

# Topology Control Algorithms

## *Applications for Market Efficiency Improvements and Overload Relief*

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# Agenda

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## Topology Control Algorithms (TCA)

- Objectives and Motivation
- Illustration of Topology Control
- Current Switching Solutions Practice
- ARPA-E TCA Project
- Relieving Overloads Through TCA
- Market Efficiency Improvements
- Concluding Remarks



# Topology Control Algorithm

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The goal of controlling the transmission network topology is to extract more value out of transmission facilities:

- 1. Identify additional operational controls to**
  - manage congestion
  - respond during contingency situations
  - accommodate outage requests
- 2. Significantly lower generation costs**
- 3. Enable higher levels of variable renewable penetration**
- 4. Increase system reliability**

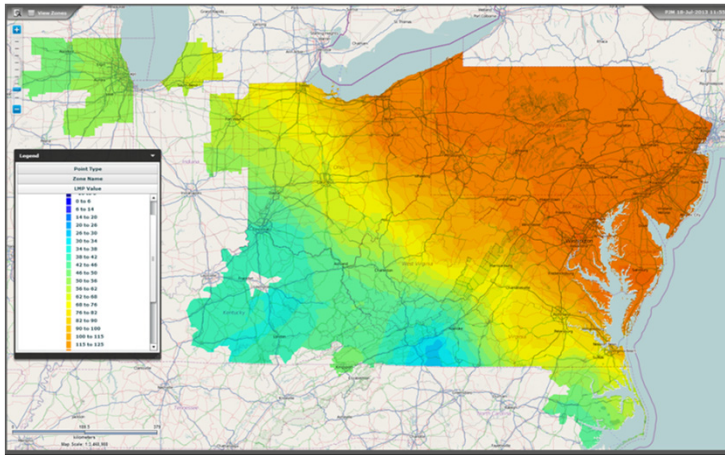
**TCA Timeframe: from operations planning up to real-time operations**



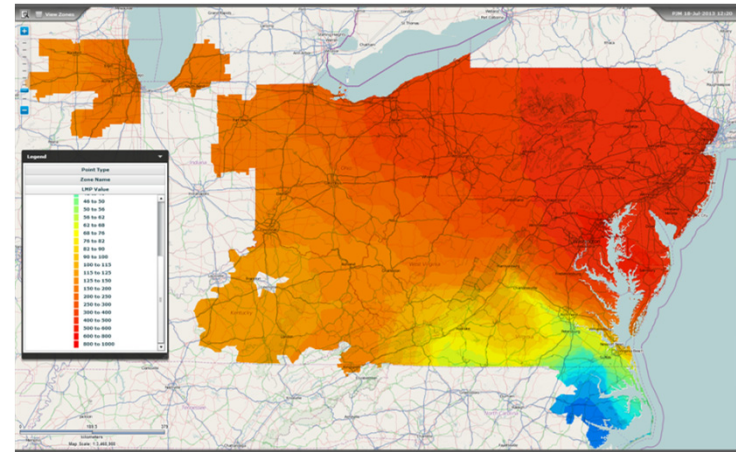
## Objectives and Motivation

# Congestion in RT Markets

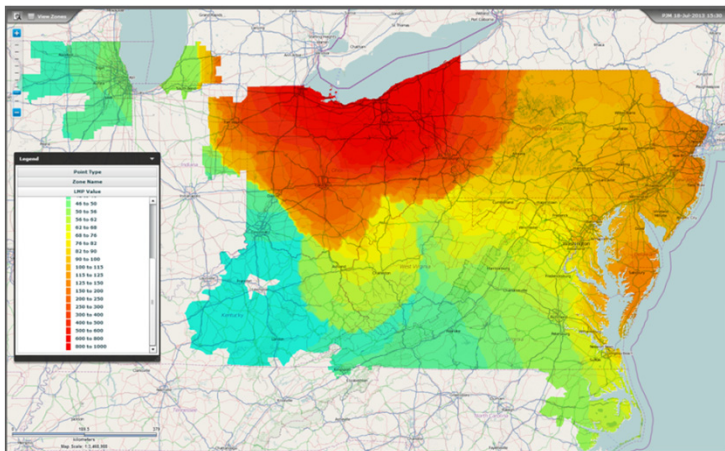
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In the course of a day, congestion patterns and prices can change significantly:

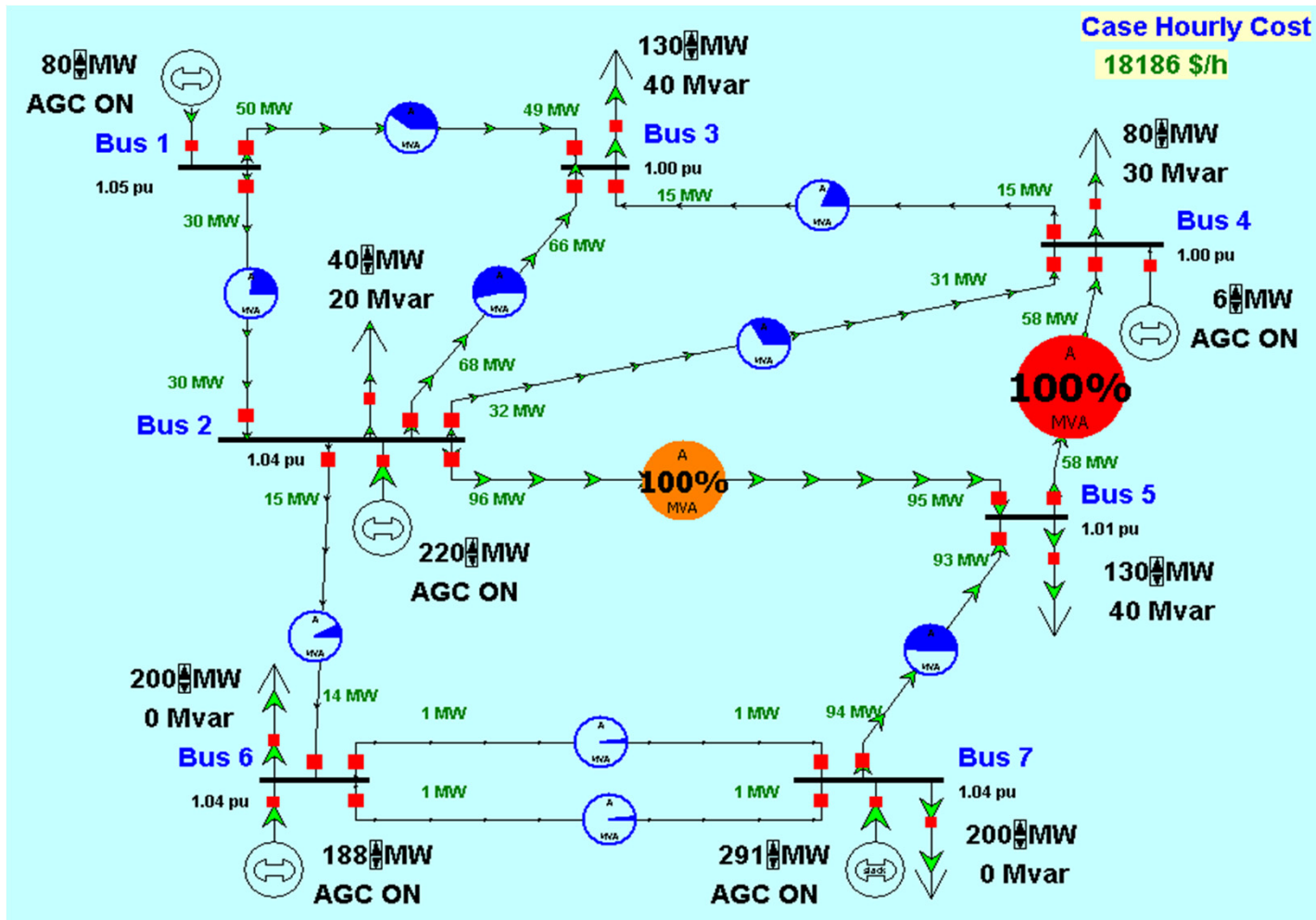
- Fuel diversity
- Lack of flexibility in the resource mix

Having the ability to dynamically increase transfer capability from areas with available low cost generation to areas with generation scarcity will help to relieve congestion, improve dispatch of renewable resources, reduce dispatch costs and increase system flexibility.



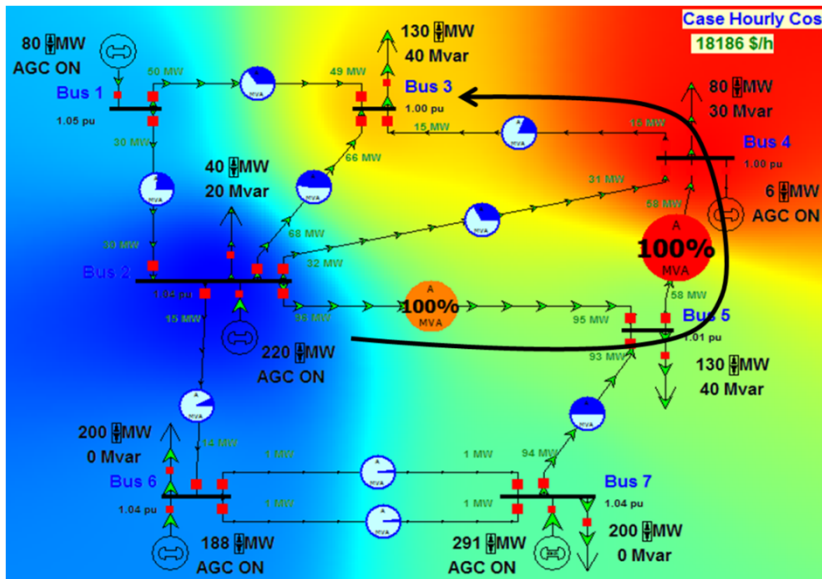
## Illustration of Topology Control

# 7-bus Example: All Lines Closed



## Illustration of Topology Control

# 7-bus Example Results



\$40/MWh



\$15/MWh

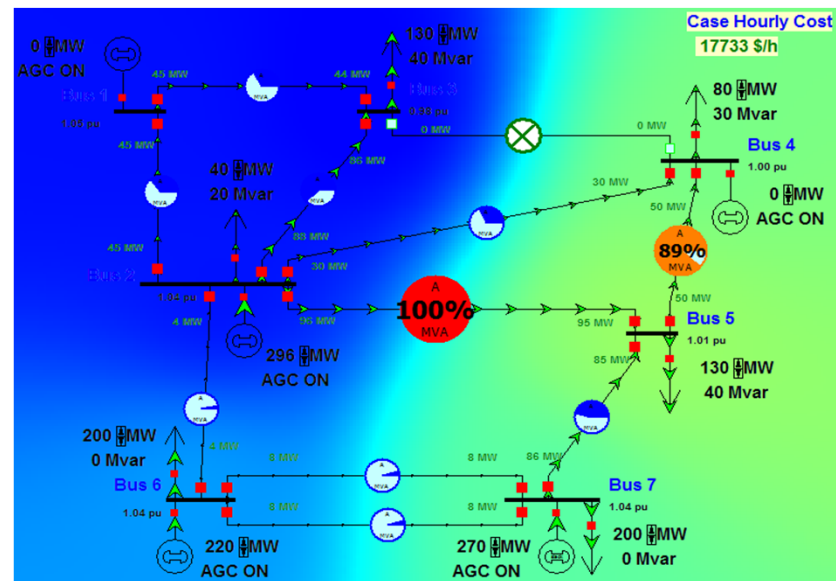
### Hourly Cost

All lines Closed: \$18,186

Line 3-4 Opened: \$17,733

Savings: \$453

Generation	Before TC	After TC
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



# Current Topology Control Applications

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## Contingency planning

- Post or pre-contingency reconfiguration to mitigate overloads (Op Guides)
- Employed by: most/all utilities/RTOs

## Outage coordination and scheduling

- Reconfiguration to enable planned outages that otherwise would cause reliability violations
- Employed by: most/all utilities/RTOs

## Congestion management

- Transmission system reconfiguration to enable more efficient unit commitment and economic dispatch
- Employed by: some RTOs, including PJM, <http://www.pjm.com/markets-and-operations/etools/oasis/system-information/switching-solutions.aspx>

*Currently, reconfigurations are developed manually using engineering judgment, there are no tools that provide quick identification of beneficial topology changes*



# Topology Control Risks and Mitigation

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**Topology reconfiguration may change the usual set of contingencies that lead to binding constraints**

- Employ a comprehensive contingency list (that is the case in operations already...)

**Multiple contingencies may occur leading to reliability problems**

- Revert back to a different/previous topology
- Topology changes can be implemented very quickly
- Multiple contingencies do not happen simultaneously, otherwise they should be modeled as a single contingency

**Breaker may malfunction during operation**

- Include breaker contingency in contingency list

**Breaker maintenance costs may increase**

- Mitigated by non-invasive preventive monitoring techniques



# Objectives and Focus

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**To develop a full-scale algorithm and software implementation for transmission network topology control**

- Operating in conjunction with existing operations and market tools (including Energy Management Systems, Market Management Systems and contingency planning tools);
- Meeting computational effort requirements aligned with operations and market timeframes

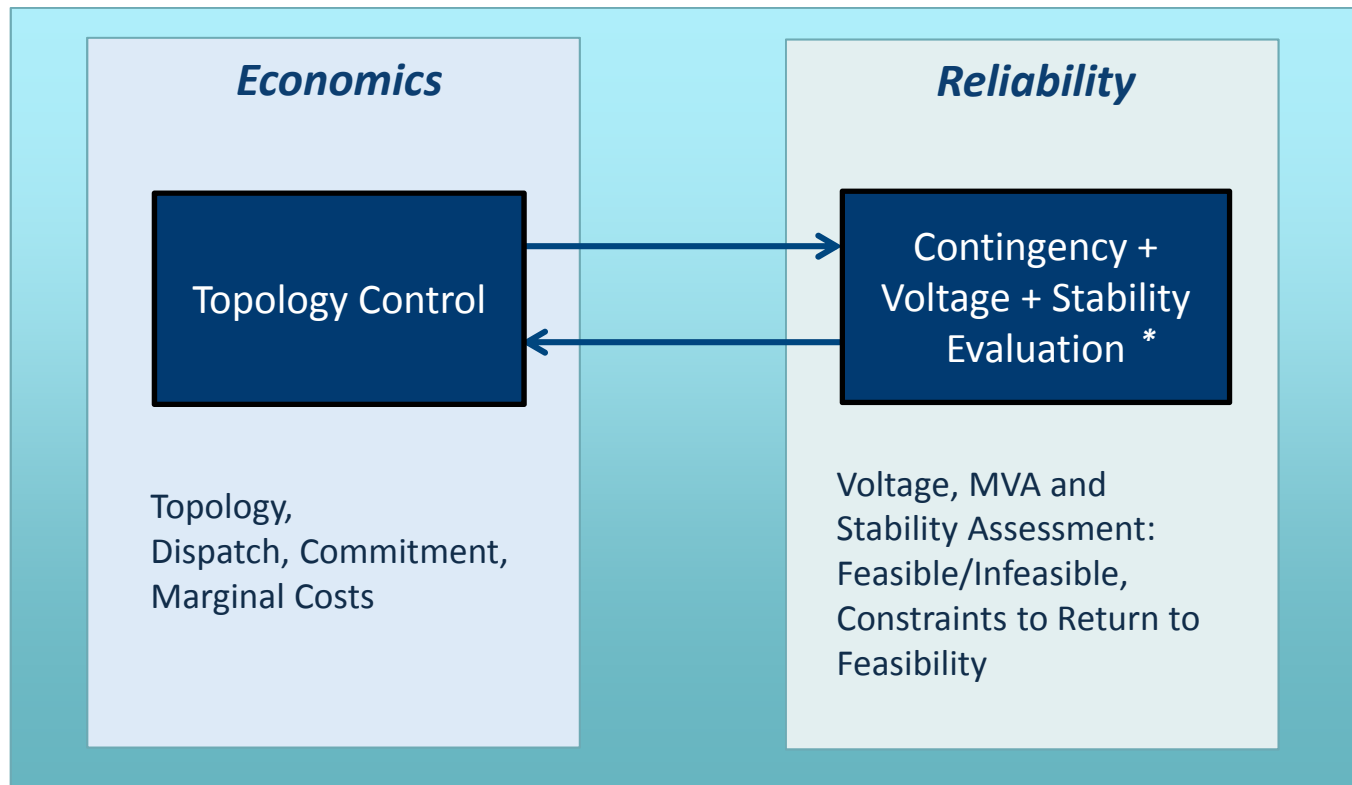
**The algorithms developed are being tested in a simulated environment replicating PJM market operations.**

**Focus:**

- Tractability: TCA must work on 13,000+ bus systems
- Dynamics: Look-ahead TC decisions in ED and UC
- Reliability: Connectivity, security constraints, transient stability and voltage criteria met
- Impact evaluation: Economic, operations and renewable integration benefit



# Basic TC Software Architecture

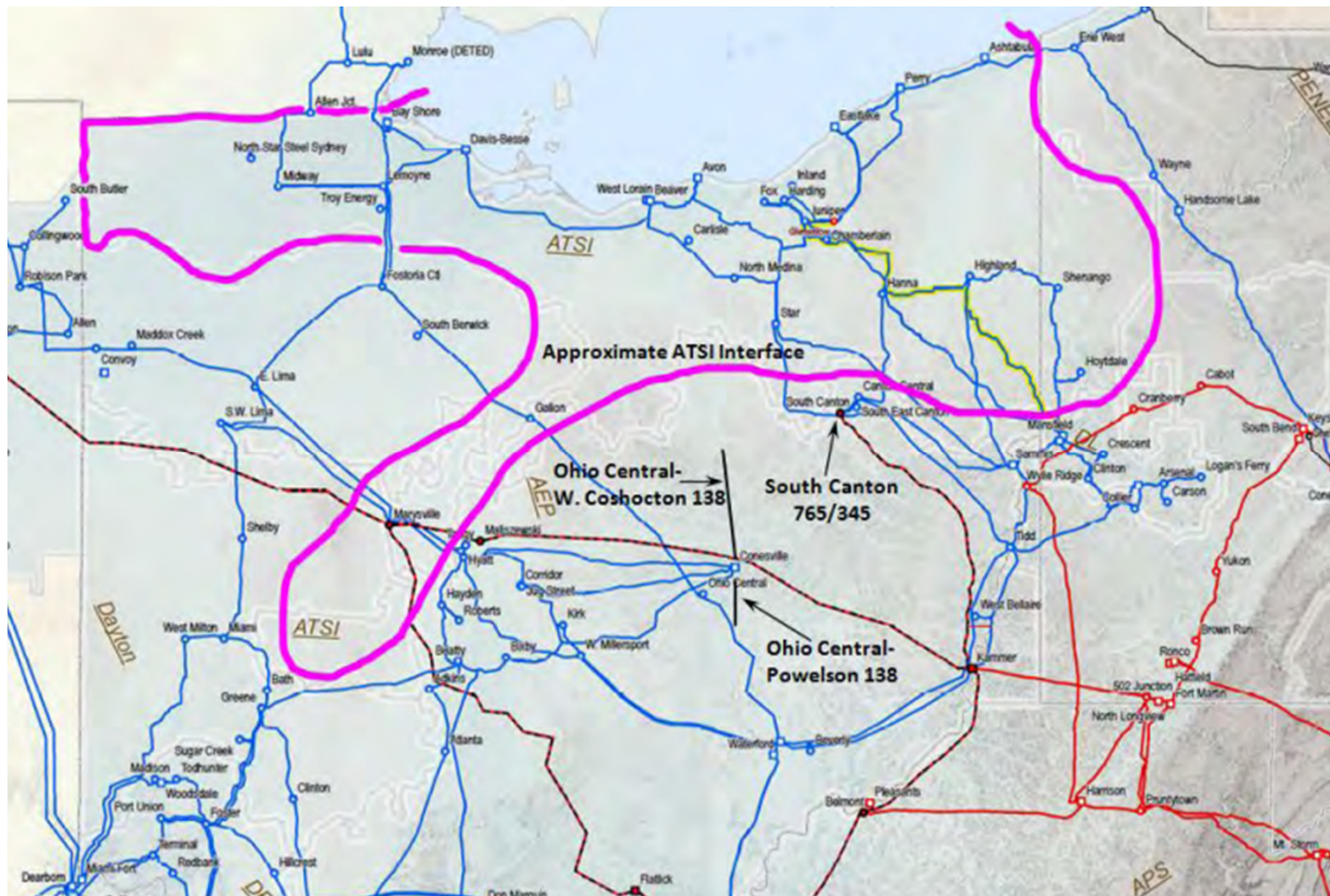


\* The simulation results in this presentation include AC modeling and linear contingency evaluation and enforcement, but do not include detailed voltage or transient stability evaluation



## Relieving Overloads Through TCA

# South Canton Potential Overload Relief



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



## South Canton Potential Overload Relief

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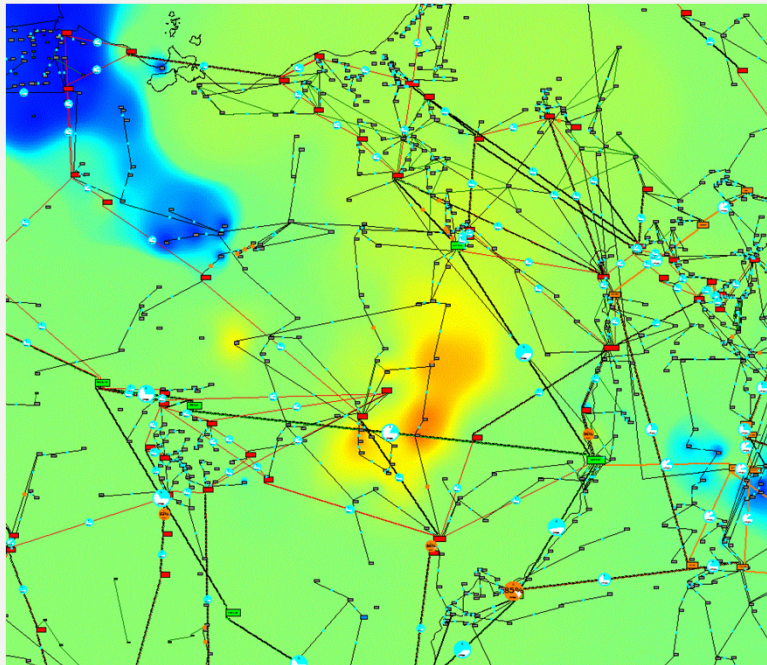
- The South Canton transformer was severely congested and with base case overloads on July 15<sup>th</sup>
  - There were post contingency overloads in the area as well
  - PJM deployed DR to lower congestion in the area
- In our analysis, transmission topology was the only variable allowed to be modified 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
- TCA was able to divert flow away from the transformer and fully relieved the base case and post contingency overloads in the area
- TCA application might have reduced the required DR deployment
- Base case voltage profile after the topology change was very similar to the initial voltage profile



## Relieving Overloads Through TCA

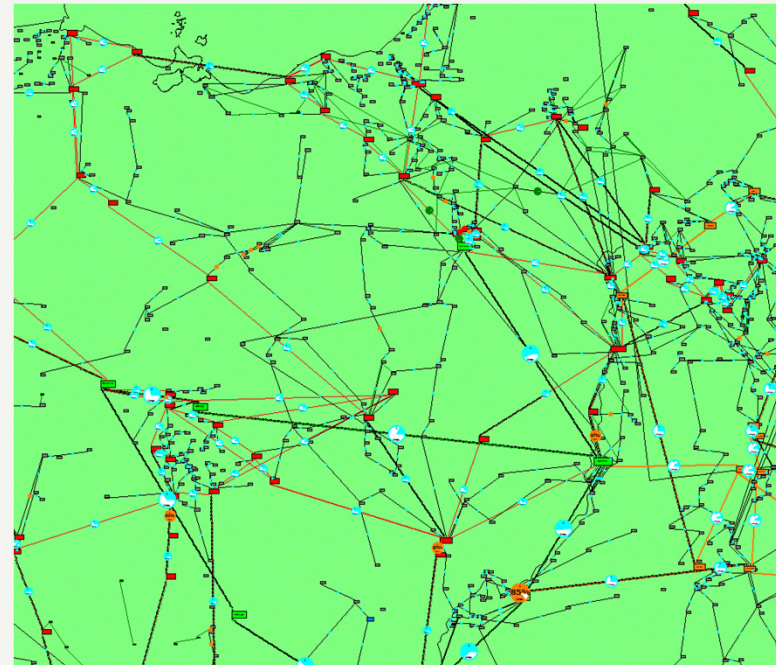
# Overload Relief Example

July 15<sup>th</sup>, 2013 at 3PM



**Before**

South Canton transformer was overloaded in base case, and 4 post contingency constraints were also overloaded



**After**

8 branches (three 345 kV and five <200 kV) were opened to divert flows and relieve all overloads in the area, without changing the system dispatch



## Stress Test – 500 kV Facility Overload Relief

- We simulated a 300 MW overload on an important contingency constraint of a 500 kV branch by reducing the facility rating on a recent (July 2014) system snapshot
- As before, in this analysis transmission topology was the only variable allowed to be modified to relieve the induced overload
- TCA identified a collection of potential switching solutions, which included between 1 and 5 switching actions
- The potential solutions were tested by RTO staff on the EMS model
- Some solutions were able to relieve the overload without causing other post- or pre-contingency violations
- Relieving a large overload on an EHV facility required removing other EHV facilities from service, to force power flow away from the overloaded branch



## PJM RT Market Models: Historical Conditions

- Models based on one operational power flow snapshot per hour for the summer peak week in 2013 (July 14-20).
  - Data used from the power flows: transmission topology, branch parameters, unit commitment and dispatch, loads, shunt devices, interchange, initial voltage state
- Generation economic and transmission constraint data from real-time market
- Assumptions made include:
  - Fixed interface constraint limits at historical value used by RTO for same interval
  - Fixed dispatch of hydro, wind, landfill, nuclear and reliability must-run thermal units for the interval
  - Network service requirements for all non-radial loads and generators
  - No reserve requirements implemented in these models
- Model dimensions: up to 15,200 nodes and 650 dispatchable thermal units, about 4,700 monitored branches and 6,100 single and multi-element contingencies (fixed contingency list assumed to be sufficient for all relevant topology changes)



## TCA Economic Performance – Metrics

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***Production Cost Savings*** = production cost without TCA (full topology)  
– production costs with TCA

***Cost of Congestion*** = production cost with transmission constraints  
– production costs without transmission constraints

- The production or market Cost of Congestion defined above (different from congestion rent, which can be many times larger) provides an upper bound on the maximum system-wide Production Cost Savings attainable with any transmission efficiency approach or technology

**The weekly production cost savings due to TCA in PJM RT markets for the 2013 summer week could have exceeded 50% of the cost of congestion**



# Notes on the TCA Economic Performance

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## Realistic Criteria

- Solution time: **5 minutes** (computation limit) for each interval solution
- Cost of switching: minimum savings of \$200 per open or close breaker operation required to switch
- Reliability
  - Full security evaluation (6,000 contingencies) and enforcement (included in the 5 minute time limit)
- Starting conditions: same historical conditions as the RT markets

## Conservative Estimate

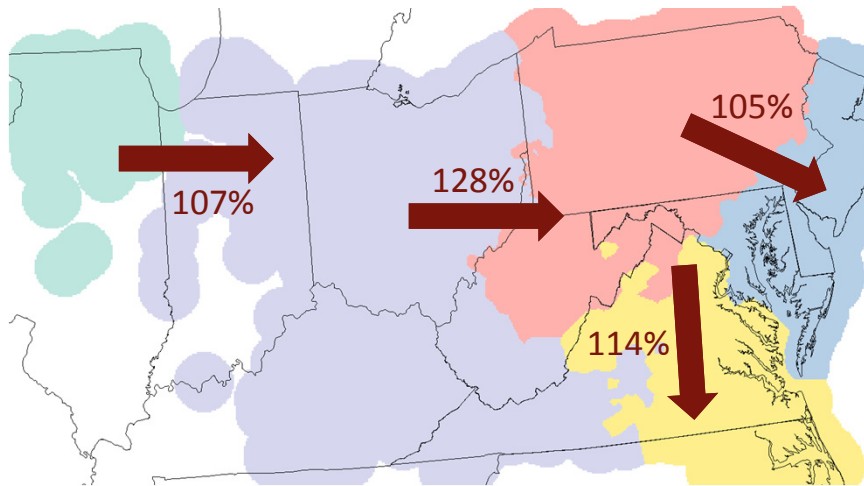
- Savings are in addition to any topology control action implemented by the RTO in that week
- Many potential topology change options are not visible in the “reduced” bus-branch power flow models (e.g., opening bus ties)



Market Efficiency Improvements

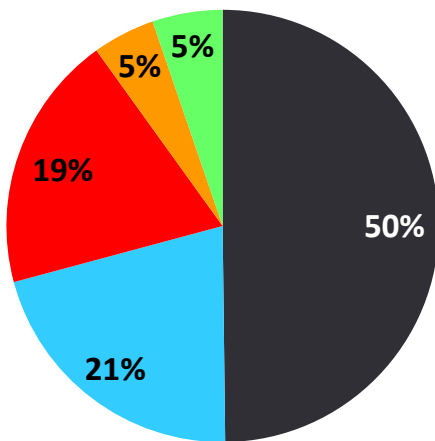
# TCA Results and Operation Statistics

Transfer Between RTO Regions

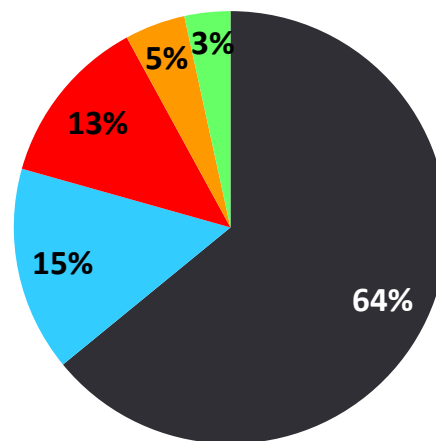


*Percentages are in reference to the weekly transfer without TCA. Flow pattern and transfer vary depending on seasons and system conditions. Overall, TCA significantly increases the transfer capability within the system.*

Breaker Operations by Voltage



Hours Facilities are Open by Voltage

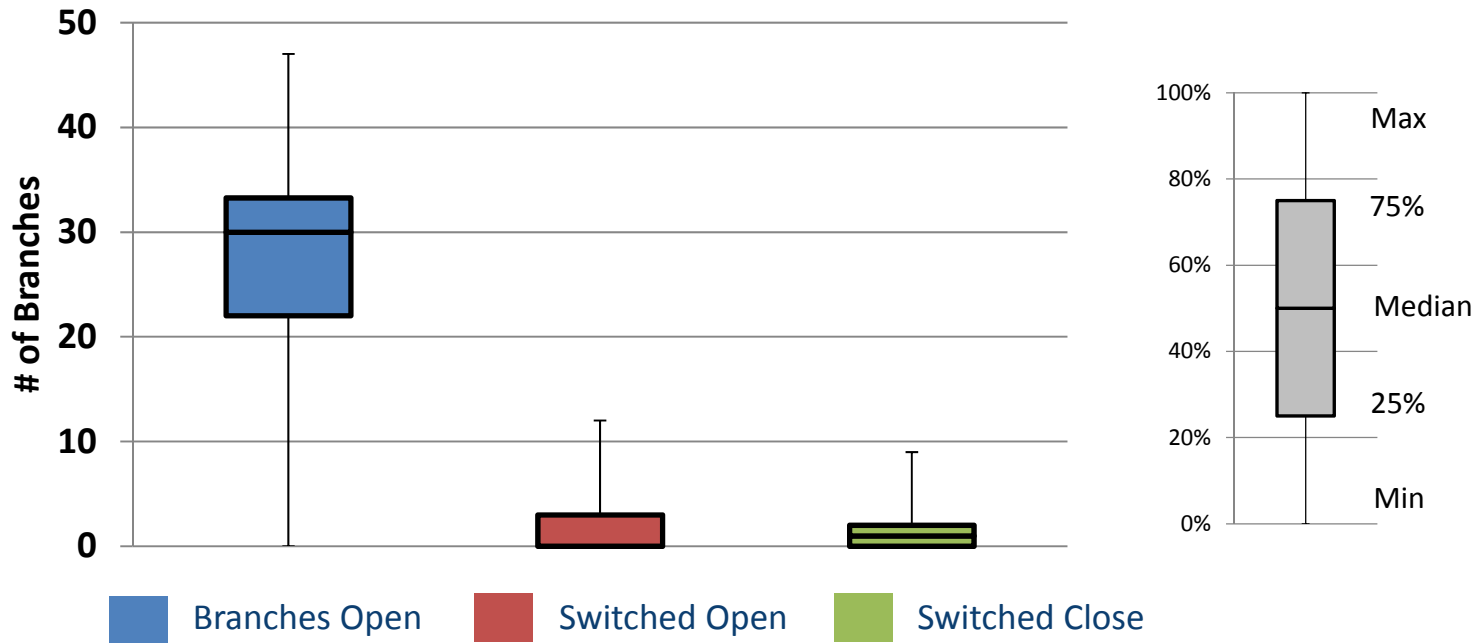


- < 200kV
- 230kV
- 345kV
- 500kV
- 765kV

*765 kV equipment is primarily switched out of service in anticipation of low load periods, such as the weekend or very early mornings, when they are not needed for reliability, are lightly loaded, and may cause over-voltage issues.*



# TCA Results and Operation Statistics



*Closed branches are branches that were opened by our algorithms in a previous hour.*

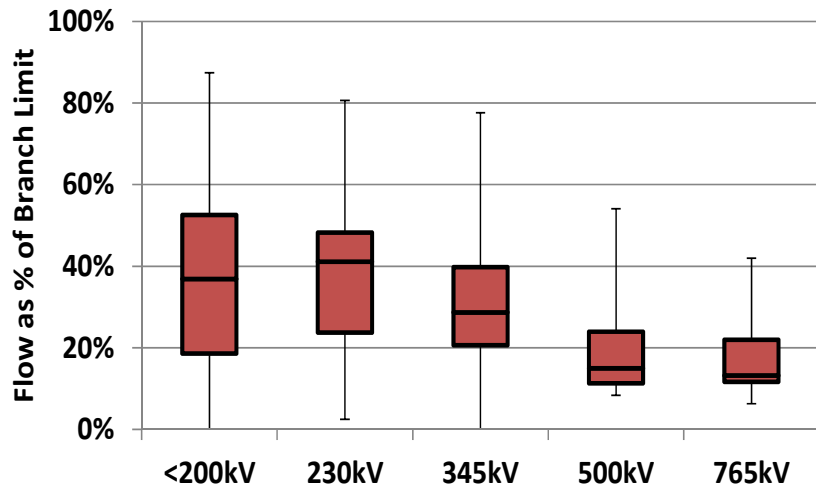
*The number of branches opened or closed in each hour is minimal, usually only a few switching actions per hour. The total number of branches opened by TCA as compared to maintenance and forced outages observed on systems today is small.*



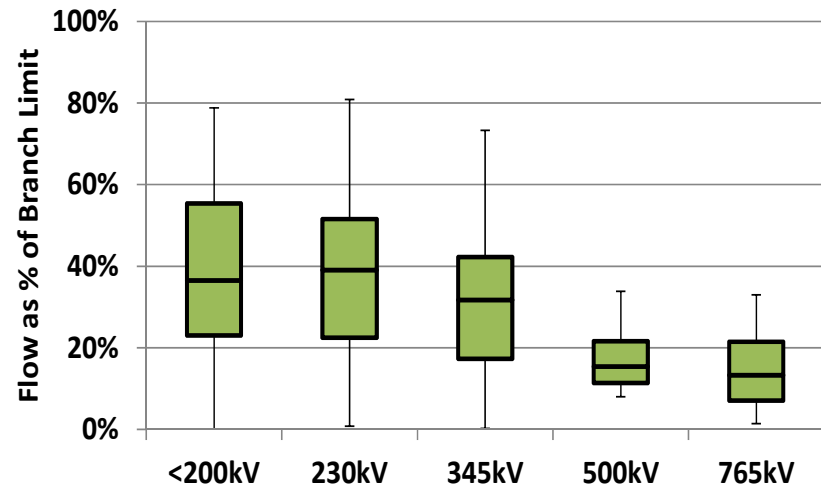
Market Efficiency Improvements

# Flow Statistics on Breakers Operated

Flows on Breakers Switched Open

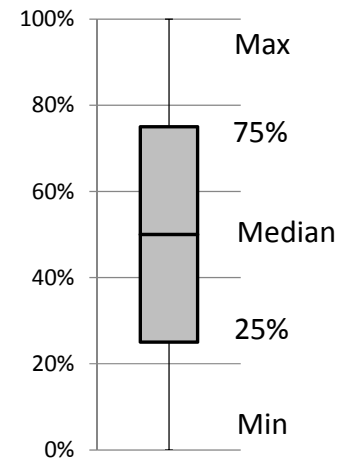


Flows on Breakers Switched Close



Switched Open      Switched Close

*Interrupted flow on breakers opened and post-closing flow on breakers closed tend to be well below normal facility ratings, and orders of magnitude below short circuit ratings, reducing the expected maintenance required to sustain the increased breaker duty*



## Concluding Remarks

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- Most system operators employ TC today, mainly on an ad-hoc basis using operators' previous experience
- The TCA project will provide practical technology to enable transparent, consistent and routine implementation of topology control with significant efficiency and reliability gains
- Lessons from simulations on detailed, full-scale RTO models:
  - Security-constrained TCA solutions are obtained in only a few minutes
  - TCA can be very effective in identifying reconfigurations for overload relief with application in contingency planning and outage coordination
  - Simulations on RT market models for a summer peak week indicate that the cost of congestion in RT markets could be reduced significantly (by over 50% in some systems)
  - Impacts of co-optimized topology and unit commitment on DA markets are expected to be significantly larger (analysis ongoing, initial results expect by Q4 2014)



# Contacts

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