Topology Control Algorithms (TCA)

Simulations in PJM with AC Modeling

Pablo A. Ruiz, Michael Caramanis, Evgeniy Goldis, Bhavana Keshavamurthy, Xiaoguang Li, Russ Philbrick, Alex Rudkevich, Richard Tabors, Bruce Tsuchida

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Agenda

Topology Control Algorithms (TCA)

- **Objectives and Motivation**
- **Illustration of Topology Control**
- **ARPA-E TCA Project**
- **Simulation Results on PJM RT Markets**
- **Relieving Overloads Through TCA**
- **Concluding Remarks**

Topology Control Algorithm

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

1. **Provide additional operational controls**
   - manage congestion
   - respond during contingency situations
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

Congestion in RT Markets: PJM

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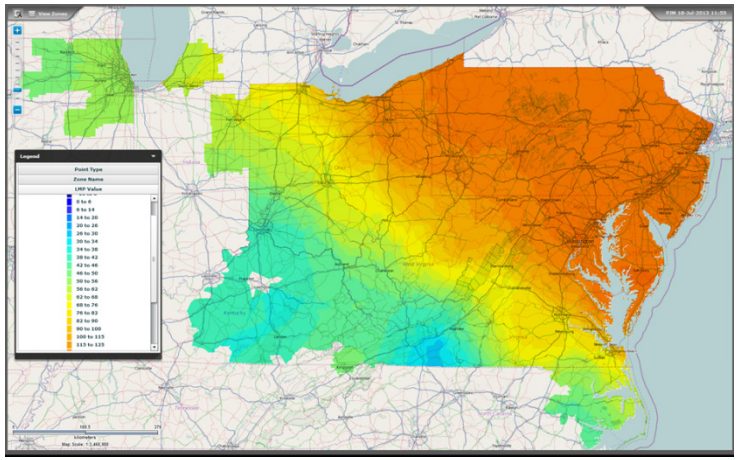

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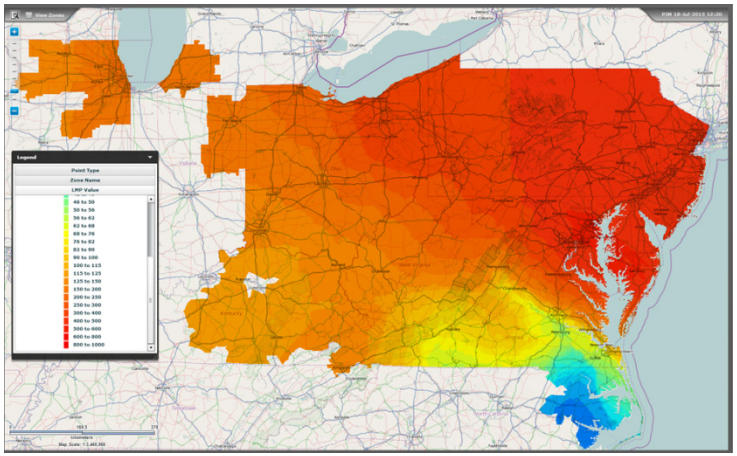

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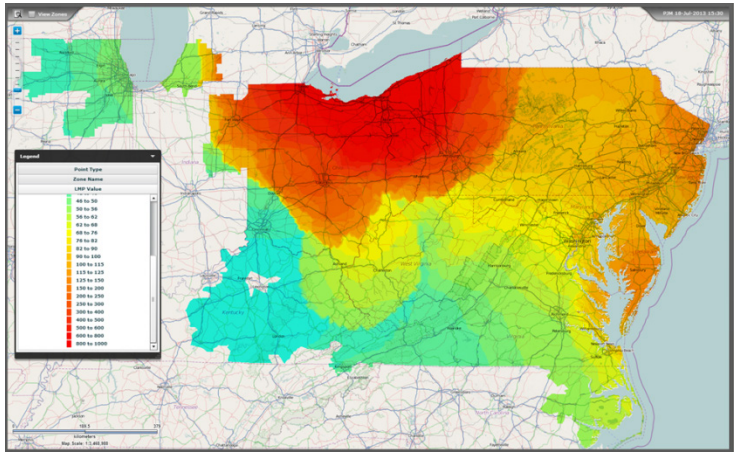


In the course of a day, congestion patterns and prices can change significantly:

- Fuel diversity
- Lack of flexibility in the resource mix

Having the ability to dynamically increase transfer capability from low price areas to high price areas will help to relieve congestion, improve dispatch of renewable resources, reduce dispatch costs and increase system flexibility.

7-bus Example: All Lines Closed

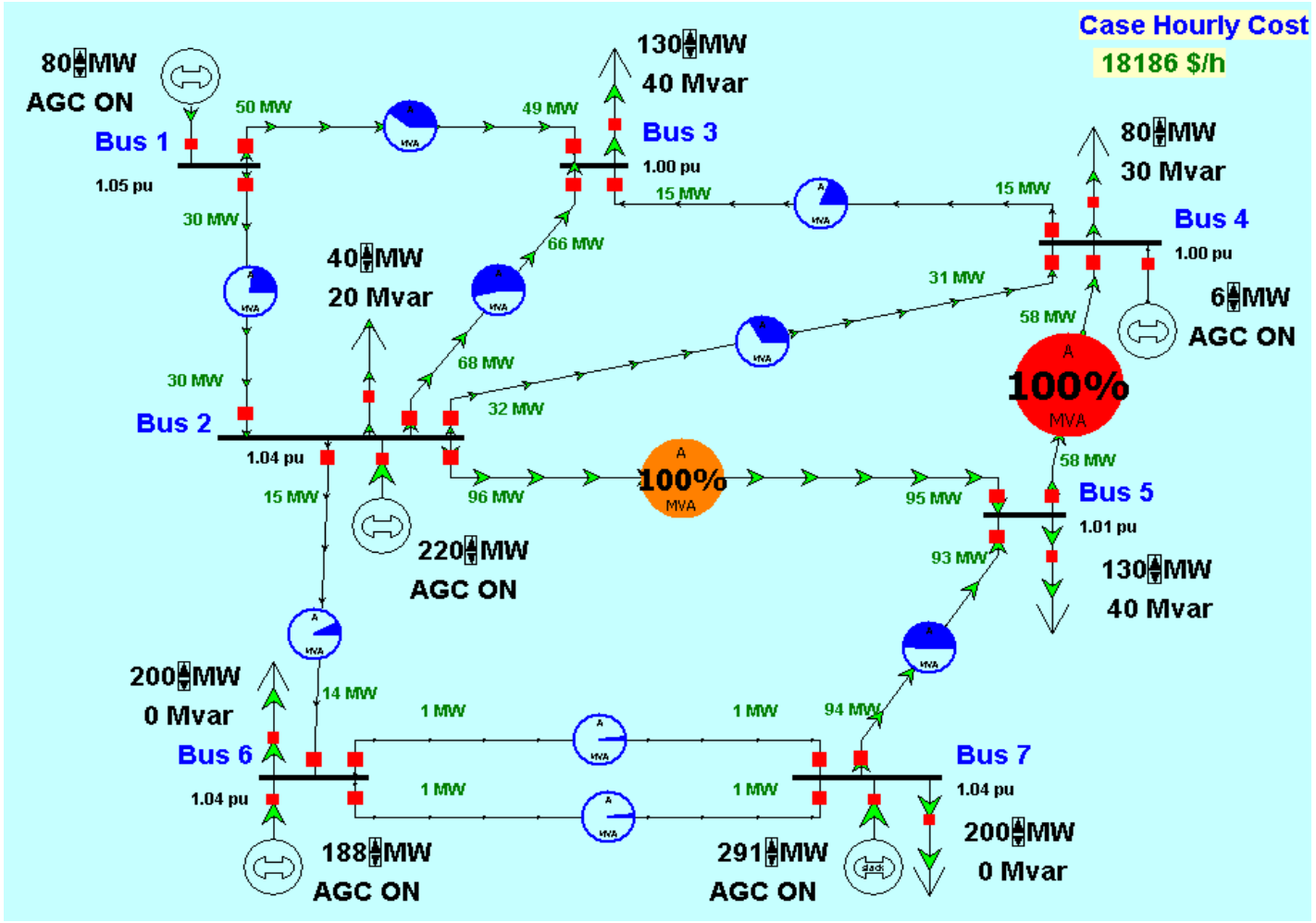
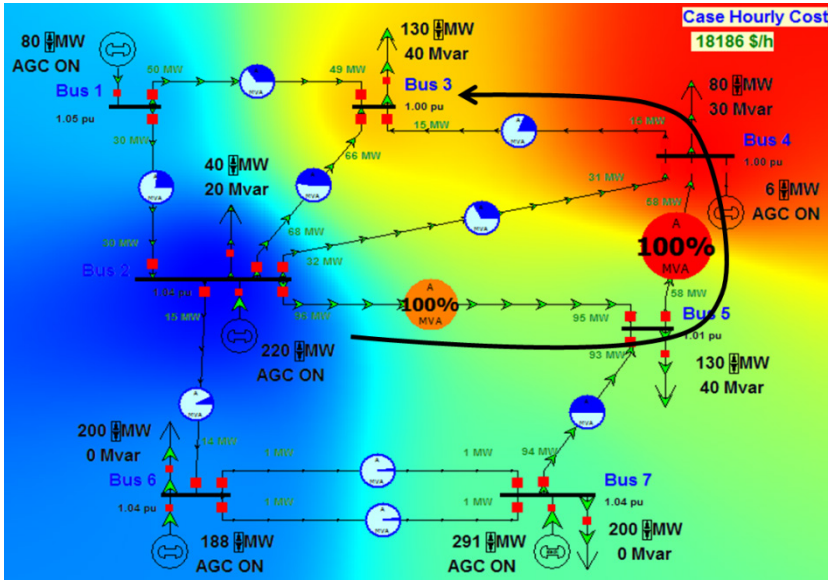


Illustration of Topology Control

7-bus Example Results



$40/MWh

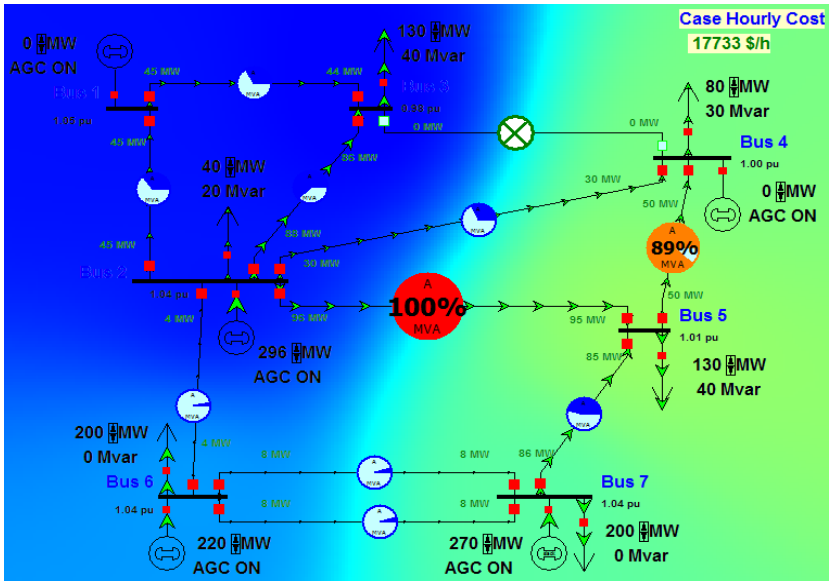
$15/MWh

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

Objectives and Focus

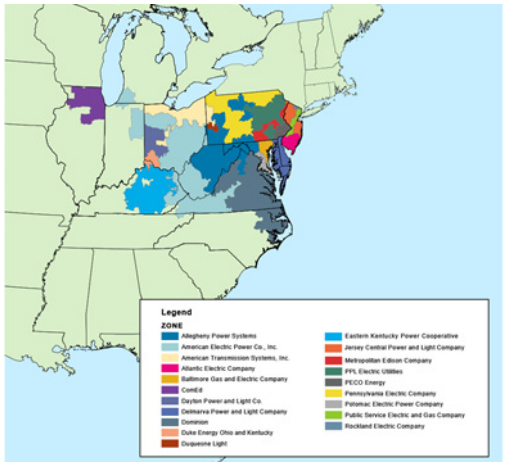
To develop a full-scale algorithm and software implementation for transmission network topology control

- Operating in conjunction with market engines for security-constrained unit commitment (UC) and economic dispatch (ED);
- Meeting computational effort requirements aligned with RT and DA market timeframes

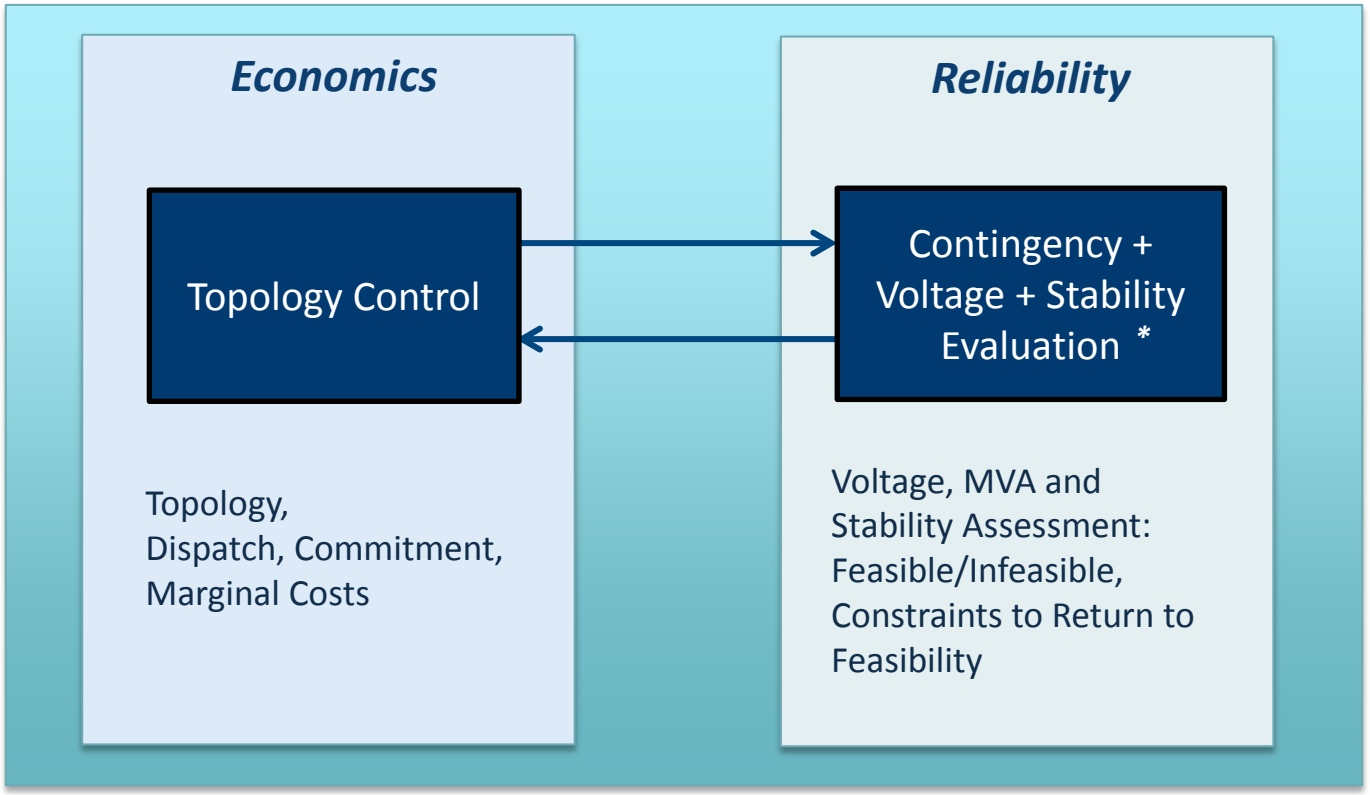
The algorithms developed will be tested in a simulated environment replicating PJM market operations.

Focus:

- Tractability: TCA must work on 13,000+ bus systems
- Dynamics: Look-ahead TC decisions in ED and UC contexts
- Reliability: Connectivity, security constraints, transient stability and voltage criteria met
- Impacts: Economic and renewable integration benefit evaluation, with estimated production cost savings in PJM of over $100 million/year



Basic TC Software Architecture



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

Transmission Flow Modeling

AC Assumptions

- Full set of power flow equations modeled: real and reactive power, nodal voltage magnitude and angle
- Losses automatically calculated from power flow solution
- Equations linearized around operating point for optimization

DC Assumptions

- Power flow equations limited to real power. Voltage magnitudes assumed to be 1.0 per unit
- Losses copied from full topology AC case, and distributed among the loads. The distribution does not change as topology and dispatch are modified

Characteristics of AC Modeling

- Ensure AC feasibility during each iteration in TCA
- Accurate modeling of losses in the system as topology changes
- Accurate modeling of branch MVA limits
- Ability to model voltage constraints
- …but it increases the computational effort

PJM RT Market Models: Historical Conditions

- Models based on one operational power flow snapshot per hour for three representative historical weeks in 2010 (summer, shoulder and winter weeks). Data used from the power flows:
  - Transmission topology, branch parameters, unit commitment and dispatch, loads, shunt devices, interchange, and 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 PJM 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 PJM units, about 4,700 monitored branches and 6,100 single and multi-element contingencies

Model setup and results reviewed by PJM

TCA Economic Performance – Metrics

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 estimated annual production cost savings in PJM RT markets under 2010 conditions are *over $100 million*

- Based on the weekly simulation results

Notes on the TCA Economic Performance

Realistic Criteria

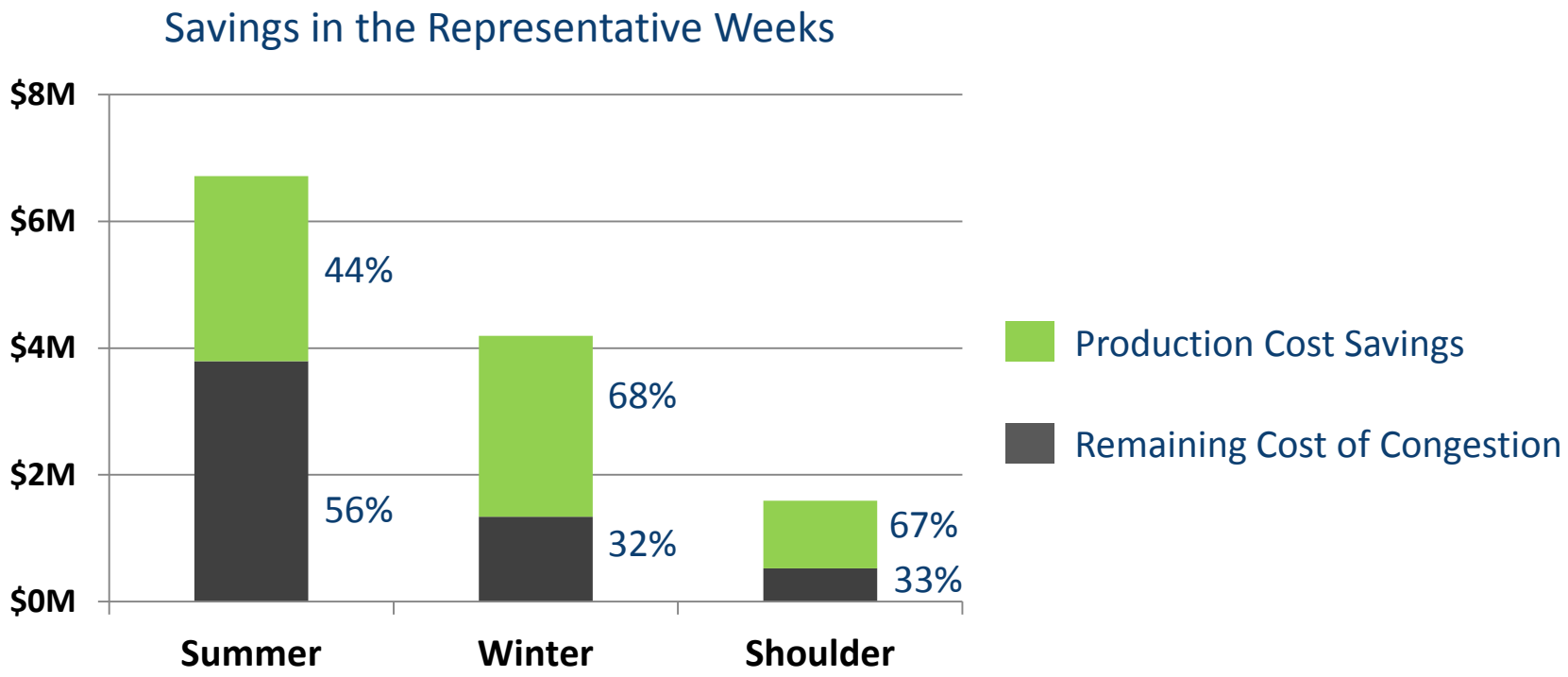
- Solution time: **5 minutes** (computation limit) for each interval solution
- Cost of switching: minimum savings of $200 per open or close breaker operation required to switch
- Reliability
  - Full security evaluation (6,000 contingencies) and enforcement (included in the 5 minute time limit)
- Starting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

Conservative Estimate

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

AC Simulation Results: Average 2010 Conditions

RT Market Production Cost Savings



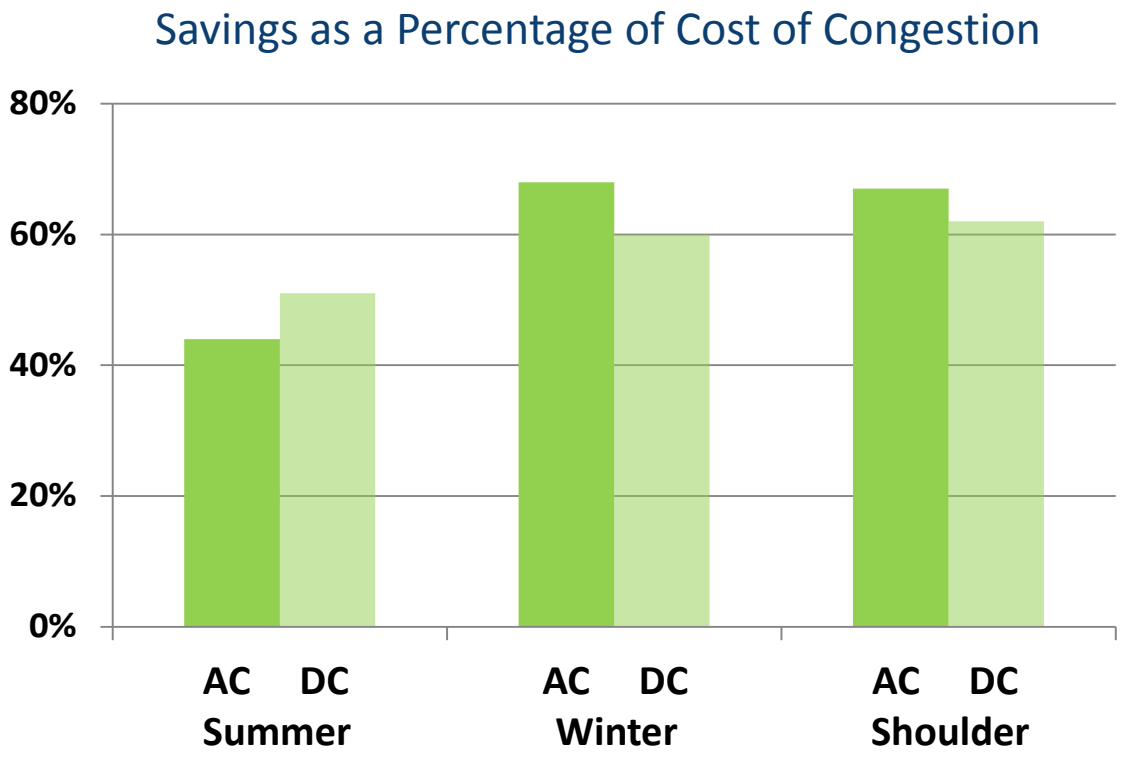
* Savings and remaining cost of congestion shown as a percentage of the total cost of congestion

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

AC Simulation Results: Average 2010 Conditions

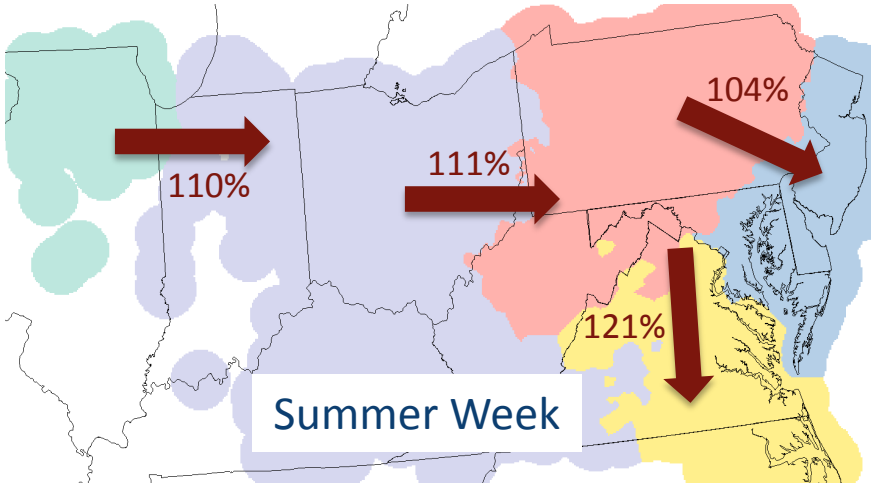
Comparison of AC and DC Simulations

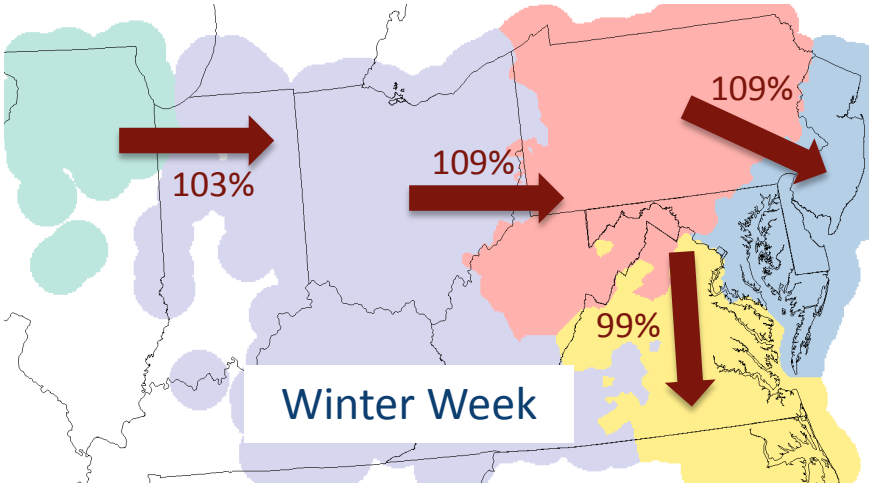


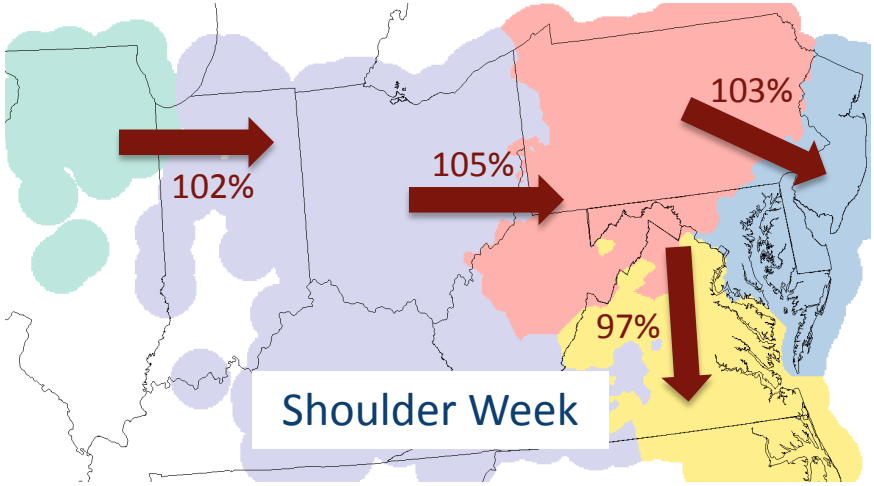
With AC modeling, the percentage of cost of congestion that is saved through TCA remains very high, and of the same magnitude as the DC results reported previously.

AC Simulation Results: Average 2010 Conditions

Transfers Between PJM Regions



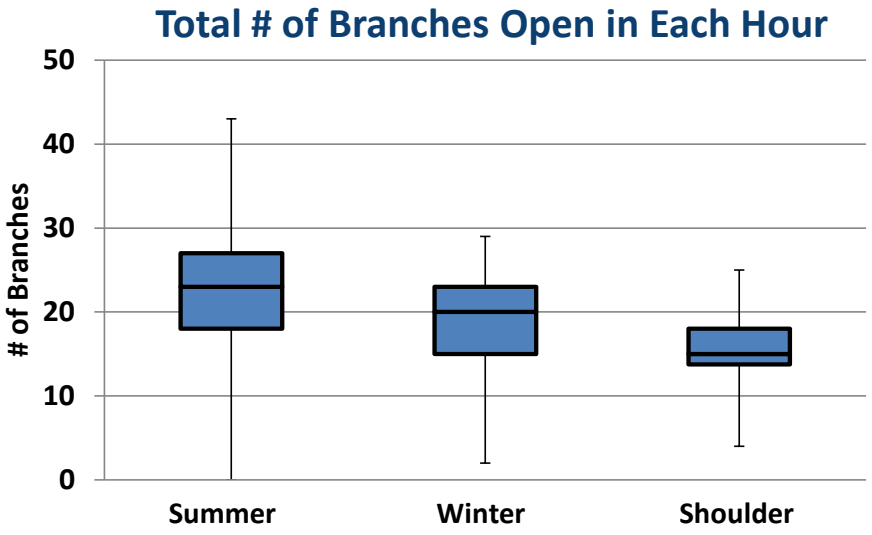


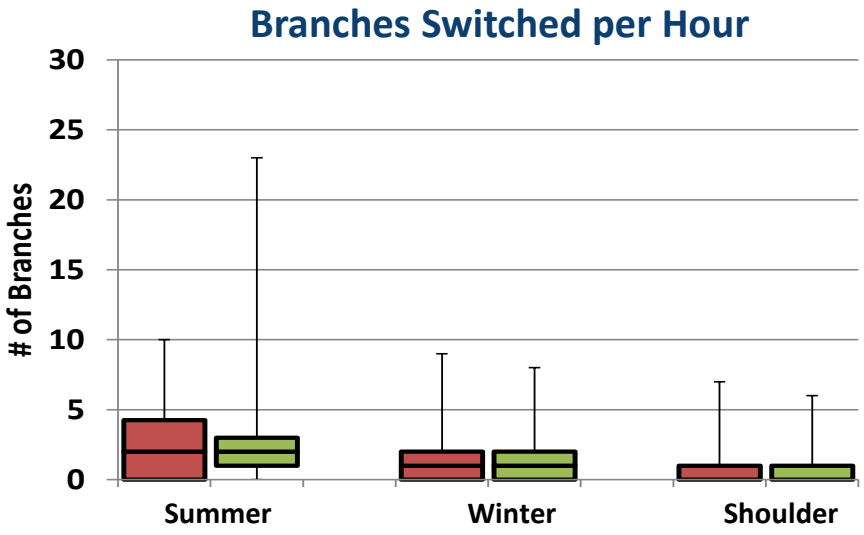


Percentages are in reference to the weekly transfer without TCA. Flow pattern and transfer vary depending on seasons and system conditions. Overall, TCA significantly increases the transfer capability within the system.

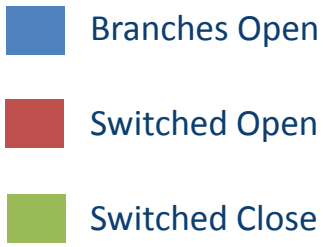
AC Simulation Results: Average 2010 Conditions

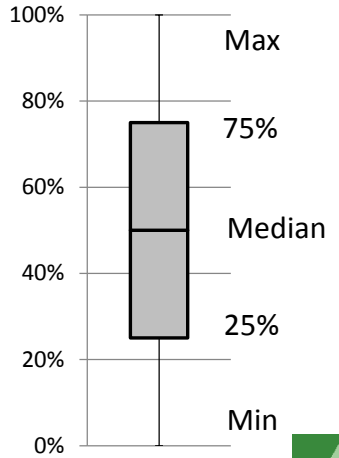
TCA Topology Change Statistics





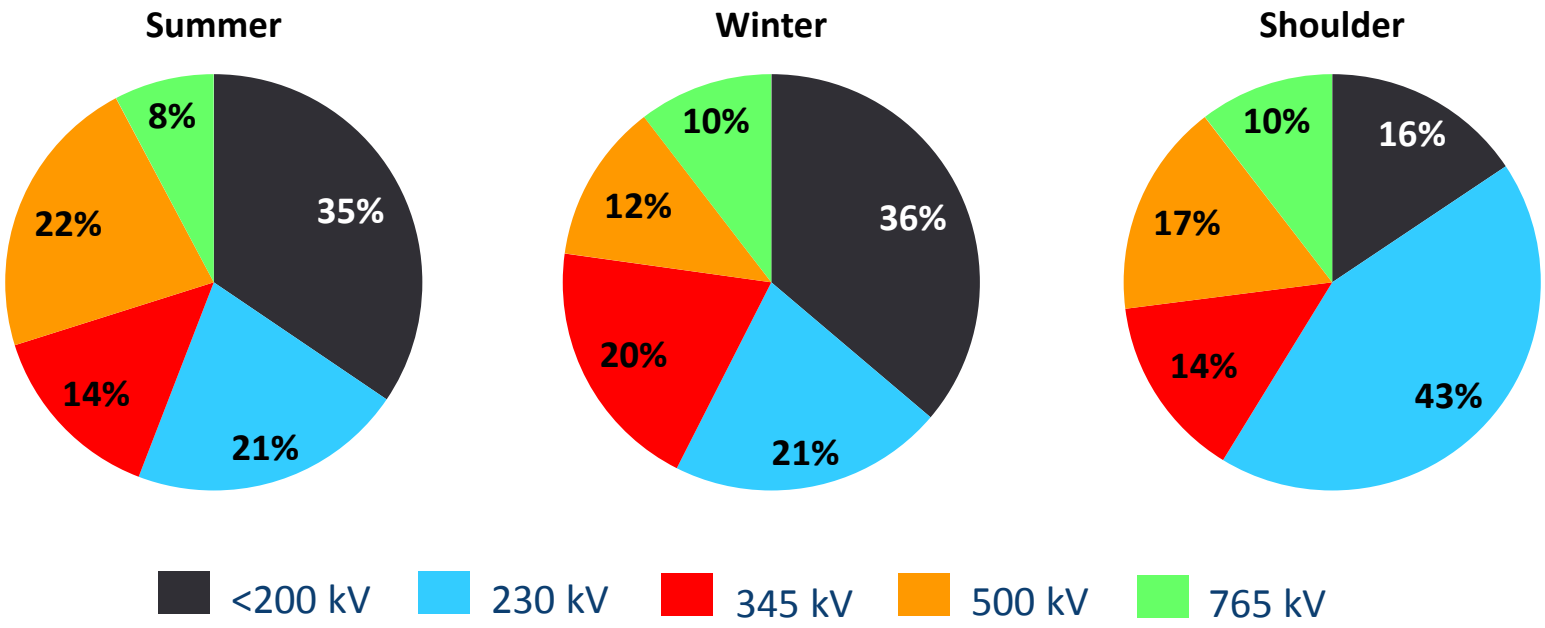
The number of branches opened or closed in each hour is minimal, usually only a few switching actions per hour. The total number of branches opened by TCA as compared to maintenance and forced outages observed on systems today is ***small****.*





Breaker Operations by Voltage Level

Percentage of Breaker Operations by Voltage Level

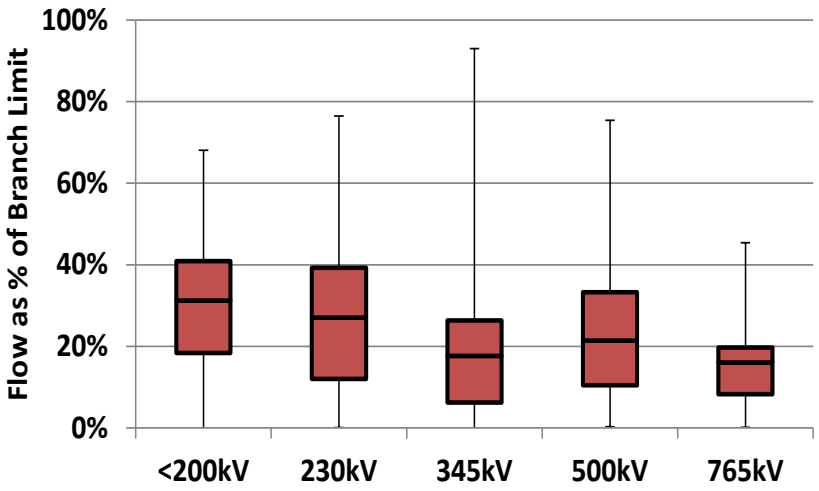


765 kV breakers are mostly opened during low load periods, such as the weekend or very early mornings, when they are not needed for reliability, are lightly loaded, and may cause over-voltage issues.

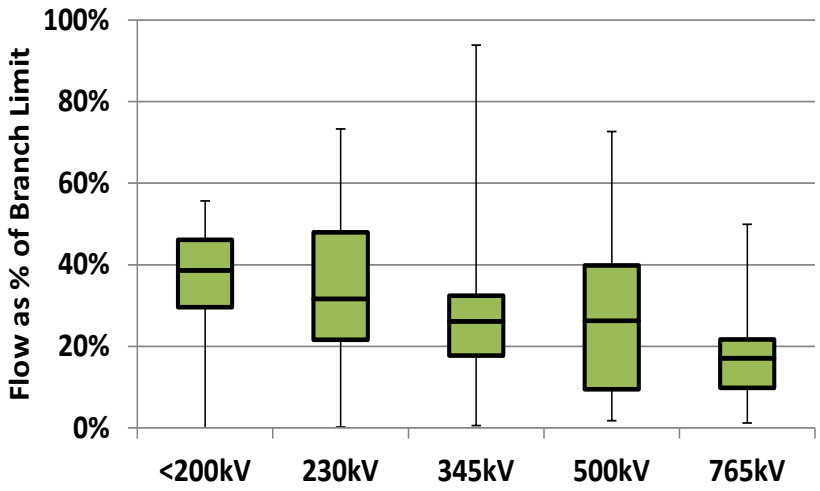
Flow Statistics on Breakers Operated

For Summer Week of 2010

Flows on Breakers Switched Open



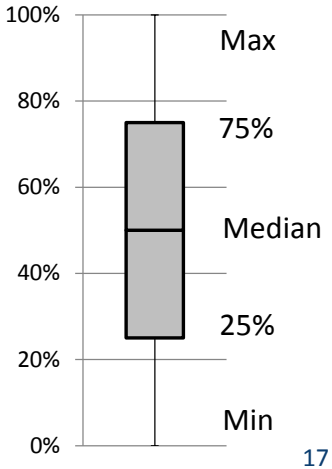
Flows on Breakers Switched Close



Flows on breakers opened or closed are well below normal facility ratings, and orders of magnitude below short circuit ratings, reducing the expected maintenance required to sustain the increased breaker duty

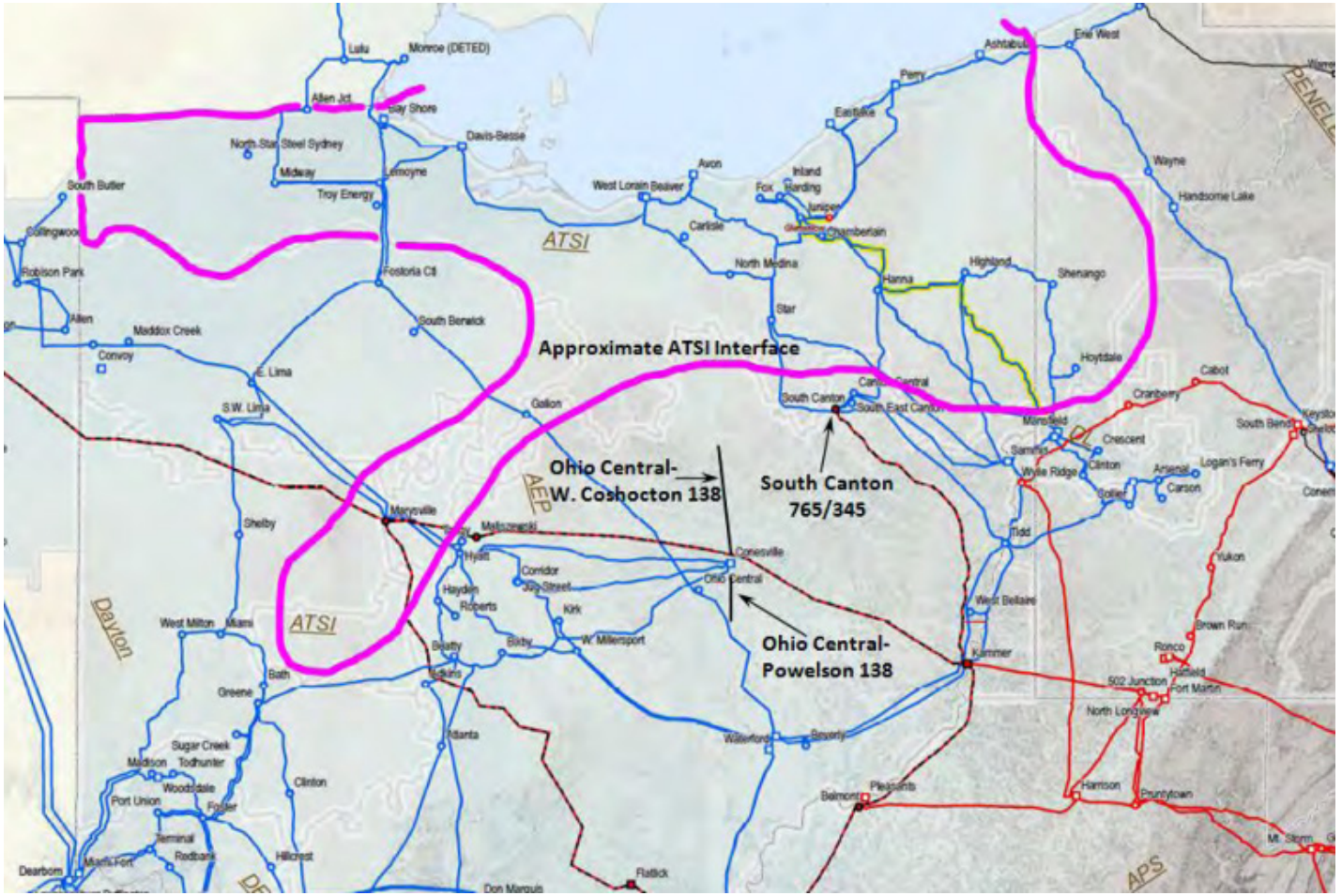
Switched Open

Switched Close



Relieving Overloads Through TCA

South Canton Congestion Relief



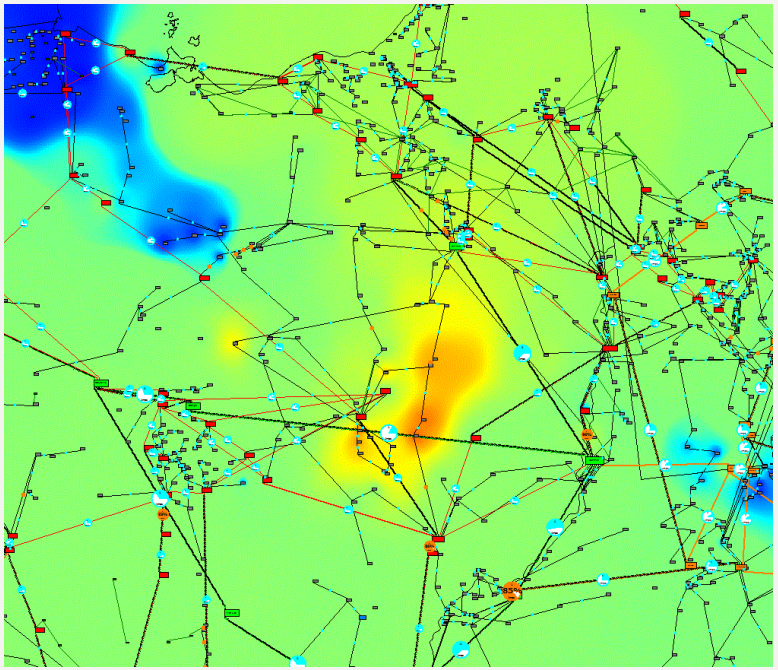
Source: http://www.pjm.com/~/media/committees-groups/committees/mrc/20130829/20130829-item-13-hot-weather-operations-presentation.ashx

South Canton Congestion Relief

- The South Canton transformer was severely congested and with base case overloads on July 15th
  - 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

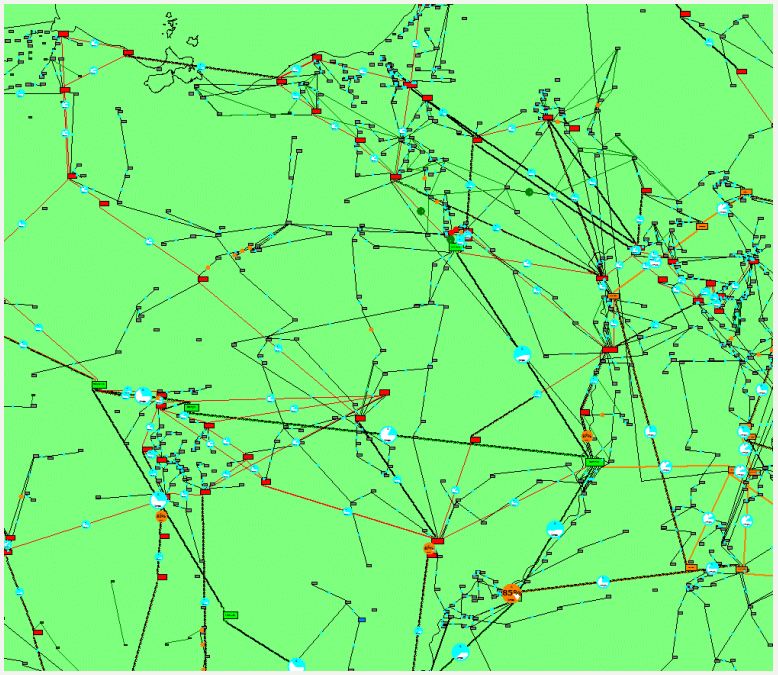
Overload Relief Example

July 15th, 2013 at 3PM



Before

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



After

8 branches (3 345 kV and 5 <200 kV) were opened to divert flows and relieve all overloads in the area, without changing the system dispatch

Concluding Remarks

- 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 the PJM evaluation:
  - Hourly security-constrained TCA solutions with AC modeling are obtained in only a few minutes
  - Simulations on detailed PJM RT market models indicate that annual PJM savings are over $100 million (under 2010 conditions), over 50% the estimated total costs of congestion observed in the PJM RT markets
  - 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)

Potential Implications

- Implementation of topology control further increases the benefits of centralized regional system operations
- Due to increases in wide-area transfers, we expect new transmission investments to be more valuable with topology control
- Topology control may reduce the need for underlying system reinforcements that otherwise would be required to support EHV transmission projects
- Topology control is very effective in relieving local congestion. As such, it will likely reduce congestion-related costs associated to transmission outages, including construction/upgrade-related outages
- Renewables curtailment would decrease significantly with topology control in areas where curtailments are driven by system-level transmission constraints (as opposed to radial line constraints)

Contacts

Pablo A. Ruiz, *Principal Investigator*
Boston University and *The Brattle Group*,
Pablo.Ruiz@brattle.com,
(617) 234-5748

http://www.topologycontrol.com

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