TCA) developed with DOE ARPA-E support automatically identify reconfiguration options to:
  - Respond to contingency situations: eliminate overloads/irresolvable constraints.
  - Improve outage scheduling: enable more requested outage plans.
  - Manage congestion: reduce associated costs by up to 50%.
- TCA software is a fast “search engine” for identifying and evaluating viable and beneficial system reconfiguration options.
- *NewGrid* is commercializing TCA software, which is being used by ERCOT in operations planning, including to support the 2017 Constraint Management Plan (CMP) Study.

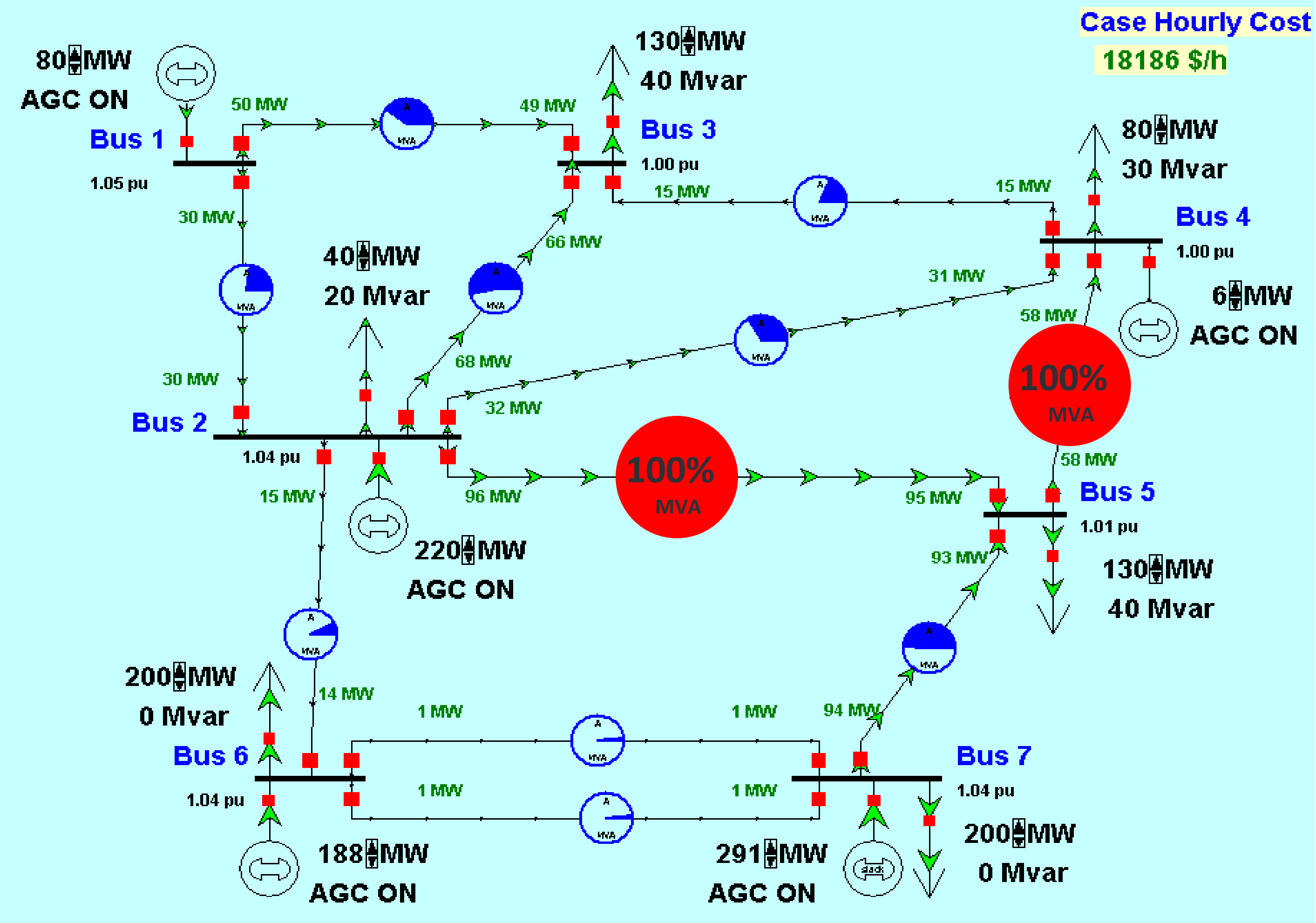
Objectives and Motivation
Current Practice for Congestion Management

- Topology optimization offers an effective complement to resource-based and hardware-based flow control and congestion management.
- Resource-based flow control: reduce (low-cost) generation upstream of congestion/overload and increase (costly) generation downstream.
  - Leads to geographic price separation.
  - ERCOT 2016 congestion costs: $497 million.
  - ERCOT renewables curtailment impacts:
    2% of annual potential wind energy in 2016.
  - ERCOT reliability impacts: real-time flows exceeded post-contingency grid capacity in 3% of the intervals in 2016 (irresolvable constraints).
- Flow control hardware (*e.g.*, phase shifters, distributed series devices, FACTS devices) require capital investments and tend to be deployed in limited locations.

ERCOT Day-Ahead Prices
Nov 28, 2016 at 8am

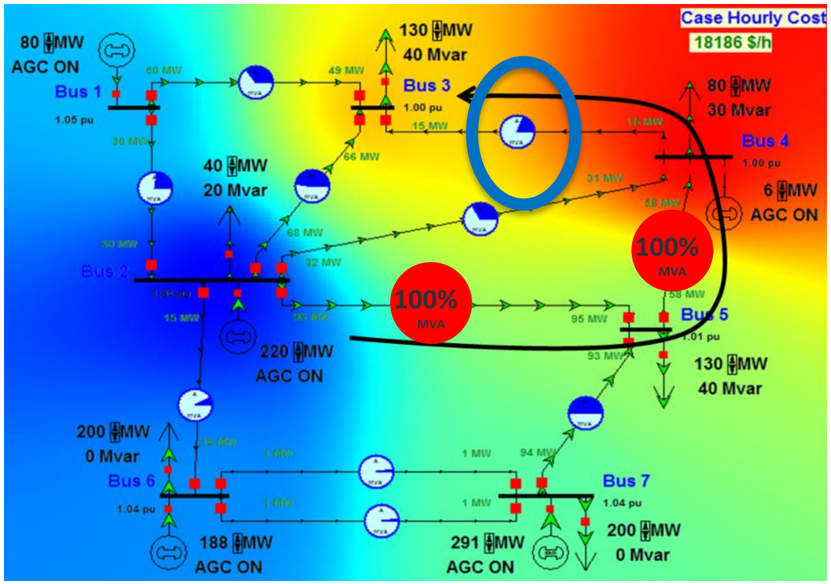


Illustrative Example
7-Bus Example: All Lines Closed

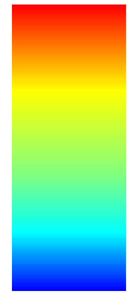


Illustrative Example
7-Bus Example Results: Before and After

Before: all lines Closed



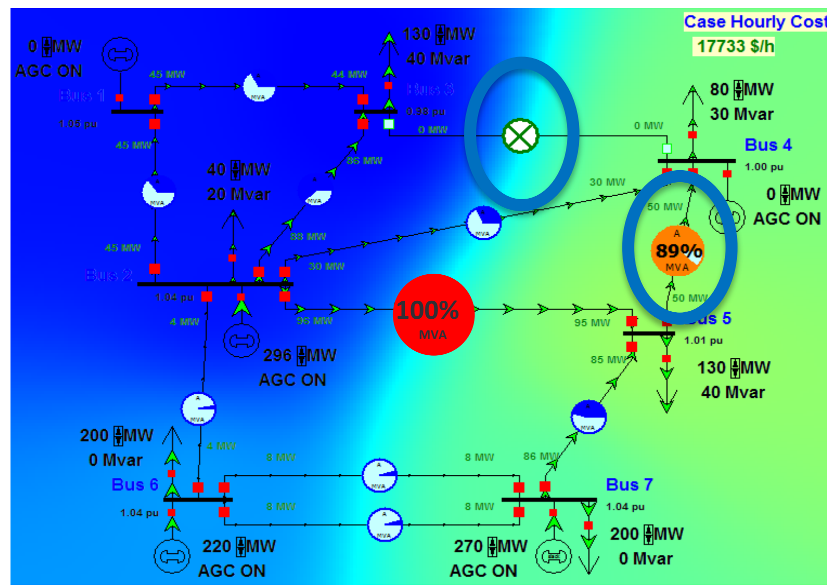
$40/MWh



$15/MWh

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

After: line 3-4 Opened



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

Reconfigurations—Current Practice

Reconfigurations are already used to some extent across system operators.

- Today, system operators adjust transmission topology on an *ad hoc* basis for the following applications:
  - *Contingency Planning*: identify pre- and post-contingency reconfigurations to mitigate overloads (*e.g.*, Operating Guides, Constraint Management Plans, Remedial Action Plans).
  - *Outage Coordination/Scheduling*: enable planned outages that otherwise would cause reliability violations/increases in congestion.
  - *Constraint Management*: allow more efficient unit commitment and economic dispatch (used in limited cases), maintain current commitment and dispatch plans.
- In order to identify beneficial reconfiguration options, operators rely on their prior experience and knowledge of the system.
- Currently, developing such switching solutions is a time-consuming, “manual” process, given the magnitude and complexity of the system.
- The flexibility that the transmission system offers is underutilized as a result.

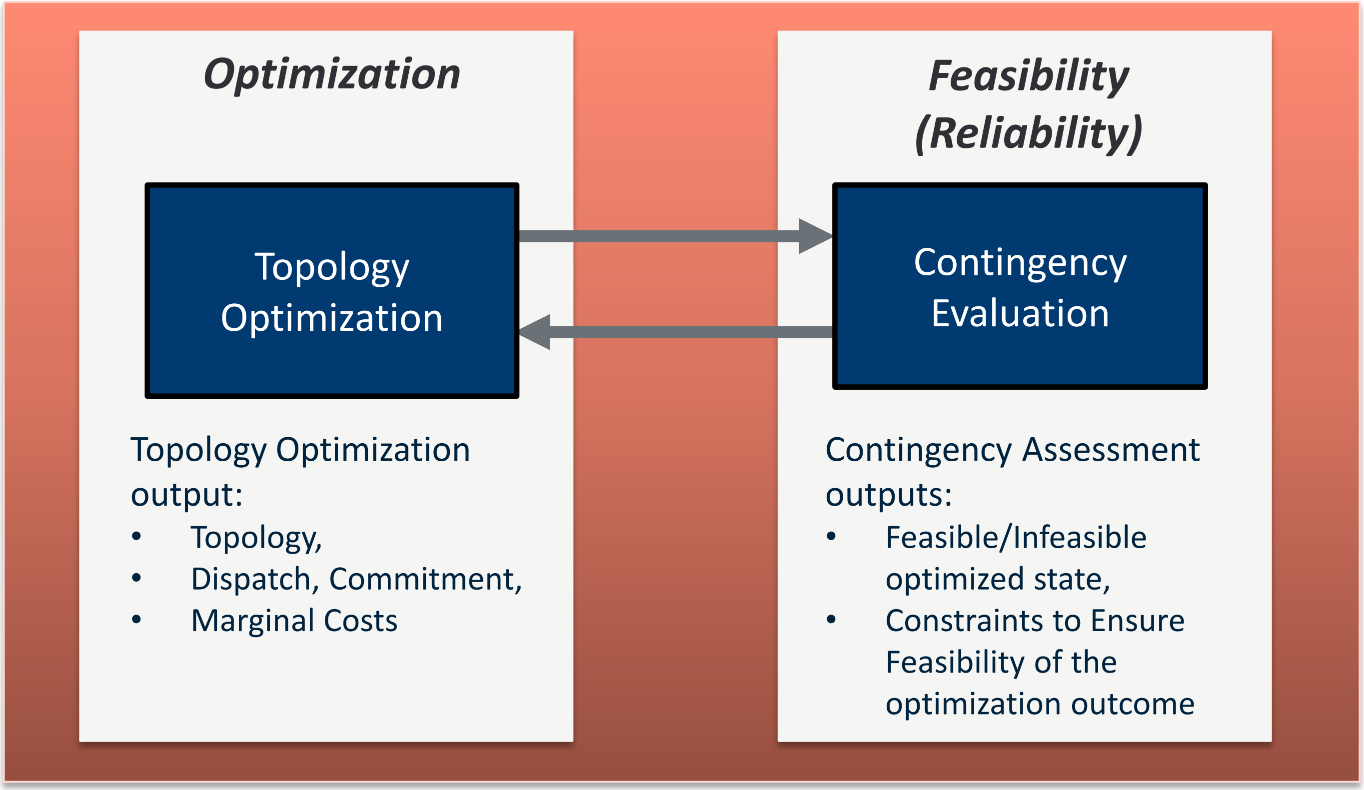
Topology Optimization Software

Topology optimization software automatically finds 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.
  - *Look-Ahead*: Optimization decisions with “topology continuity” constraints.
- With PJM staff, tested the algorithms developed and assessed their impacts in a simulated environment replicating PJM market operations and outage coordination.
- With ERCOT staff, 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.

NewGrid Router Architecture

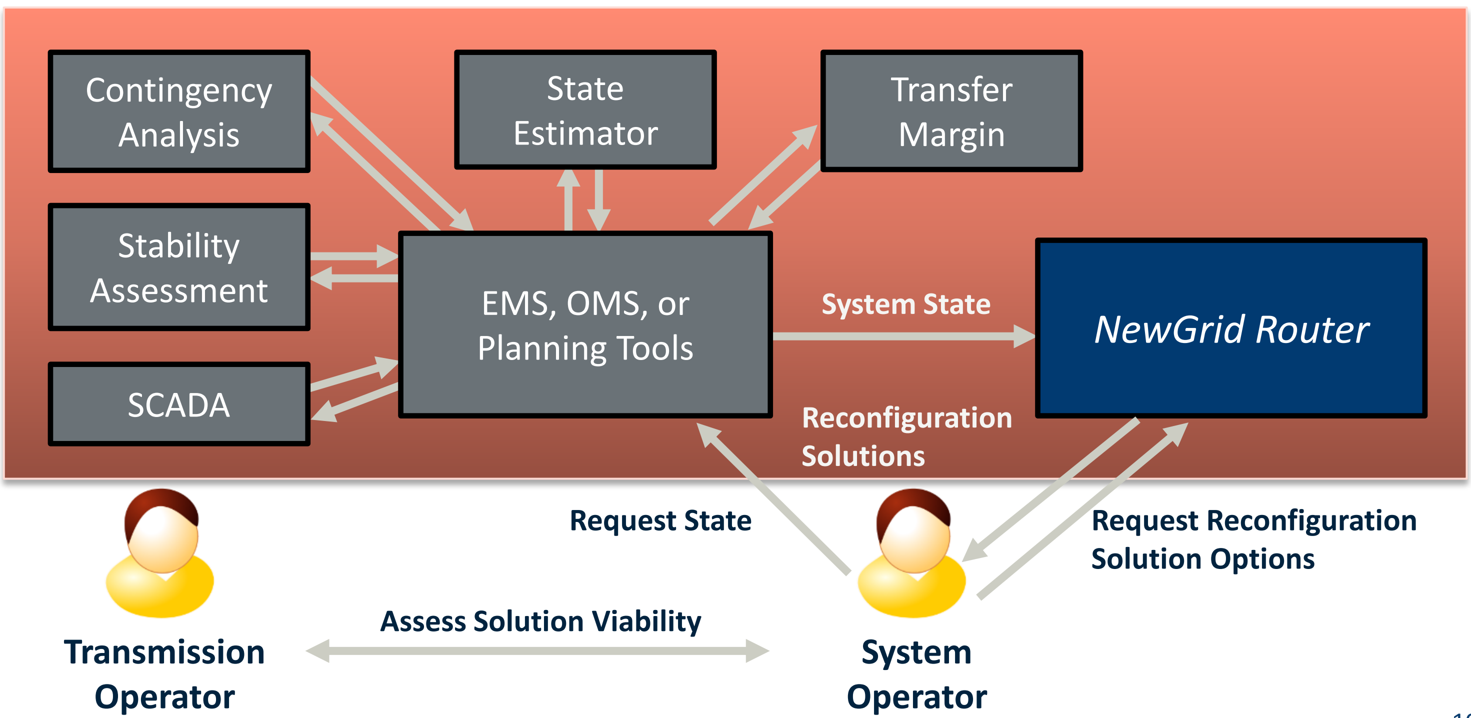
NewGrid Router **uses the same general architecture used by Energy Management Systems (EMS).**



Topology Optimization Software

Advisory Application: Operations & Planning

- In operations and planning decision making, *NewGrid Router* provides the engineers with reconfiguration options to select and further evaluate.
- Router reduces time to identify options and leads to better outcomes:
  - Develop CMPs/RAPs quickly for *irresolvable constraints* if existing plans do not work.
  - Increase operator visibility of reconfiguration options in congestion management.
  - Resolve conflicts to enable desired outage schedules.
  - Reduce outage impacts when conditions change.



Topology Optimization Software
Case Studies Overview

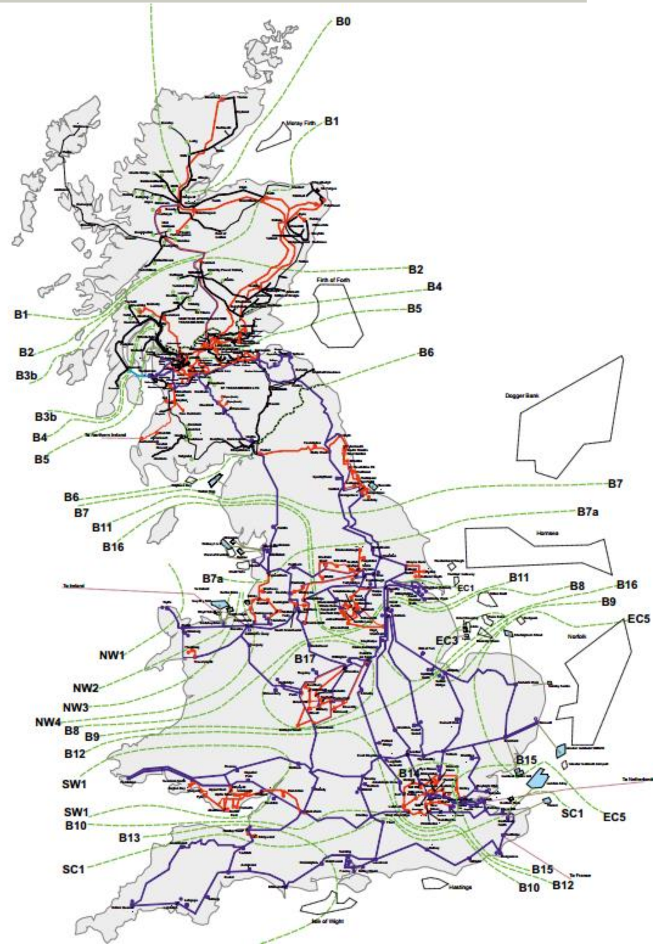
Topology optimization finds highly beneficial reconfigurations.

- Case Study 1 – National Grid UK (Ref. [1], [2]):
  - Increased transfer capability 3-12% for critical constraints under severe outages.
- Case Study 2 – ERCOT (Ref. [3]):
  - Relief of most frequent market constraint in 2014-2015 (operations planning case).
- Case Study 3 – PJM (Ref. [9]):
  - Topology Optimization in the RT Markets, 40-70% congestion cost relief (2010 conditions).
- Additional analyses to date:
  - PJM operations: Full relief of critical historical base-case overloads (Appendix 1, Ref. [9]).
  - PJM DA markets: 30-50% congestion cost relief, 2010 conditions (Ref. [5]).
  - PJM high renewables: Reduced curtailments under 30% penetration case (Ref. [11]).
  - PJM outage coordination: overload and congestion relief (EMS cases).
  - SPP operations: Full relief of recurring post-contingency overloads (Ref. [4]).
  - MISO operations: Full relief of recurring overloads under outage and high load conditions.
  - MISO wind plant: Increase of transfer capability out of a frequently constrained wind plant.

Case Study 1: Impacts in National Grid UK

Increased Transfer Capability in Great Britain

- National Grid (NG) and Brattle studied the potential to increase transfer capability and reduce constraint management costs with topology optimization.
- Iteratively and collaborative analysis:
  - National Grid identified historical scenarios where thermal limits had been active on major (zonal) “boundary constraints.”
  - Brattle identified reconfigurations for those scenarios.
  - National Grid assessed the reconfiguration impacts and provided feedback.
- Decision variables: line switching, substation reconfigurations, phase-shifting transformer settings.
- Topology optimization impacts:
  - Increases in boundary constraint capacity: **3% to 12%** per National Grid assessment.
  - Annual Balancing Market costs savings: **£14-40 million**, under historical conditions.



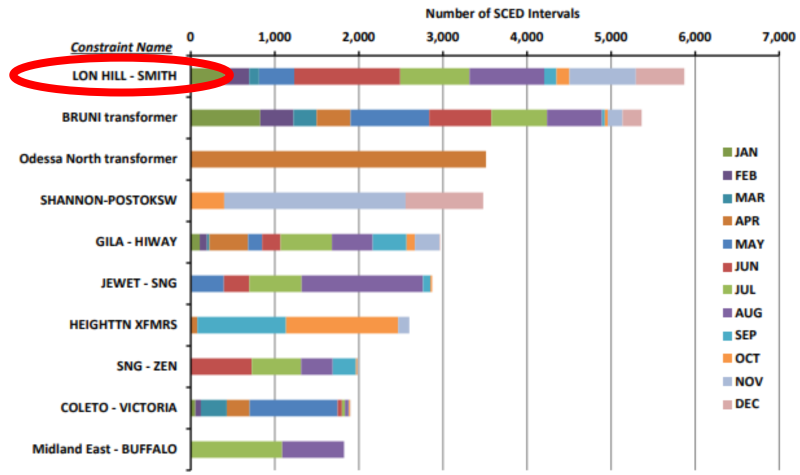
Source: Electricity Ten Year Statement 2015, National Grid, November 2015, Figure 3.1.

Case Study 2: ERCOT Historical Constraint Relief

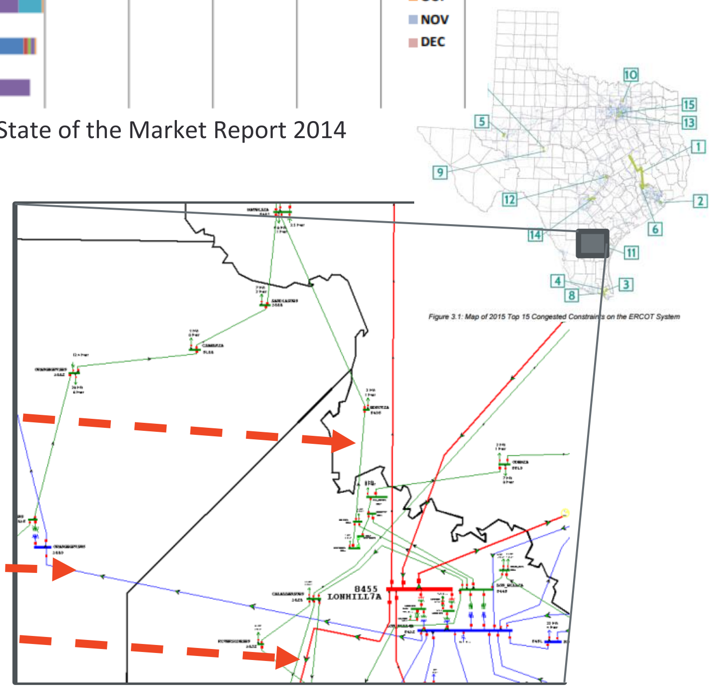
Lon Hill-Smith 69 kV Constraint

- The Lon Hill-Smith 69 kV line was *the most frequent constraint* in ERCOT in 2014-2015.
  - Constraint was binding during almost 6,000 real-time market intervals (5 minutes) in 2014.
  - Congestion was caused by increased demand due to oil and gas activity in the Eagle Ford Shale.
  - A transmission upgrade in the area solved the congestion after May 2015.
- Constraint monitors Lon Hill-Smith 69 kV line for the double outage of:
  - Lon Hill to Orange Grove 138 kV,
  - Lon Hill to North Edinburg 345 kV.

Figure 40: Most Frequent Real-Time Constraints



Source: ERCOT State of the Market Report 2014



Source: ERCOT ETWG Dec 2016 Meeting presentation (Ref. [3])

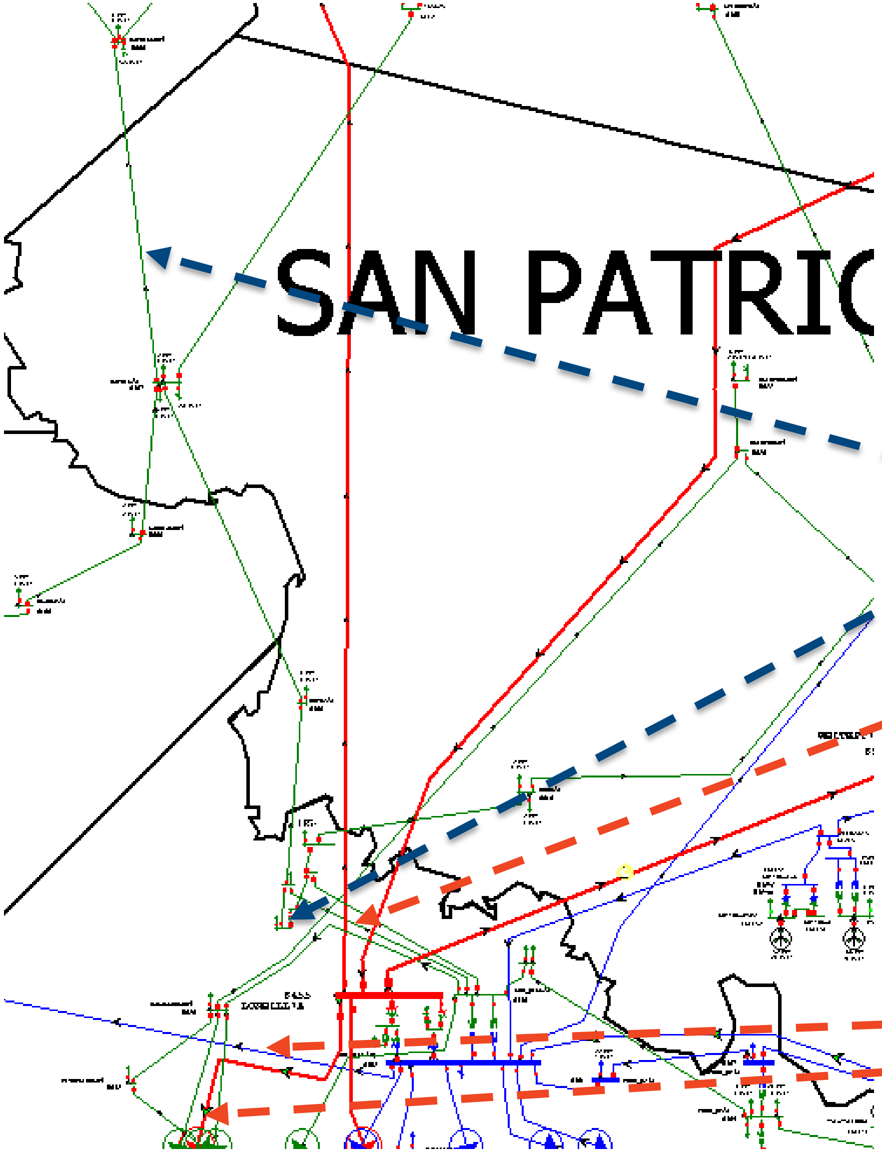
Case Study 2: ERCOT Historical Constraint Relief

Solution Search Criteria and Results

- ERCOT Operations Planning provided a 2015 Summer Peak case for reconfiguration analysis, which had a 24% violation on the contingency constraint.
- The topology optimization software searched for topology changes that would relieve the constraint violations while:
  - Keeping the generation dispatch fixed (for demonstration purposes only; allowing for dispatch changes could enable more or better solutions),
  - Limiting additional violations (pre- or post-contingency, thermal or voltage).
- The solutions would be implemented in corrective mode.
  - Corrective mode—implement the reconfigurations after the occurrence of the specified contingency, should it occur, to avoid the post-contingency overload.
  - The reconfiguration does not worsen potential contingency overloads for a subsequent contingency (*N* –1–1).
- Sample reconfiguration found effectively **increases local system capacity by 20%** (under the conditions analyzed):
  - Close one 69 kV tie and open one 69 kV line,
  - Relieves the 24% (14 MVA) violation, causing a 4% (2 MVA) violation on another 69 kV line.

Case Study 2: ERCOT Historical Constraint Relief

Reconfiguration Alternative



Closing the Stevens 69 kV bus tie breaker diverts some flow from Lon Hill – Smith to Lon Hill – W Work – Stevens – Smith, fully relieving the overload but causing another, smaller overload downstream, at Smith – Edroy – Mathis 69 kV.

Opening the Mathis – Mathis Sub 69 kV line fully relieves the overload, causing a 2 MVA overload downstream.

Reconfiguration

Open Mathis – Mathis Sub 69 kV

Close Stevens 69 kV bus tie

Lon Hill – Smith 69 kV

Initial Configuration:

24%, 14 MVA overload

With Reconfiguration:

Full relief on Lon Hill – Smith

4%, 2 MVA overload on different 69kV line

Two-Element Contingency:

Lon Hill to Orange Grove 138 kV

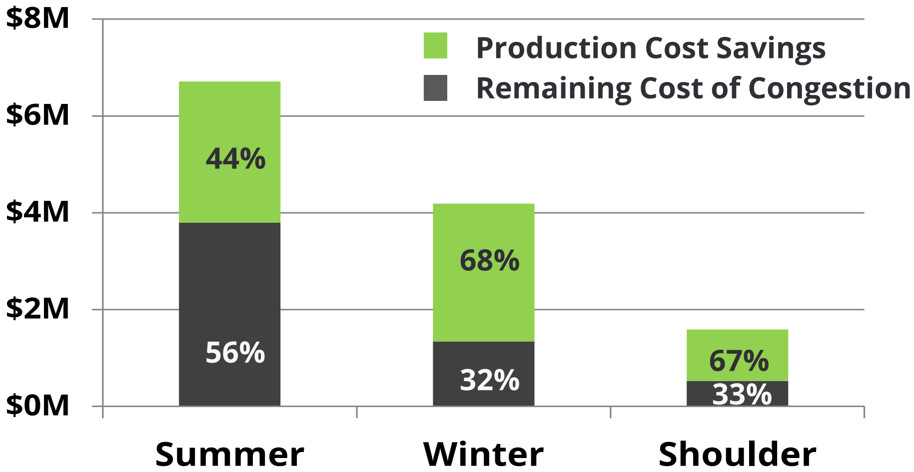
Lon Hill to North Edinburg 345 kV

Case Study 3: Congestion Relief in PJM RT Markets
Historical PJM RT Market Models

- As part of the ARPA-E TCA project, we simulated the impacts of topology optimization on PJM RT markets.
- Models based on one operational power flow real-time snapshot per hour for three representative historical weeks of average conditions in 2010—summer, shoulder (fall), and winter weeks. Data used from the power flows:
  - Transmission topology, branch parameters, initial voltage state.
  - External system conditions (*e.g.*, interchange, reciprocal flowgate use).
  - Nodal load levels; unit commitment for all units.
  - Dispatch of hydro, wind, landfill, nuclear, and RMR thermal units.
- Generation economic and transmission constraint data from operations and historical market conditions.
- Model dimensions: up to 15,200 nodes and 650 dispatchable thermal PJM units, about 4,700 monitored branches and 6,100 single and multi-element contingencies.

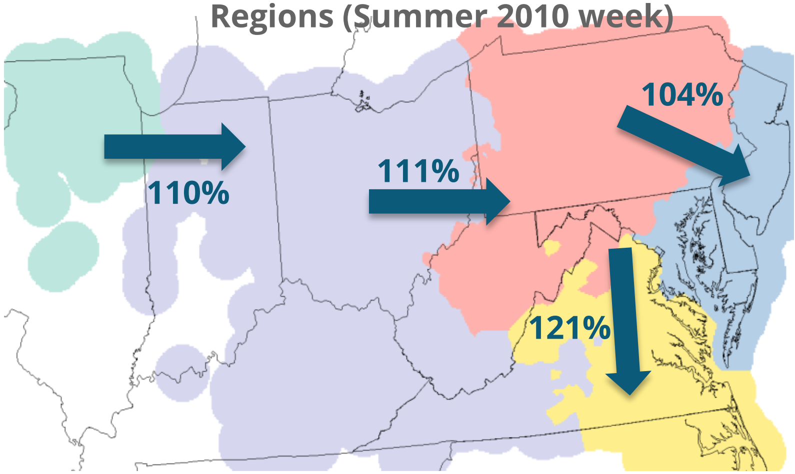
Case Study 3: Congestion Relief in PJM RT Markets
Impacts on PJM Real Time Market

Weekly Real-Time Market Congestion Cost Savings

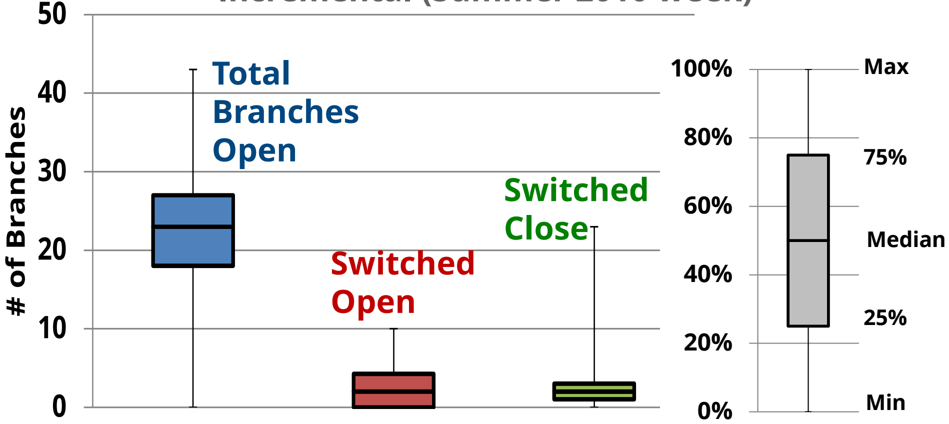


50% reduction in Real Time PJM congestion costs
⇒ extrapolate to a potential for **$100 million savings** in annual production costs

Increase in Weekly Energy Transfers Between PJM Regions (Summer 2010 week)



Hourly Topology Statistics – Cumulative and Incremental (Summer 2010 week)



Concluding Remarks
A Transmission Owner's Perspective

Topology optimization software finds system reconfiguration options to:

- Help reduce the costs and increase the feasibility of construction-related outages.
- Increase the value of system expansions that provide operational flexibility (*e.g.*, investments that create more switching options).
- Increase the effective capability and resiliency of the existing grid.
  - Could avoid/defer certain upgrades (usually lower voltage ones).
  - May increase the reliability and economic benefit of system expansions and upgrades (making it easier to pass benefit-cost ratio tests).
- Increase the long-term attractiveness of transmission solutions compared to non-transmission alternatives.
  - Topology optimization will likely move the optimal spending mix more toward transmission, as transmission would become more cost effective.

Concluding Remarks

Options for System and Transmission Operators

- Topology optimization solutions and analyses are available as a consulting service.
  - Feasibility and exploratory studies.
  - Benefit assessment analyses.
  - Assessment of impacts on resource revenues and demand costs.
- *NewGrid Router* is available for licensing from NewGrid.
- Possible applications:
  - Decision support for contingency planning.
  - Quickly identify switching solutions to address specific reliability and congestion events efficiently as they appear.
  - Adapt system configuration as flow patterns change:
    - Increased wind and solar generation.
    - Retirement of legacy thermal units.
  - Identify temporary reconfiguration plans:
    - Manage transmission outages.
    - Address high load growth in load pockets

Contact

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Dr. Pablo A. Ruiz, a senior associate 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, and has held Research and Teaching Assistant positions at the University of Illinois and at Universidad Tecnológica Nacional. Dr. Ruiz holds a Ph.D. in Electrical and Computer Engineering from the University of Illinois at Urbana-Champaign.

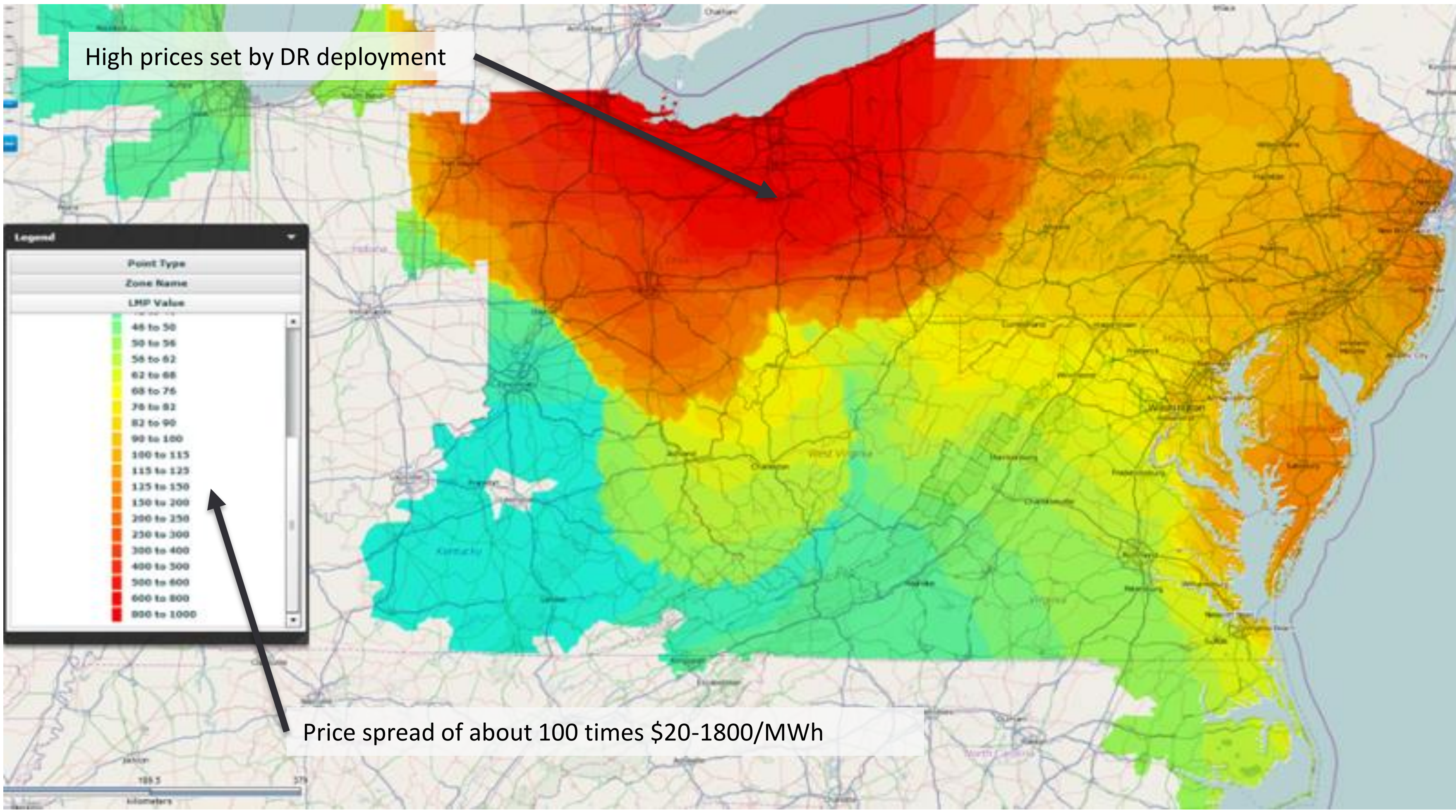
Appendix Contents

Appendix 1: PJM Overload Relief Under Extreme Conditions

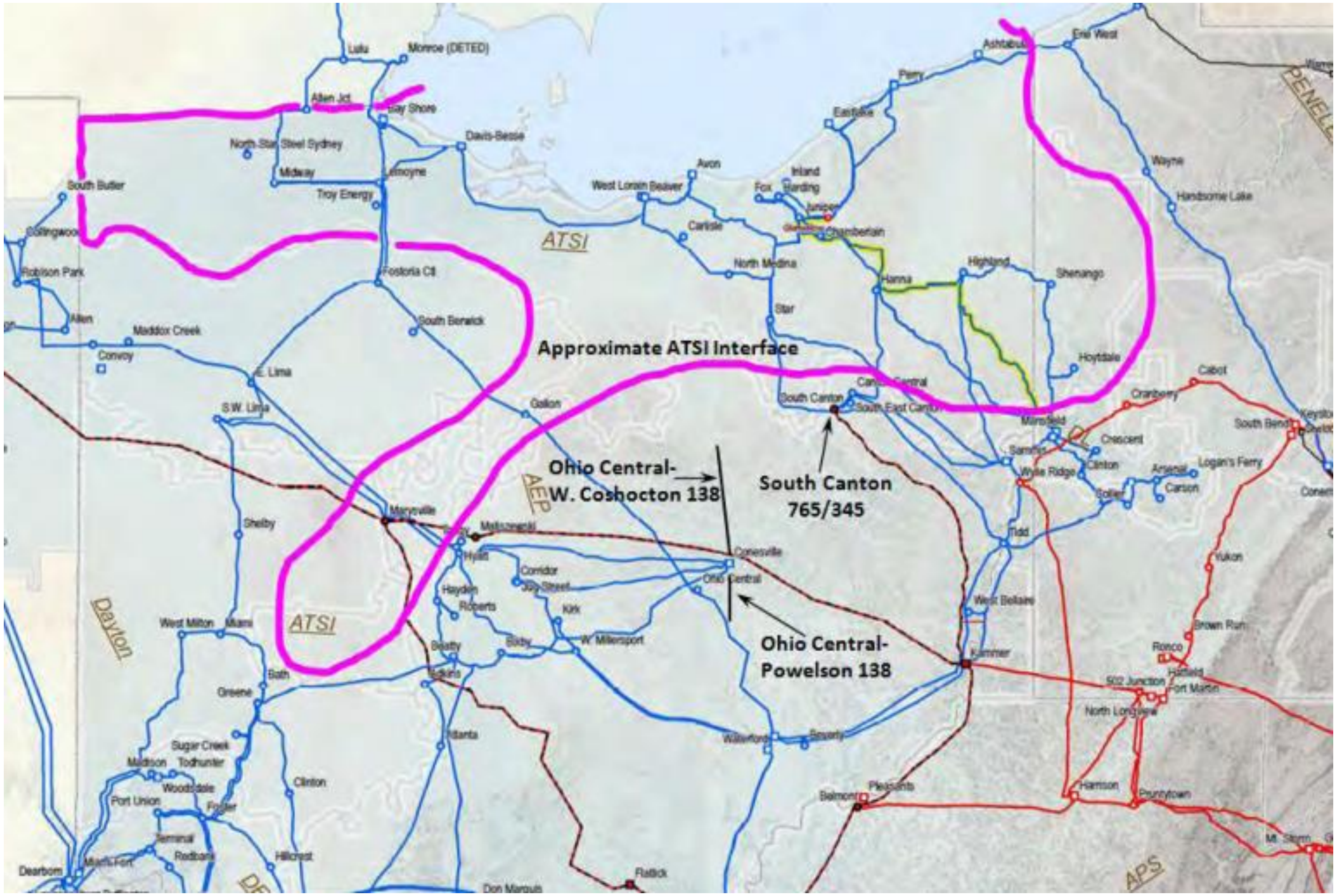
Appendix 2: References

Appendix 1: PJM Overload Relief Under Extreme Conditions
South Canton Transf. Overload Relief

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



Appendix 1: PJM Overload Relief Under Extreme Conditions
South Canton Transf. Overload Relief

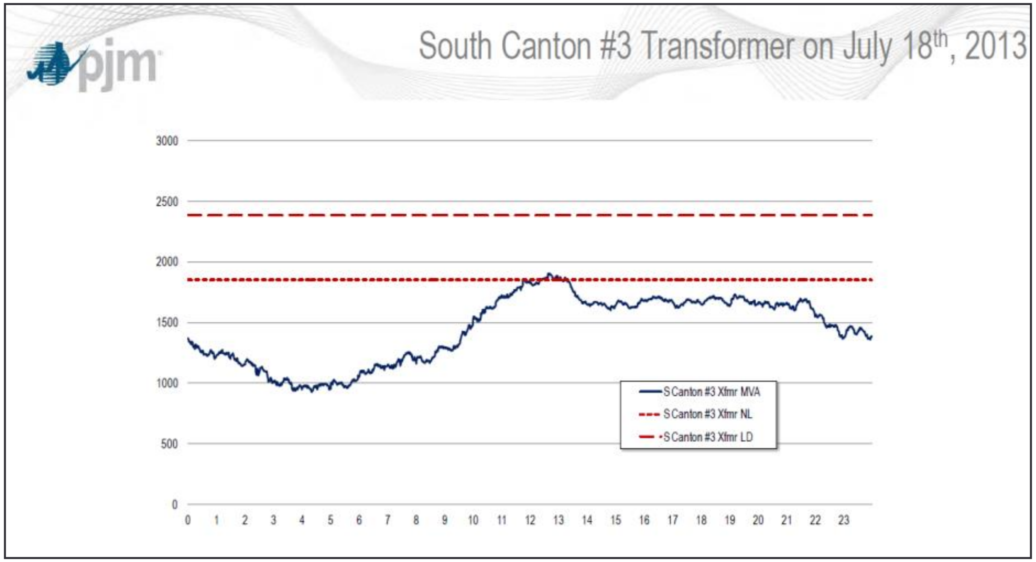


Source: http://www.pjm.com/~/media/committees-groups/committees/mrc/20130829/20130829-item-13-hot-weather-operations-presentation.ashx

Appendix 1: PJM Overload Relief Under Extreme Conditions
South Canton Transf. Overload Relief

The South Canton 765/345 kV transformer was severely congested, even overloaded, on July 15, 17 and 18, 2013.

- Unplanned generation outages in the area: 2700 MW.
- PJM deployed demand response (DR) to lower congestion in the area (650 MW).
- There were four 138 kV line post contingency overloads in the area as well.



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Appendix 1: PJM Overload Relief Under Extreme Conditions

South Canton Transf. Overload Relief

We automatically found reconfigurations that fully relieved historical PJM overloads under worst-case conditions.

- In our analysis, transmission topology was the only variable allowed to be modified to relieve overloads
  - Due to the extreme conditions for that day, the dispatch was kept the same as the initial EMS dispatch to capture any additional generation operation constraints not captured in the case
- TC was able to divert flow away from the transformer and fully relieved the base case and post contingency overloads in the area
- TC application would have reduced the required DR deployment.
- Voltage profiles with and without reconfigurations were very similar.

Appendix 2
References (I/II)

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Appendix 2
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