Transmission Topology Control Algorithms (TCA)

Simulations on PJM Real Time Markets

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TCA/RATC Workshop on Topology Control
PJM Conference and Training Center
Norristown, PA
November 19, 2013

Agenda

Topology Control Algorithms (TCA)

- Objectives and Motivation
- Illustration of Topology Control
- ARPA-E TCA Project
- Simulation Results on PJM RT Markets
  - Average 2010 Conditions
  - Summer Peak 2013 Conditions
  - High Renewables Scenarios (preliminary)
- Concluding Remarks

Topology Control Algorithm

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

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

TCA Timeframe: from a few days ahead up to real-time

Congestion in RT Markets: PJM

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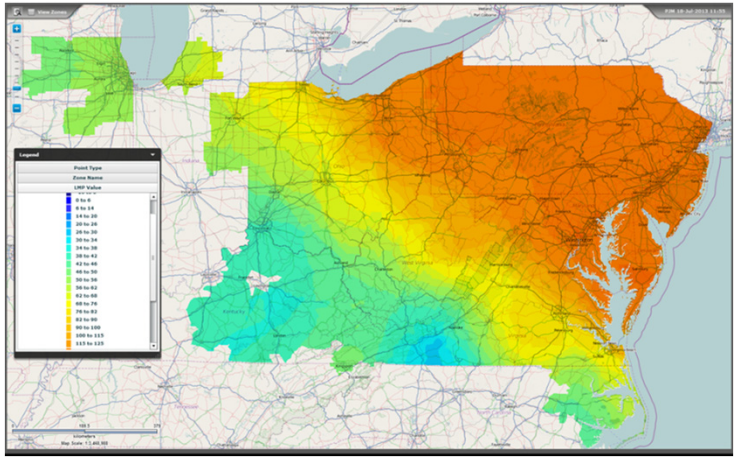

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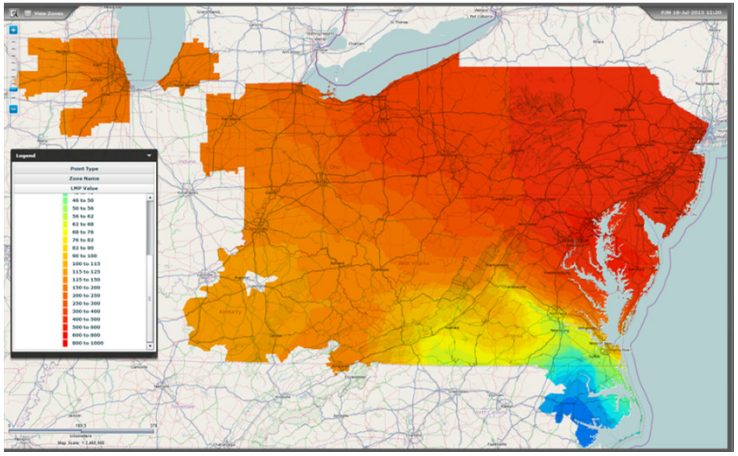

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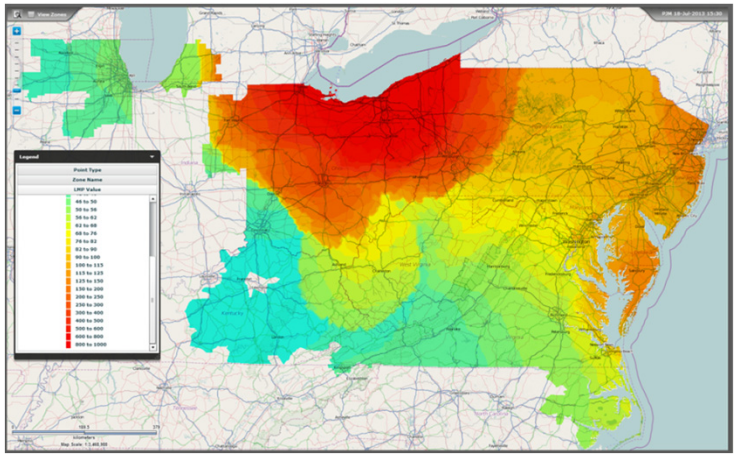


In the course of a day, congestion patterns and prices can change significantly:

- 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.

Illustration of Topology Control

7-bus Example: All Lines Closed

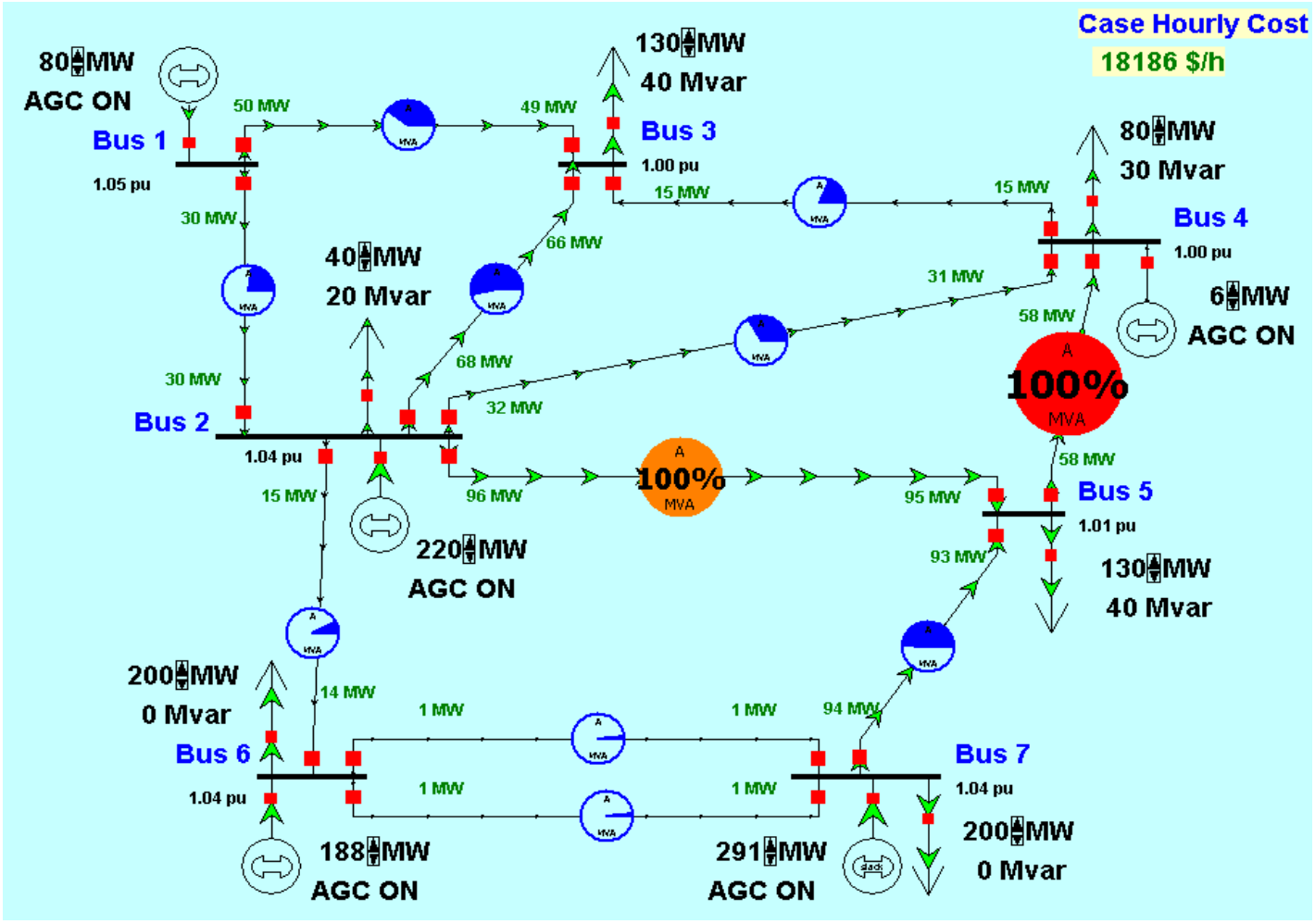
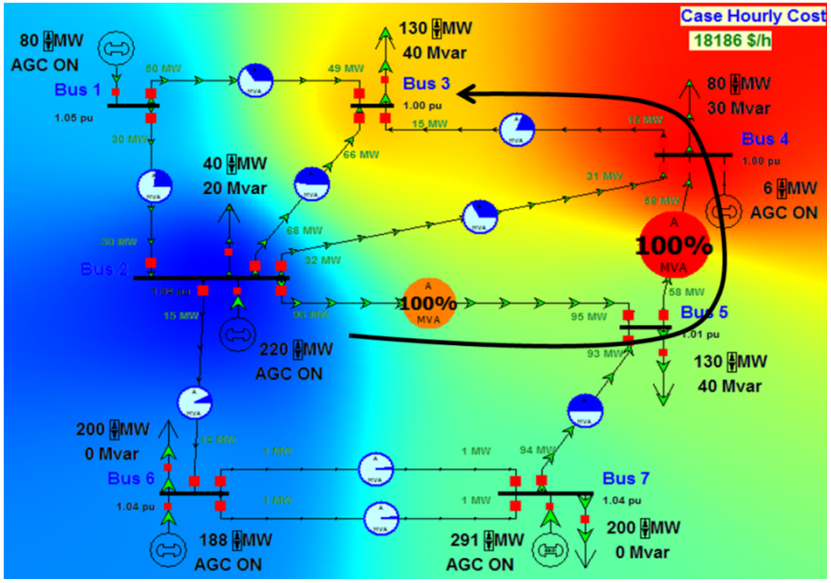


Illustration of Topology Control

7-bus Example Results



$40/MWh

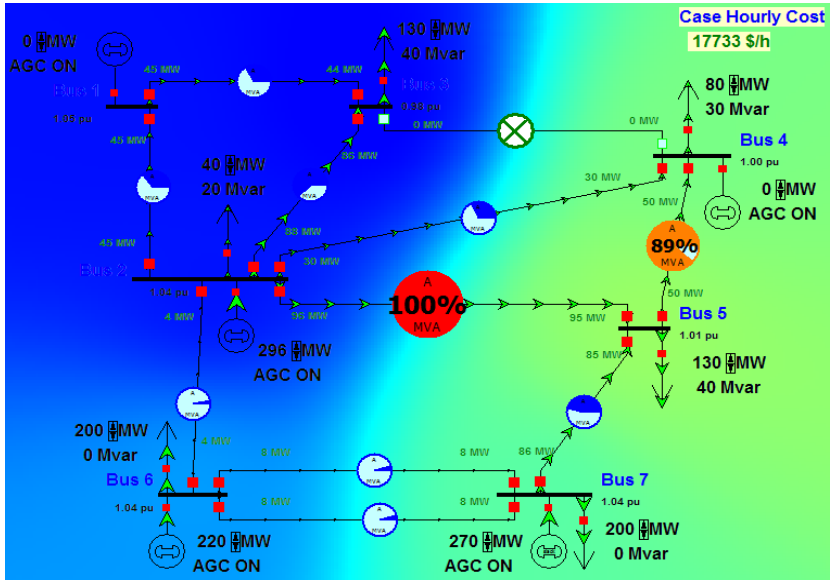
$15/MWh

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

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ARPA-E TCA Project

Objectives and Focus

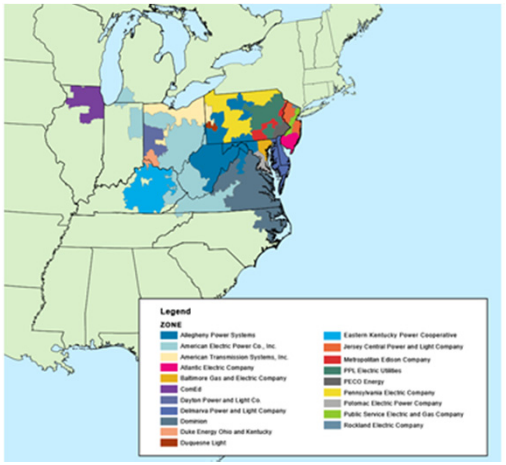
To develop a full-scale algorithm and software implementation for transmission network topology control

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

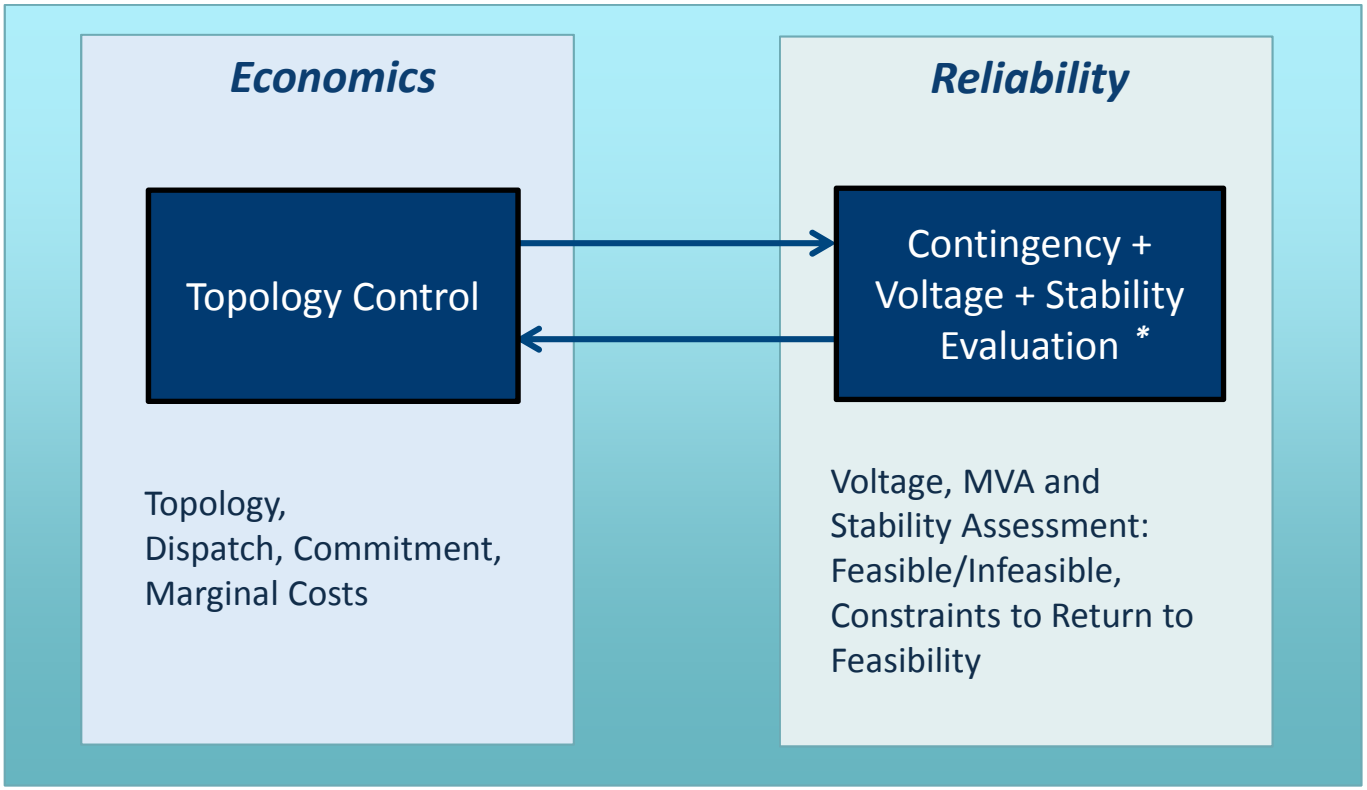
The algorithms developed will be tested in a simulated environment replicating PJM market operations.

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 expected production cost savings in PJM of over $100 million/year



Basic TC Software Architecture



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

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) and one summer peak week in 2013. Data used from the power flows:
  - Transmission topology, branch limits, unit commitment and dispatch, loads, losses, and interchange
- Generation economic and 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

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Simulation Results: Average 2010 Conditions

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*

Average load LMP decrease, leading to estimated annual energy payment reductions of over $1 billion (under 2010 conditions)

- Based on the weekly simulation results

Notes on the TCA Economic Performance

Realistic Criteria

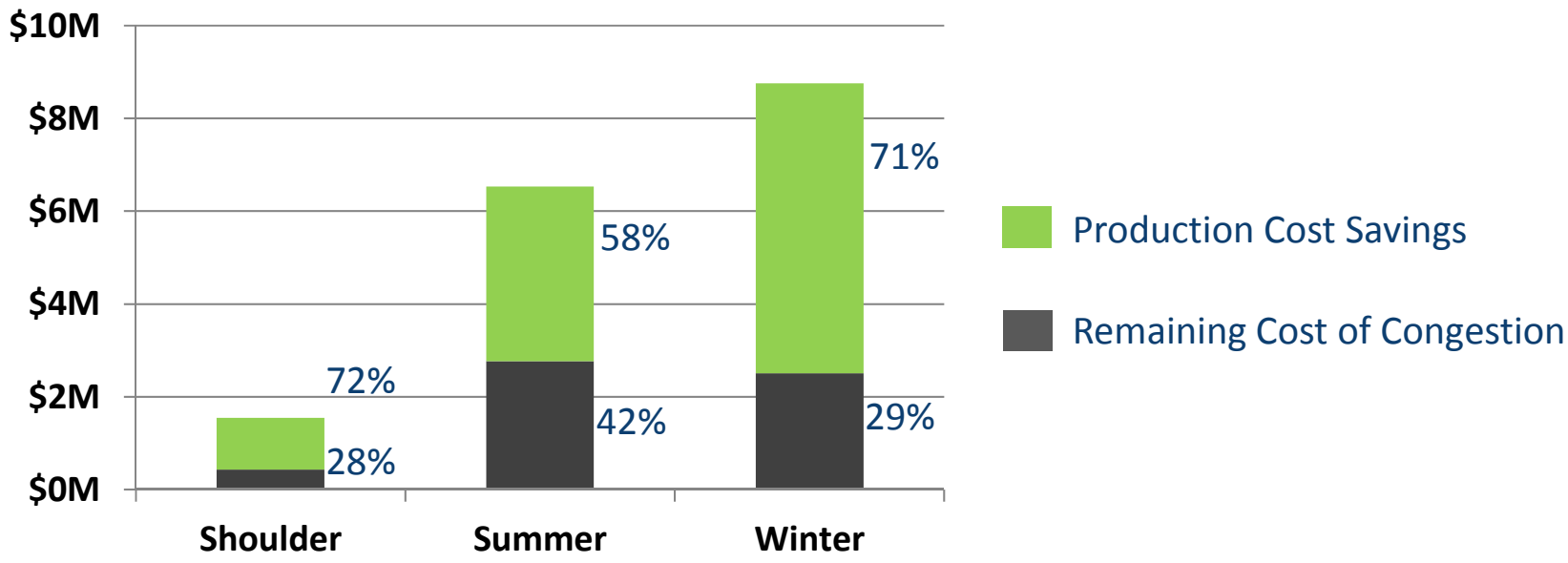
- Solution time: **5 minutes** (computation limit) for each interval solution
- Cost of switching: minimum savings of $100 per open or close breaker operation required to switch
- Reliability
  - Full security evaluation (6,000 contingencies) and enforcement (included in the 5 minute time limit)
- Starting 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)

Simulation Results: Average 2010 Conditions

RT Market Production Congestion Savings

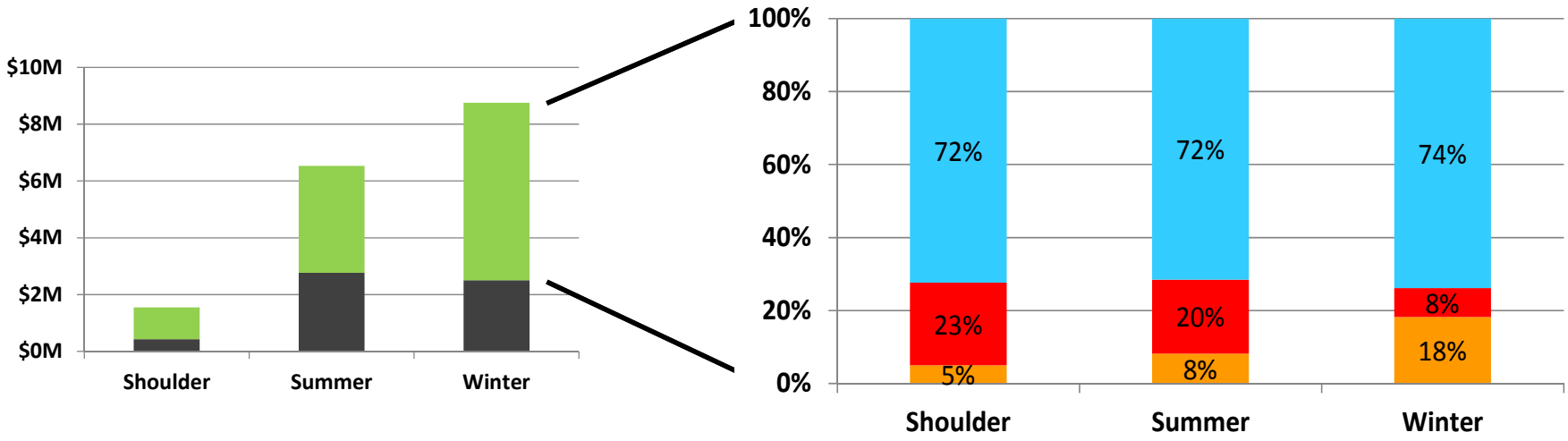


* Savings and remaining cost of congestion shown as a percentage of the total cost of congestion

Simulation Results: Average 2010 Conditions

RT Market Production Congestion Savings

Impacts of Limiting the Switchable Set on Production Cost Savings



Production Cost Savings

Remaining Cost of Congestion

Savings Captured by Branches ≤ 230 kV

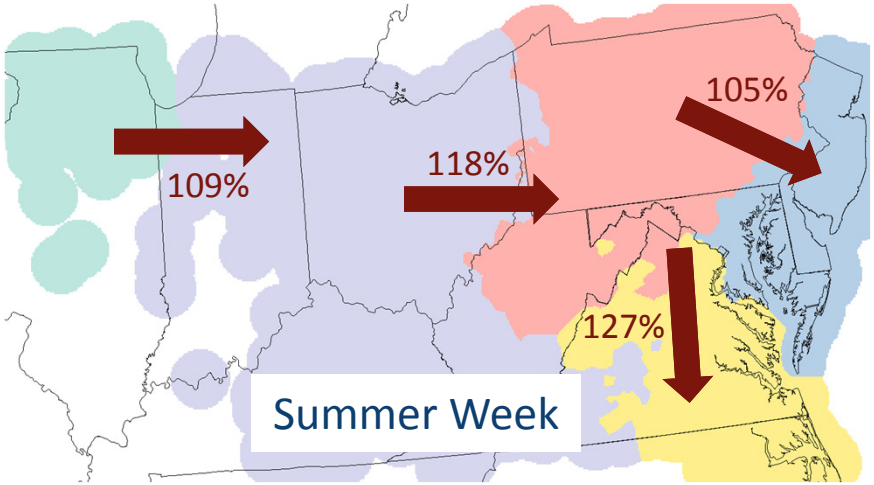
Additional Savings Enabled by 345 kV Branches

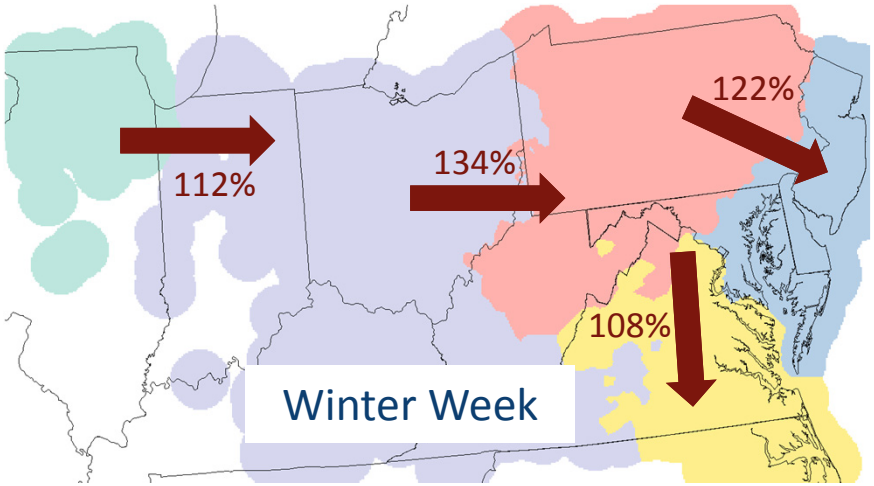
Additional Savings Enabled by Branches ≥ 500 kV

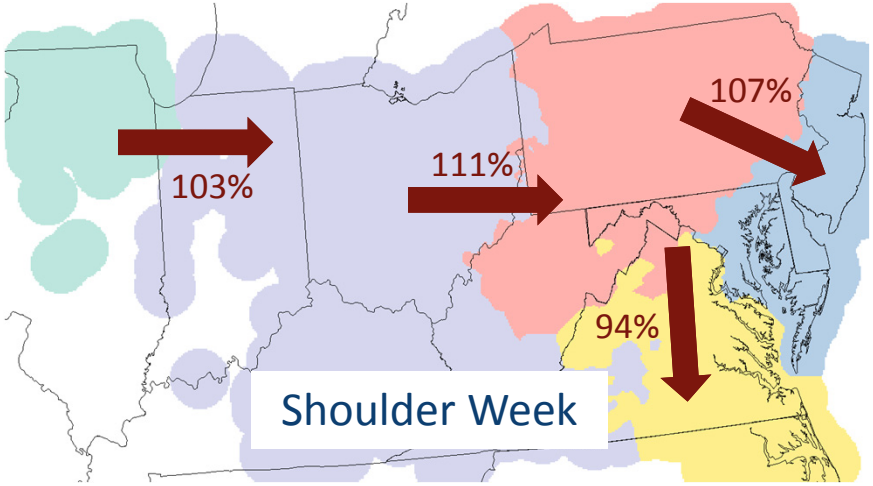
* Savings enabled by voltage level shown as a percentage of the total savings

Simulation Results: Average 2010 Conditions

Transfers Between PJM Regions



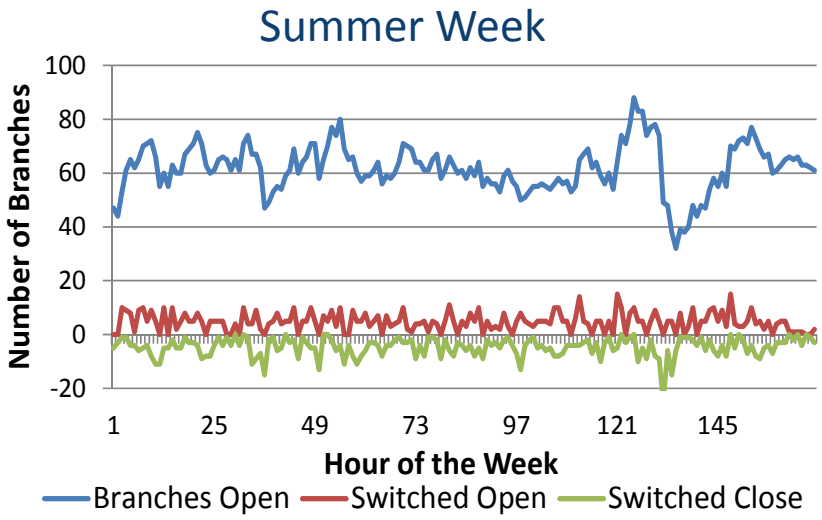


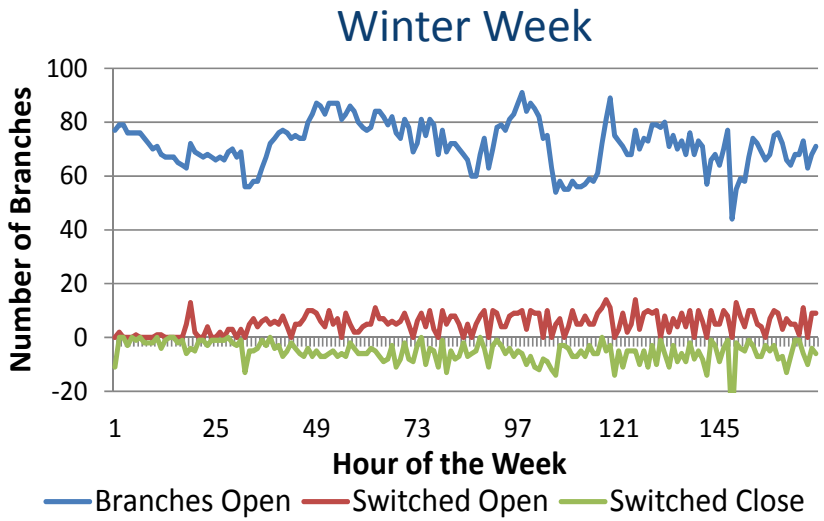


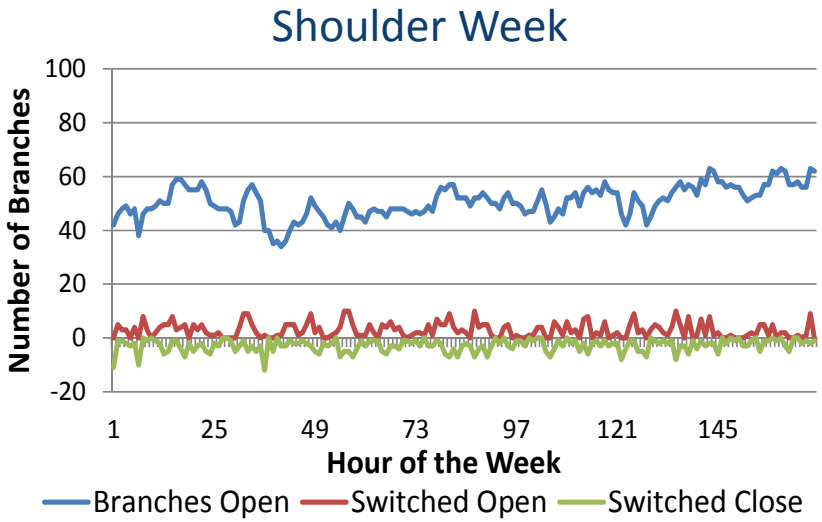
Percentages are in reference to the weekly transfer without TCA. Flow pattern and transfer vary depending on seasons and system conditions. Overall, TCA significantly increases the transfer capability within the system.

Simulation Results: Average 2010 Conditions

Number of Topology Changes per Hour



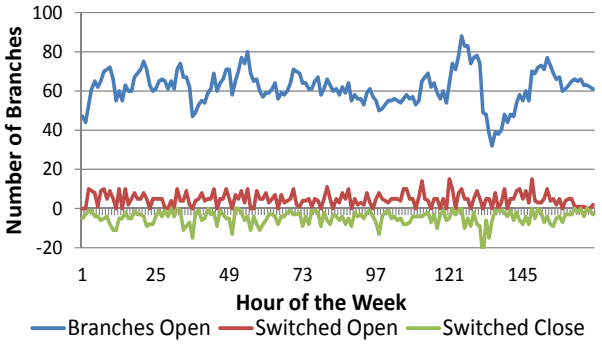


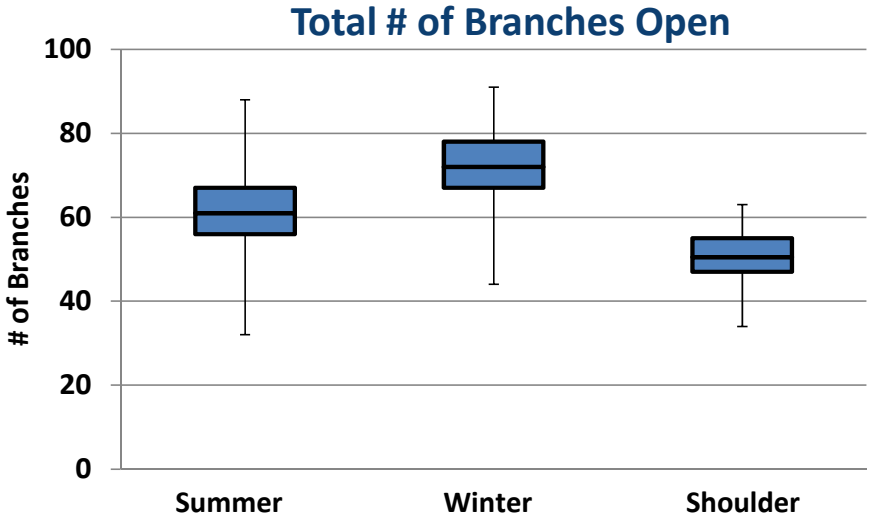


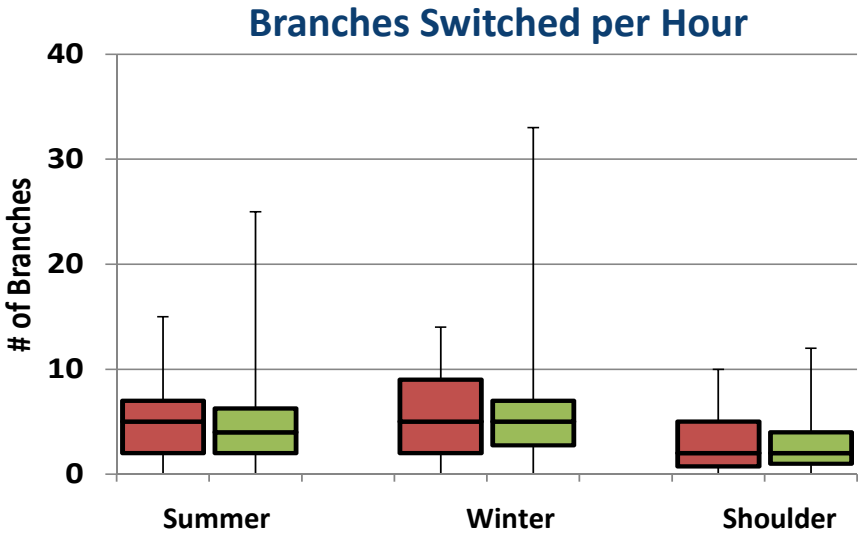
The total # of branches open with TCA is stable during the week and does not exceed 100 at any given hour

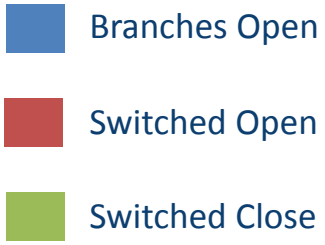
Simulation Results: Average 2010 Conditions

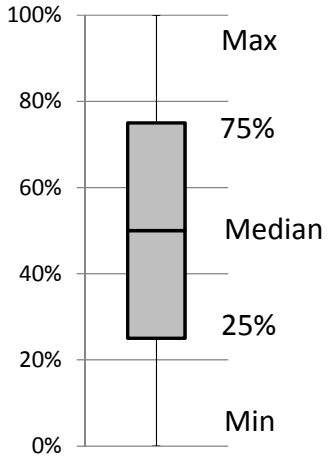
Topology Change Statistics





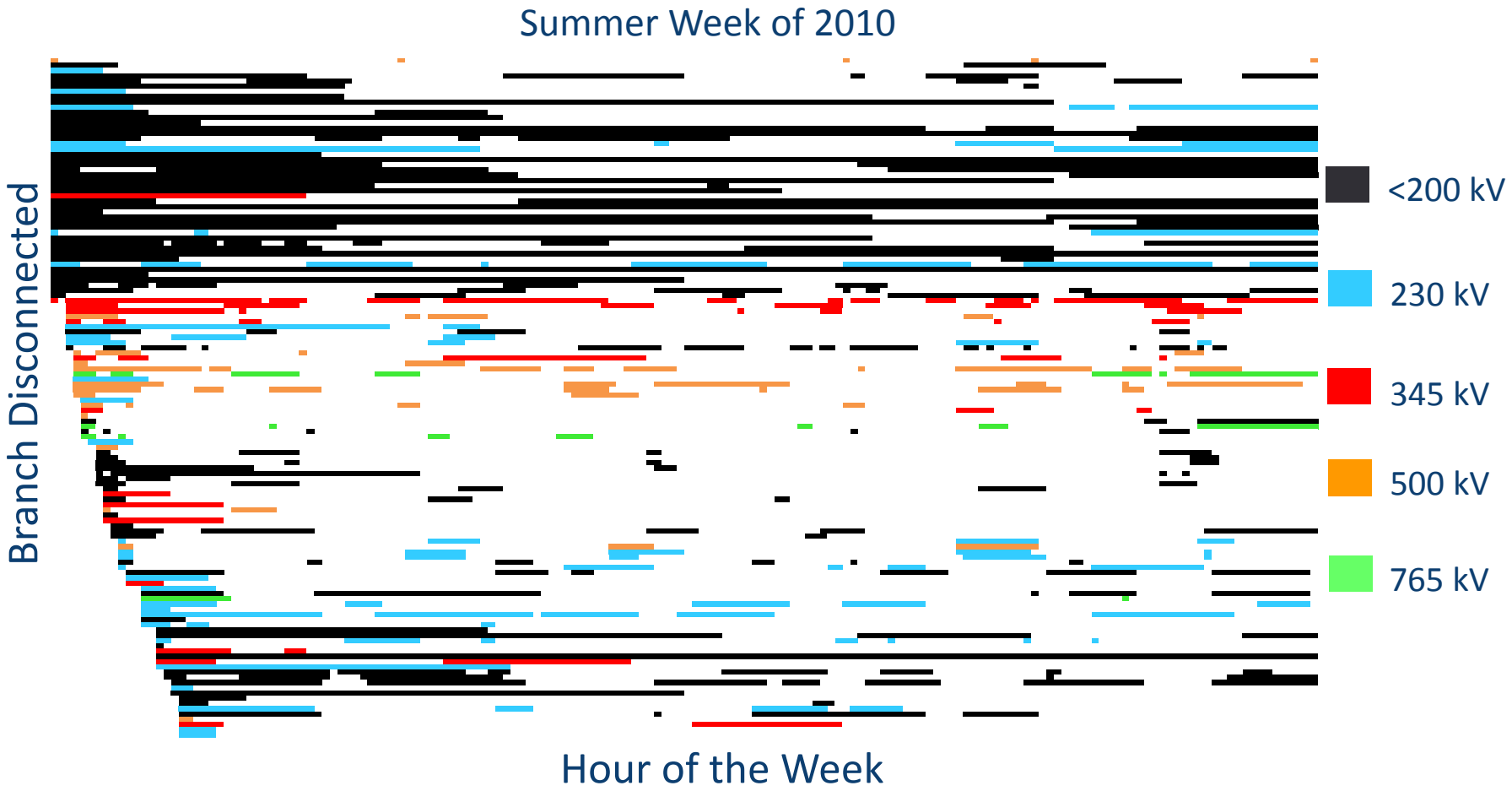






Simulation Results: Average 2010 Conditions

Pattern of Breakers Operated (Summer)

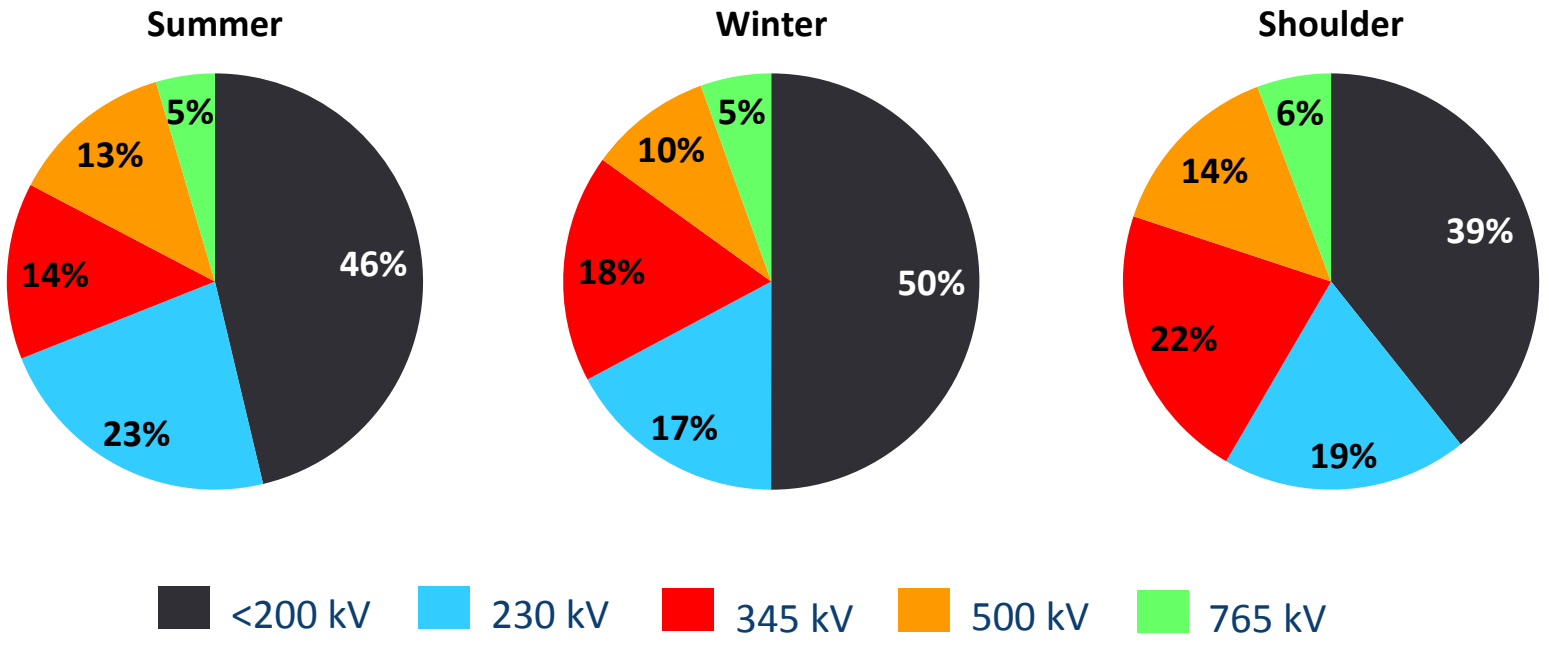


The branches indicated in the rows of this chart are those that were opened in the first 18 hours of the week, or remained opened from the previous week, sorted by the time they were first opened.

Simulation Results: Average 2010 Conditions

Breaker Operations by Voltage Level

Percentage of Breaker Operations by Voltage Level



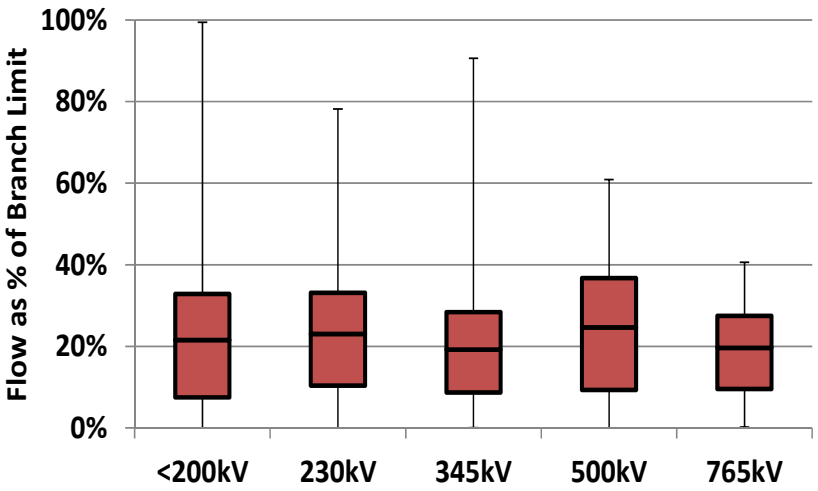
765 kV breakers are mostly opened during low load periods, such as the weekend or very early mornings, when they are not needed for reliability, are lightly loaded, and may cause over-voltage issues.

Simulation Results: Average 2010 Conditions

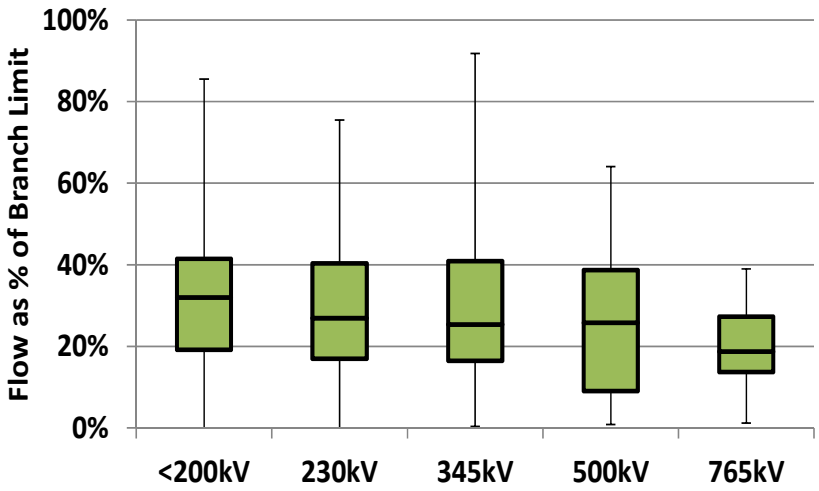
Flow Statistics on Breakers Operated

For Summer Week of 2010

Flows on Breakers Switched Open



Flows on Breakers Switched Close

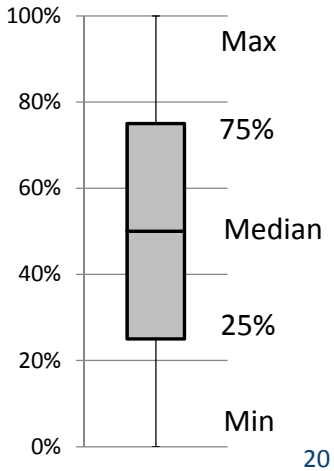


Flows opened or closed are well below normal facility ratings, and orders of magnitude below short circuit ratings, reducing the expected maintenance required to sustain the increased breaker duty

Branches Open

Switched Open

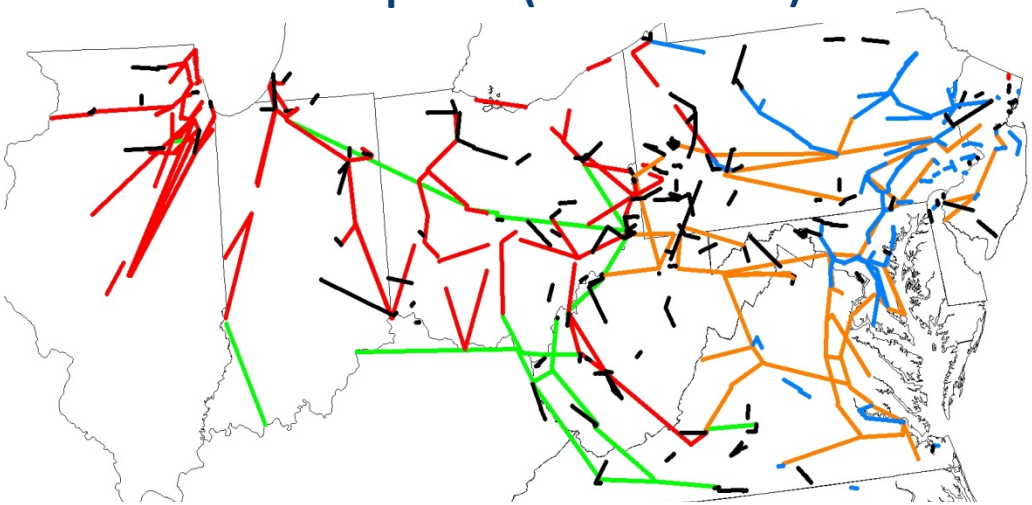
Switched Close



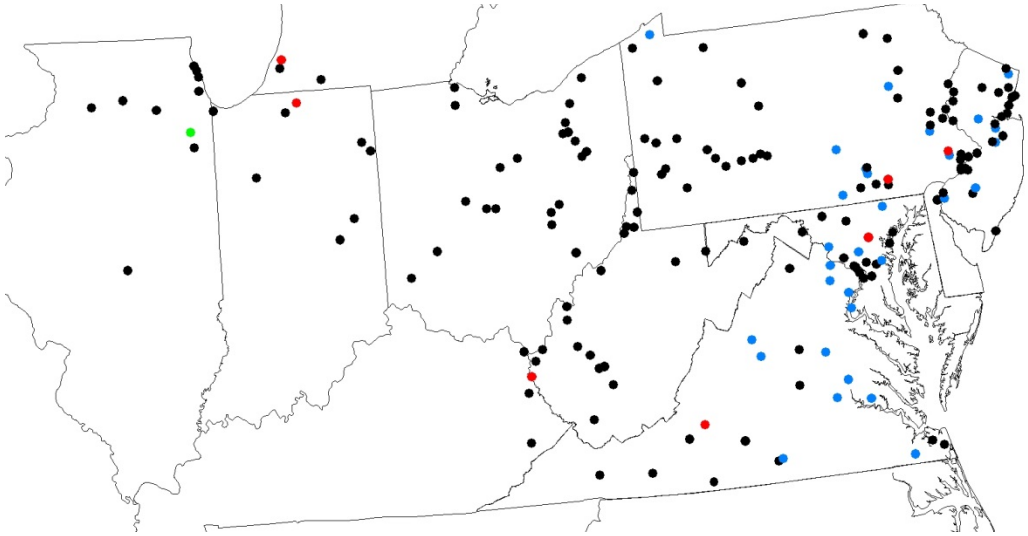
Simulation Results: Average 2010 Conditions

Location of Breakers Operated

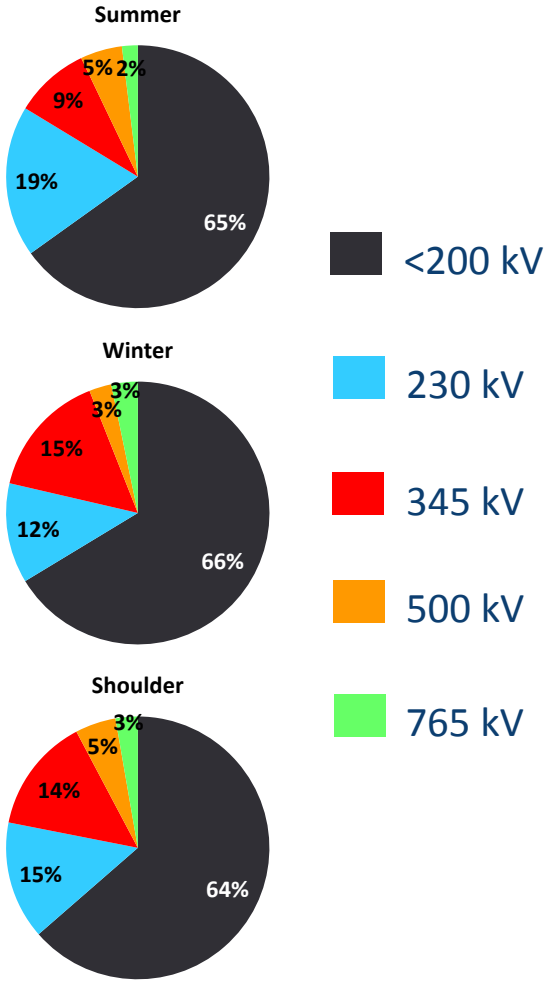
Lines Opened (at least once)



Transformer or Bus Tie Opened (at least once)



Percentage of Open Hours by Voltage Level



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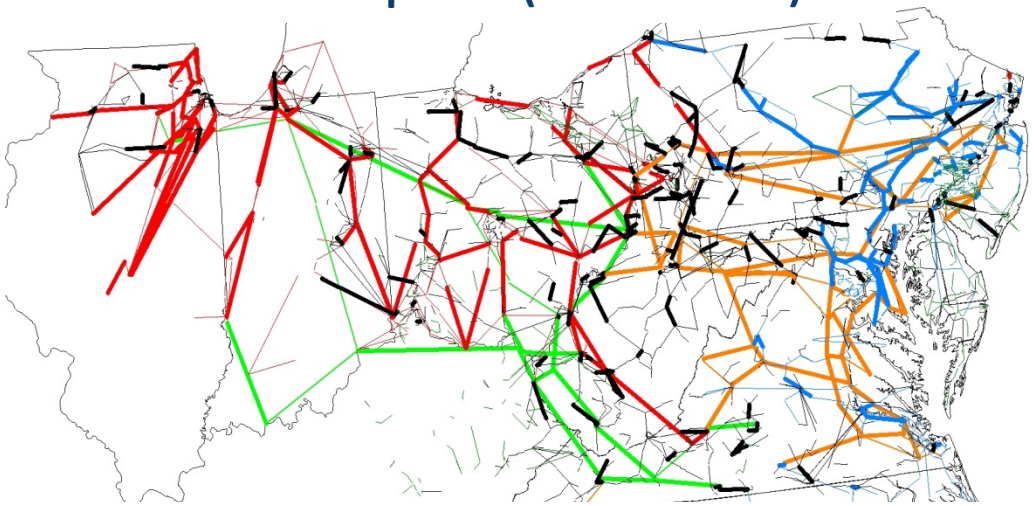

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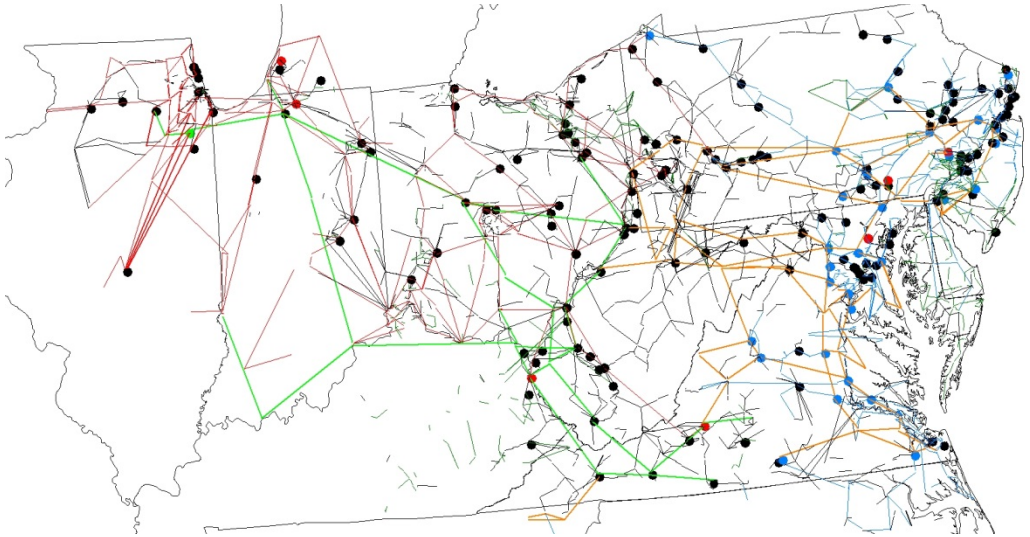

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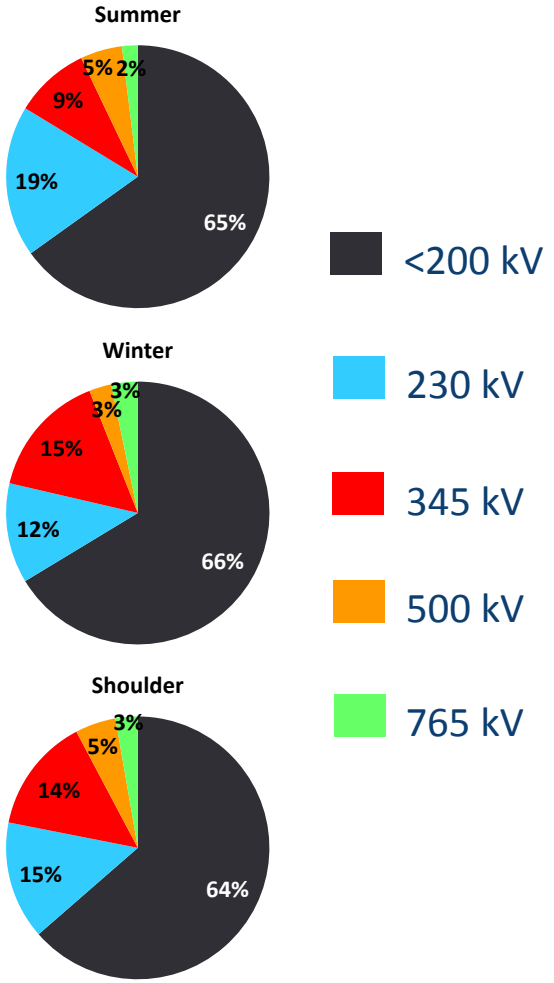

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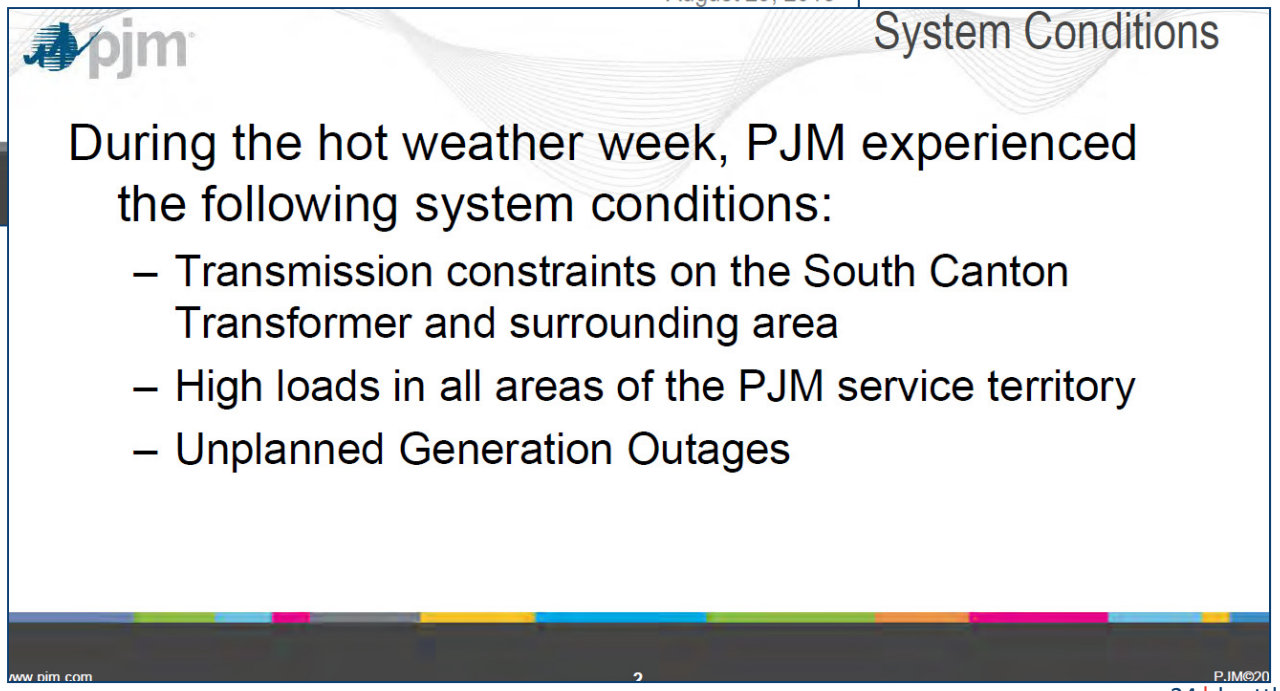
Simulation Results: Summer Peak 2013 Conditions

Challenging Conditions: 14-20 July 2013



Simulation Results: Summer Peak 2013 Conditions

Challenging Conditions: 14-20 July 2013

Time Line of Week of July 15th, 2013

Sunday, July 14th

10:00	Hot Weather Alert – RTO (except CE) thru July 17th, Mid-Atlantic and Dominion only for 7/18 & 7/19

Monday, July 15th

13:50	Long Lead DR, EEA2, Max Emerg Gen Action – ATSI to help control actual overloads on the South Canton #3 765/345kV XF.
14:45	PJM Responds to TVA TLR5b (RTO Spin and Shared Reserves with NYISO)
18:00	Cancel Long Lead DR, EEA2, Max Emerg Gen – ATSI
20:00	Max Emerg Gen Alert, EEA1 – RTO for July 16th

Tuesday, July 16th

08:30	HLV Schedule Warning – RTO
11:30	Long Lead DR, EEA2, Max Emerg Gen Action – ATSI
16:30	Cancel Long Lead DR, EEA2, Max Emerg Gen – ATSI
20:00	Max Emerg Gen Alert, EEA1 – RTO for July 17th

Wednesday, July 17th

11:00	Hot Weather Alert Revised – RTO thru July 19th
20:00	Max Emerg Gen Alert, EEA1 – RTO for July 18th

Thursday, July 18th

12:40	Long Lead DR, EEA2 – PECO, PPL, ATSI
12:40	Max Emerg Gen Action – ATSI
13:00	Long Lead DR, EEA2 – AEP S. Canton
18:00	Cancel Long Lead DR, EEA2, Max Emerg Gen Action - PECO, PPL, ATSI, AEP S. Canton

Friday, July 19th

08:25	HLV Warning – RTO
10:25	Hot Weather Alert – Mid-Atlantic & Dominion for July 20th
10:25	HLV Schedule – RTO

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Simulation Results: Summer Peak 2013 Conditions

PJM RT Price Contours on 18 July 2013

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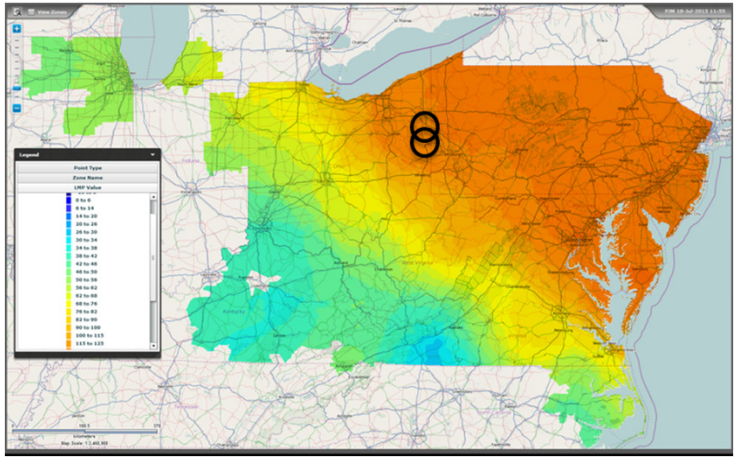

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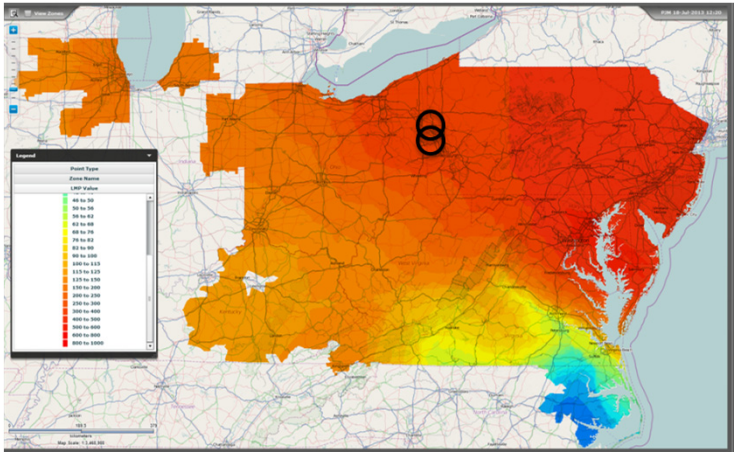

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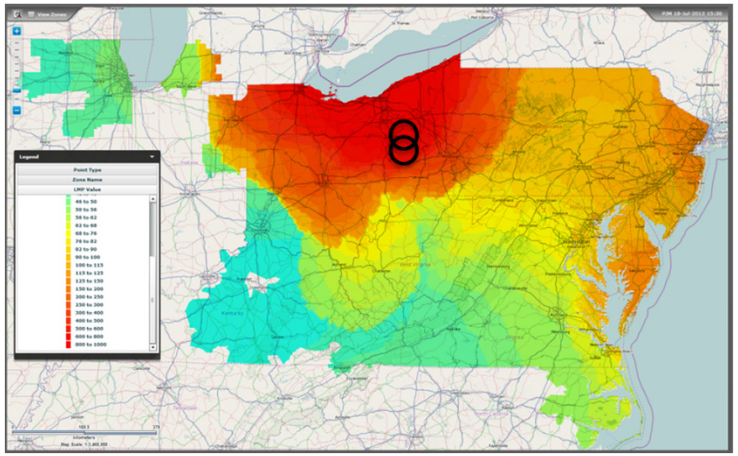
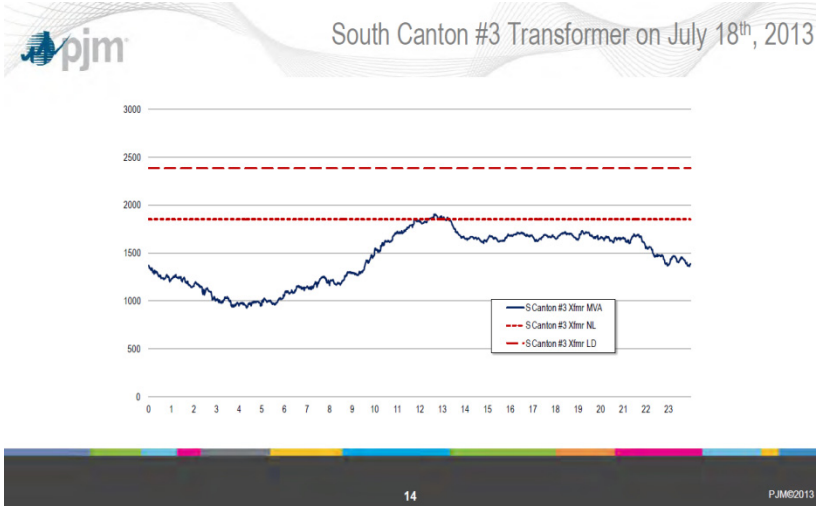
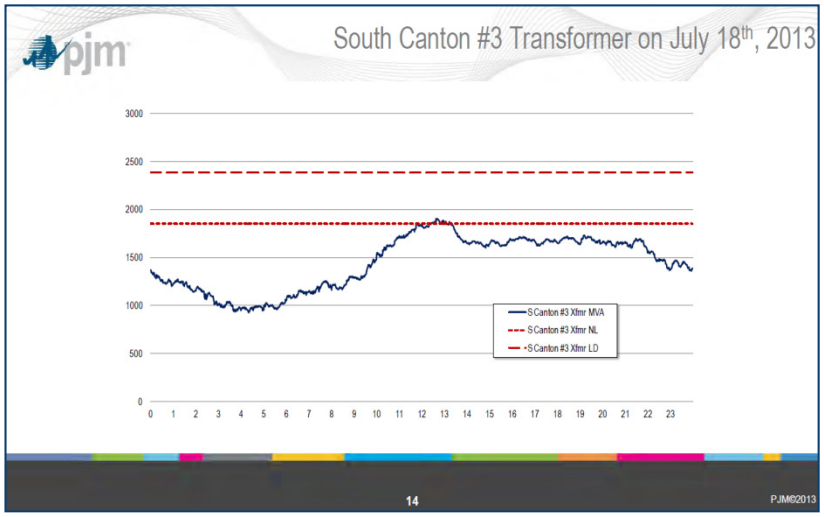




Simulation Results: Summer Peak 2013 Conditions

South Canton Congestion Relief

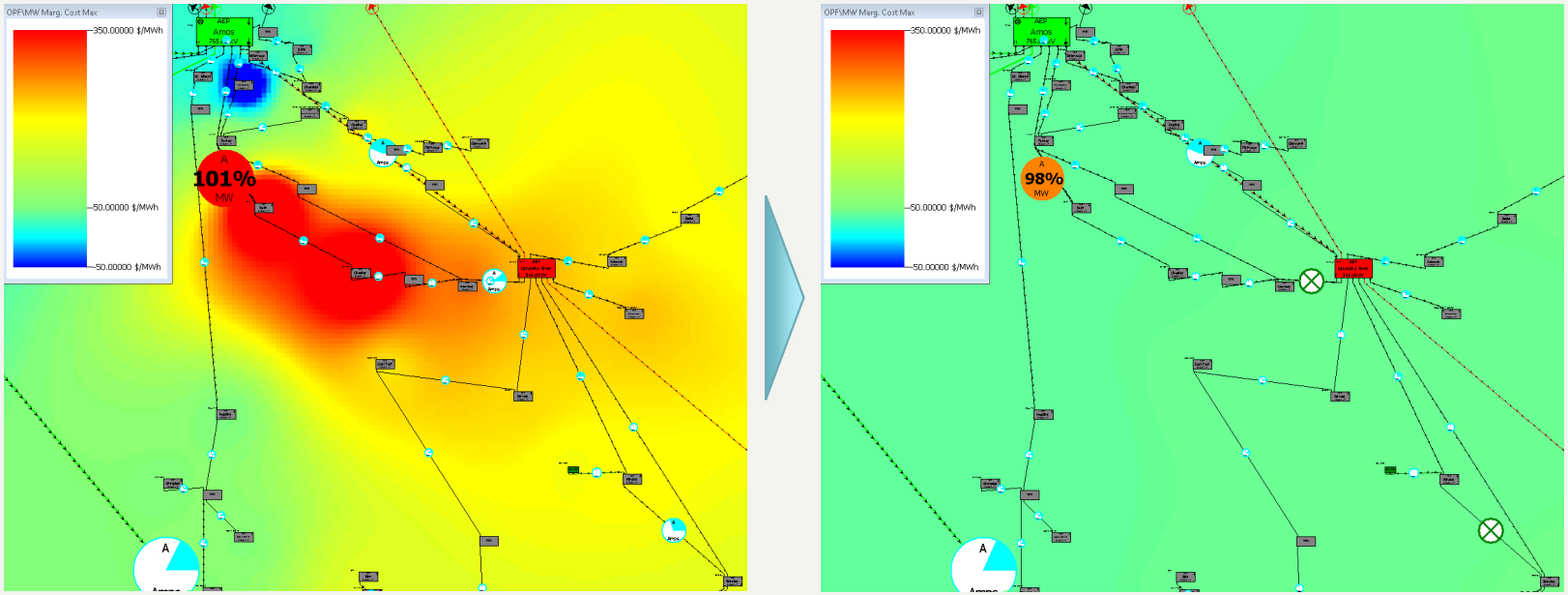
- The South Canton transformer was severely congested on July 15th, 17th and 18th
- TCA was able to divert flow away from the transformer, reducing the weekly congestion on the facility by over 60%
- The transformer was not overloaded during any period in the day with the application of TCA
- TCA application may have reduced the required DR deployment



Simulation Results: Summer Peak 2013 Conditions

Overload Relief Example

July 15th, 2013 at 8PM



Before

Contingency constraint for Ruth-Turner 138kV was mildly overloaded, causing price separation in the region

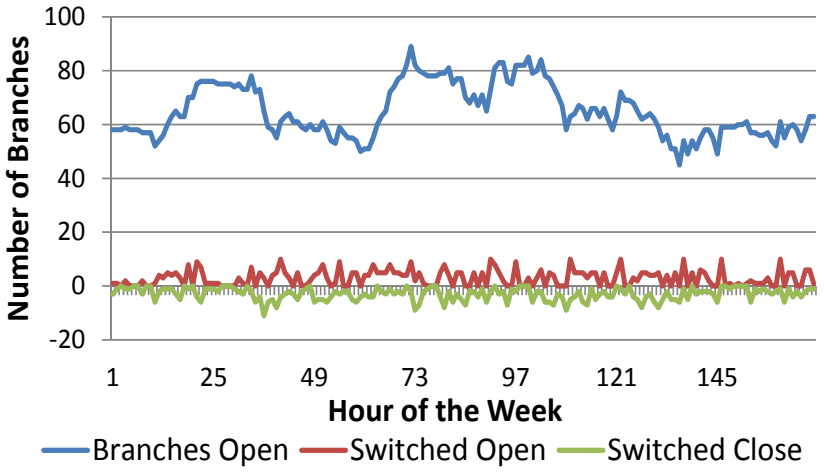
After

Constraint was relieved by opening two nearby 138kV lines, diverting flow away from the Ruth-Turner line

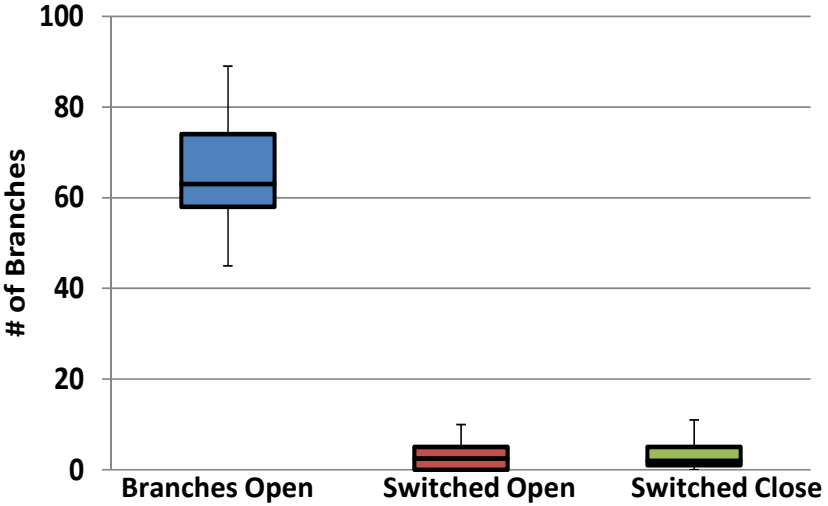
Simulation Results: Summer Peak 2013 Conditions

TCA Operations Statistics

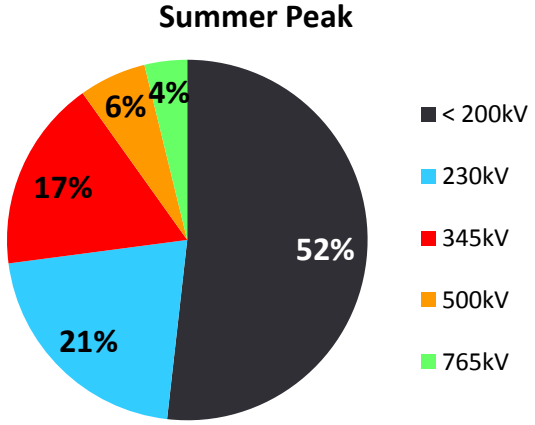
Topology Changes

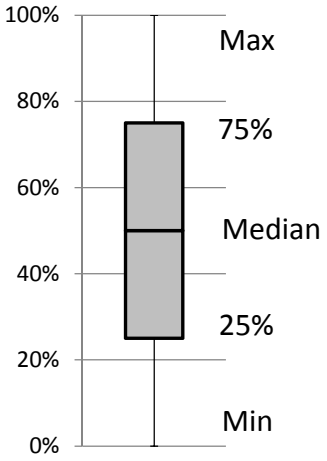


Topology Change Statistic s



Percentage of Breaker Operations by Voltage Level

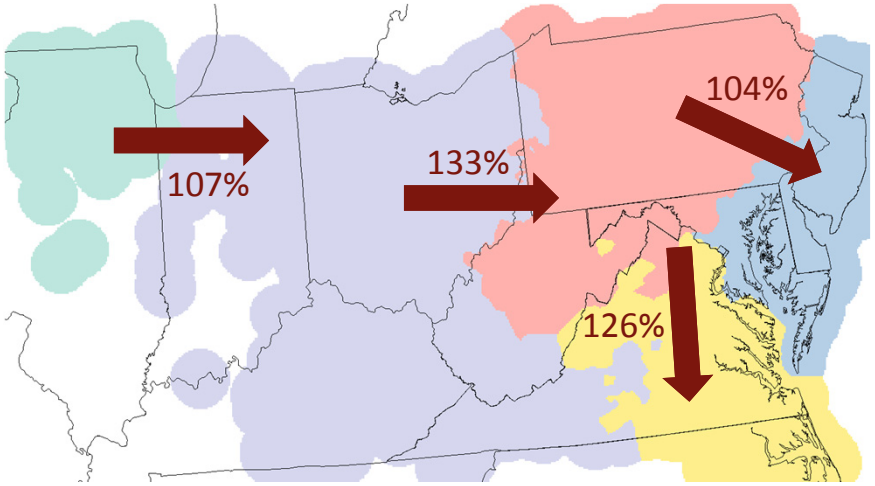




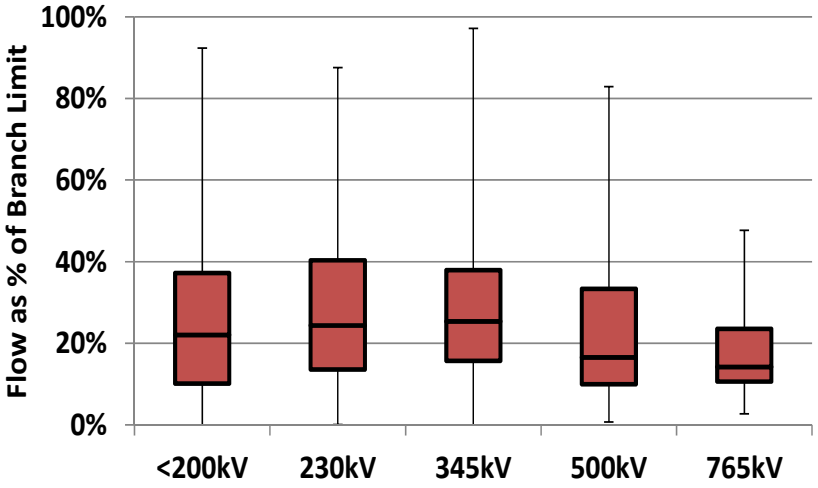
Simulation Results: Summer Peak 2013 Conditions

TCA Operations Statistics

Transfer between PJM Regions



Flow on Breakers Switched Open



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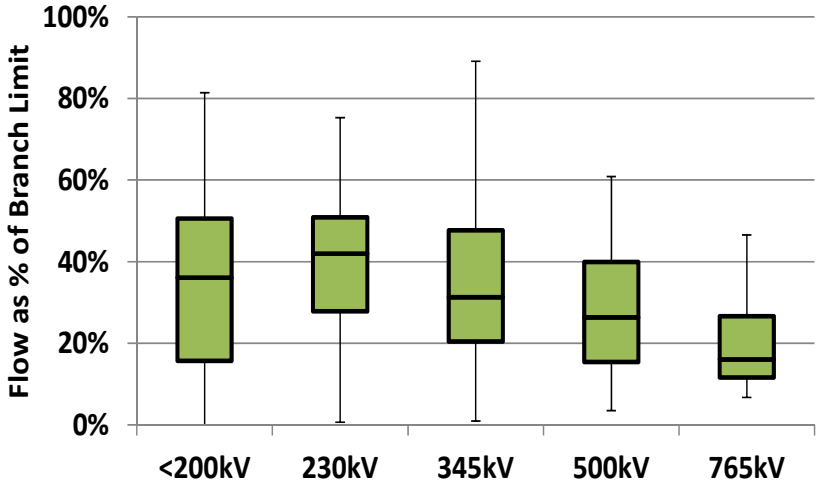
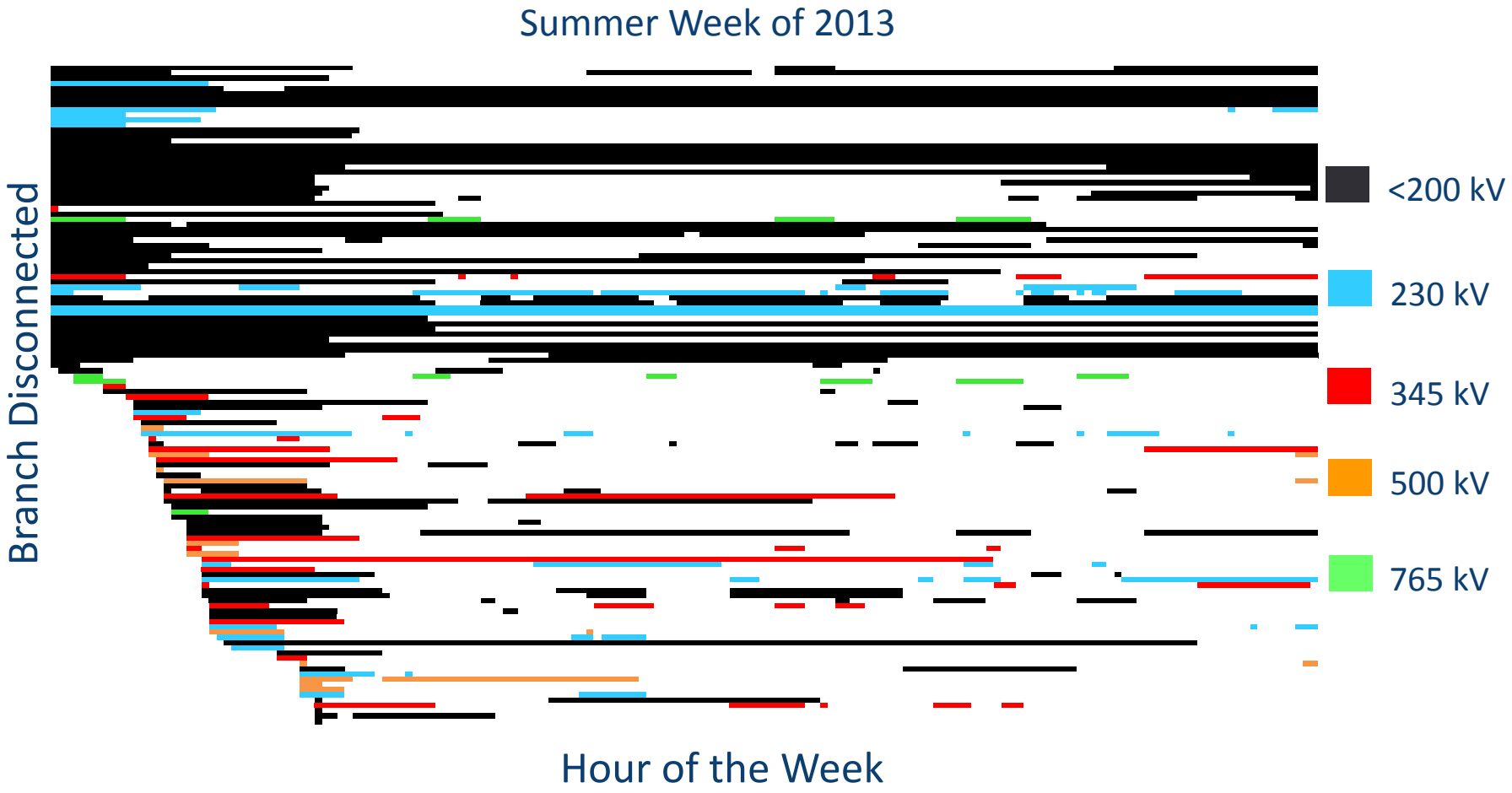


Simulation Results: Summer Peak 2013 Conditions

Pattern of Breakers Operated



The branches indicated in the rows of this chart are those that were opened in the first 36 hours of the week, or remained opened from the previous week, sorted by the time they were first opened.

Agenda

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  - **High Renewables Scenarios (preliminary)**
- Concluding Remarks

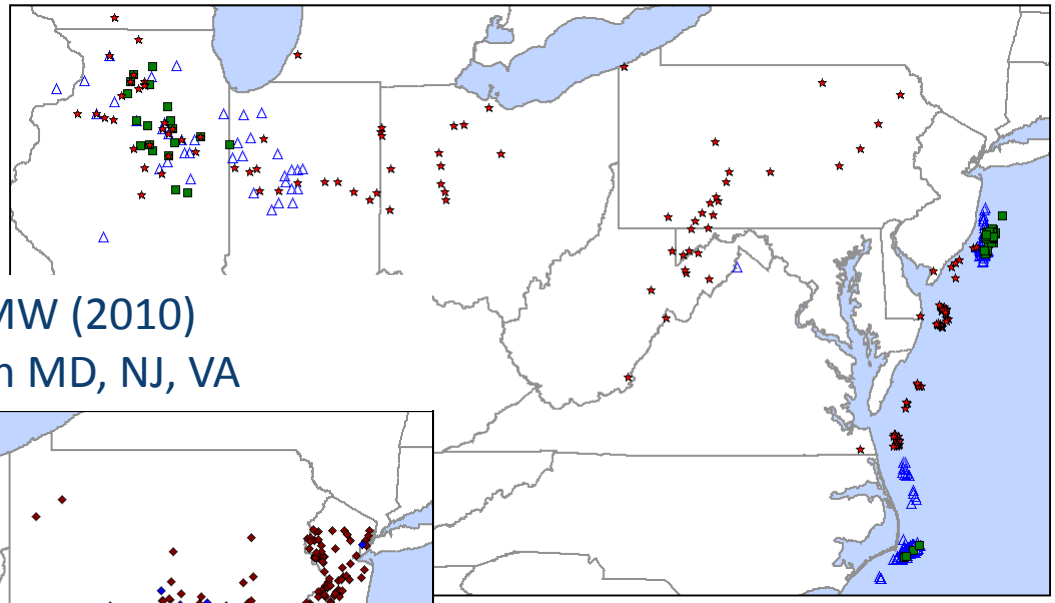
PJM High Renewables Scenario Setup

- Implemented the PJM Renewable Integration Study 30% Low Off-shore Best sites On-shore Scenario (PRIS 30% LOBO) on the historical June 2010 models
  - Added renewable units at locations identified through PRIS
  - Implemented transmission upgrades in the 2010 power flows
  - Included additional contingencies for the transmission upgrades
- Commitment status of thermal units determined from production simulation of the PJM system with the additional renewable units
- Dispatch of non-thermal units maintained at their June 2010 levels
- Renewable capacity scaled down to maintain 30% penetration level
  - Total installed renewable capacity is 71,216 MW
  - Weekly PJM load is 16,216 GWh, with 18% weekly renewable penetration
- Solar time series from PRIS, wind time series from NREL EWITS
- Generation bids for all renewable units assumed to be $0/MWh

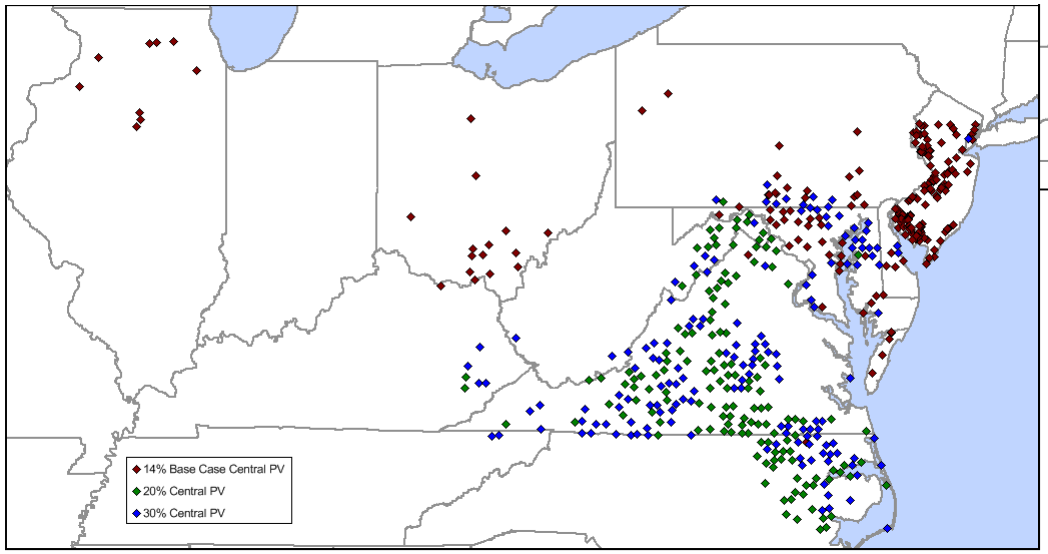
Simulation Results: High Renewables Scenario (preliminary)

PRIS 30% LOBO Resource Locations

Wind Plants: 49,306 MW (2010)
Most of the capacity is in IL and IN

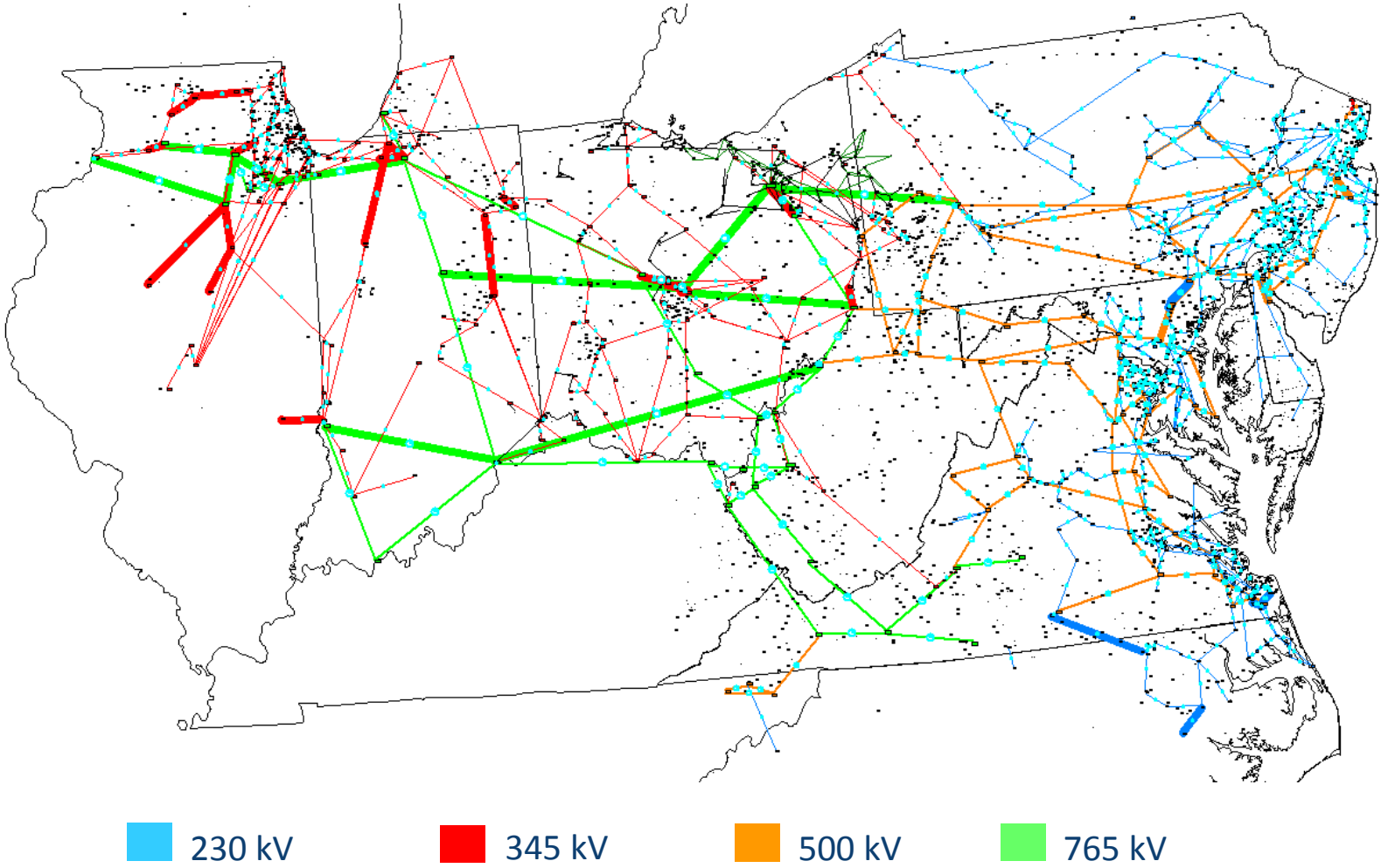


Solar Plants: 21,910 MW (2010)
Most of the capacity is in MD, NJ, VA



Simulation Results: High Renewables Scenario (preliminary)

PRIS 30% LOBO Transmission Expansion

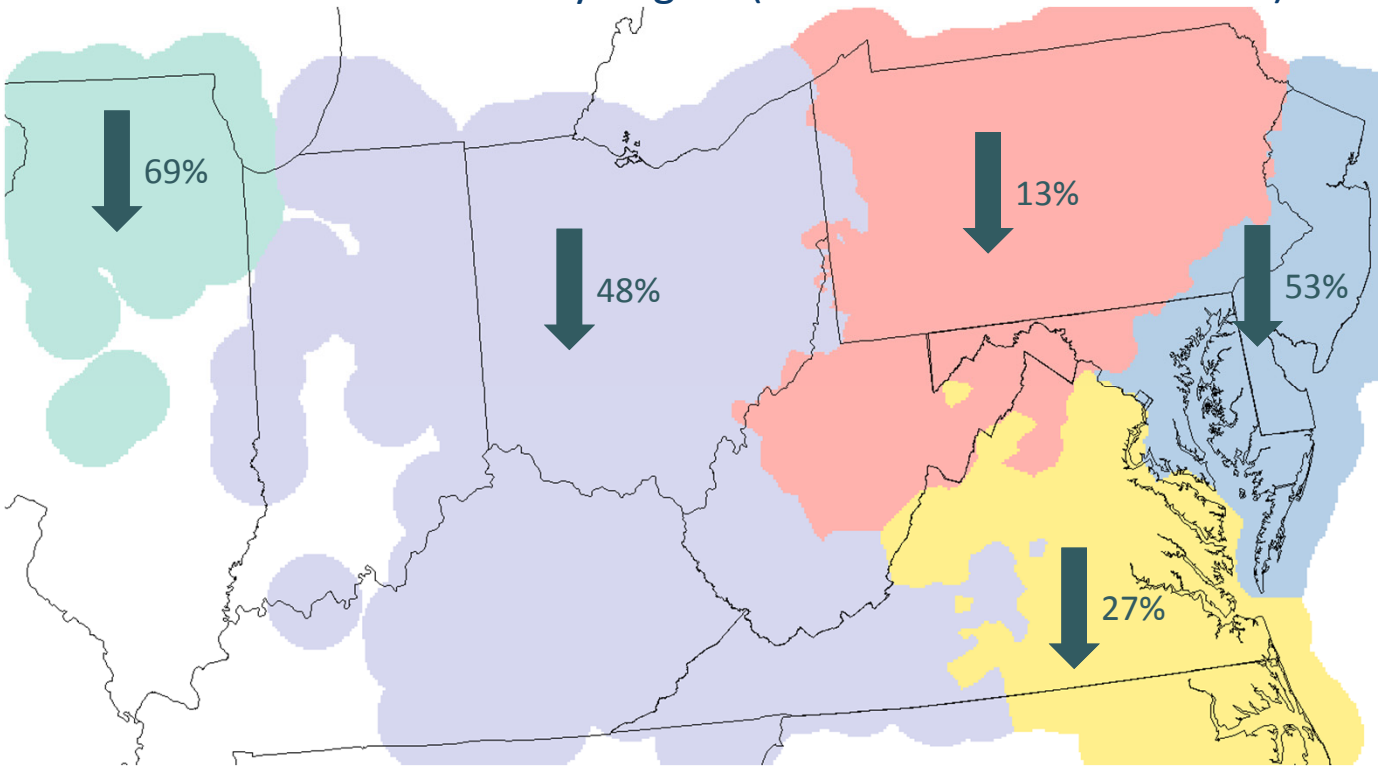


Simulation Results: High Renewables Scenario (preliminary)

Renewable Curtailment Reduction

Type	Renewable Potential (GWh)	Curtailment at Full Topology	Curtailment with TCA	Reduction in Curtailment
Wind	1,794	5.8%	2.8%	51%
Solar	1,150	18.2%	14.7%	19%

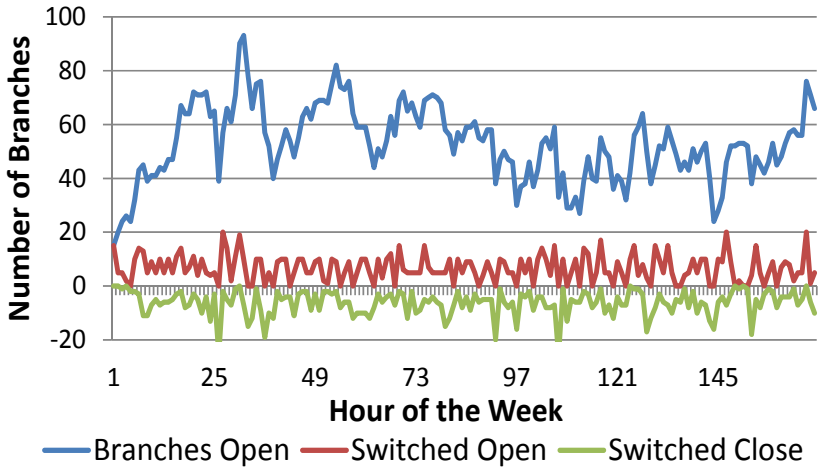
Curtailment Reduction by Region (Wind and Solar Combined)



Simulation Results: High Renewables Scenario (preliminary)

TCA Operations Statistics

Topology Changes



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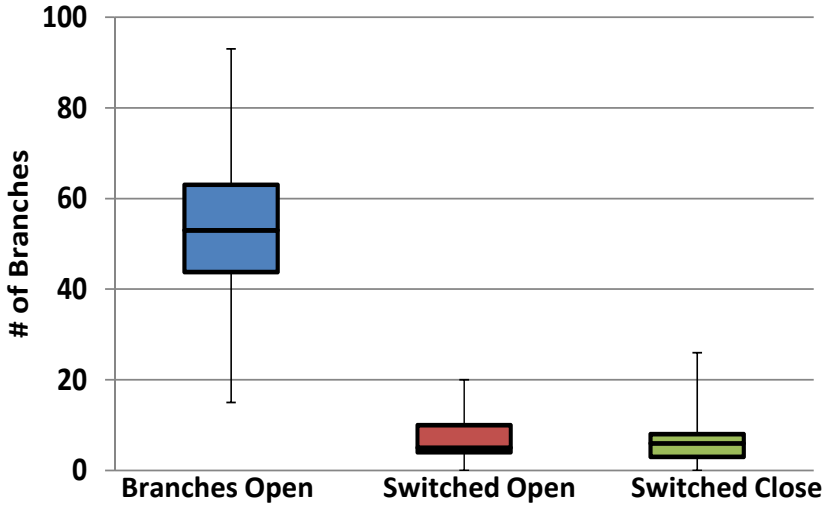

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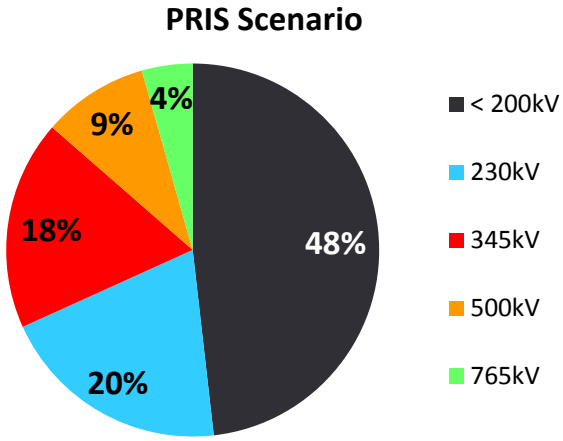

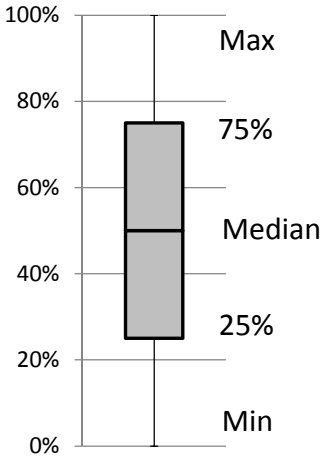

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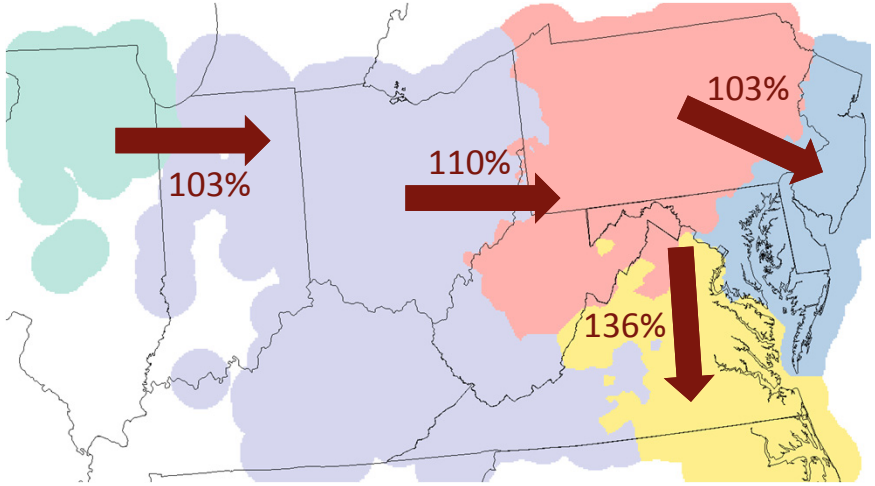

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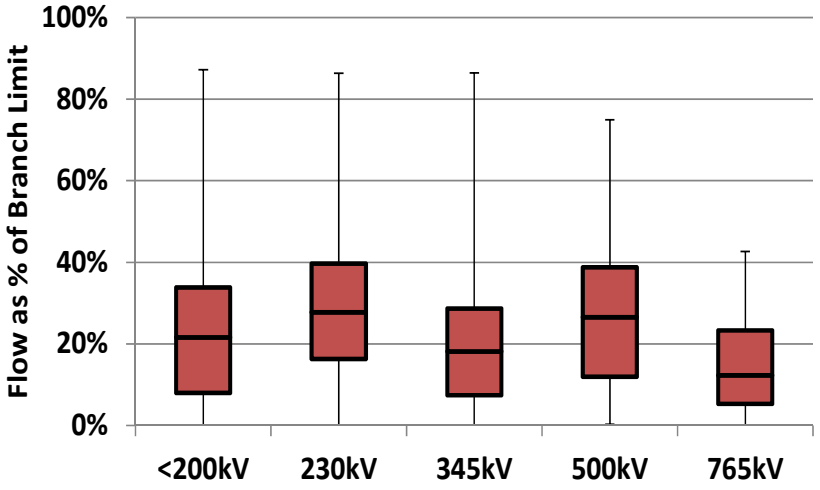
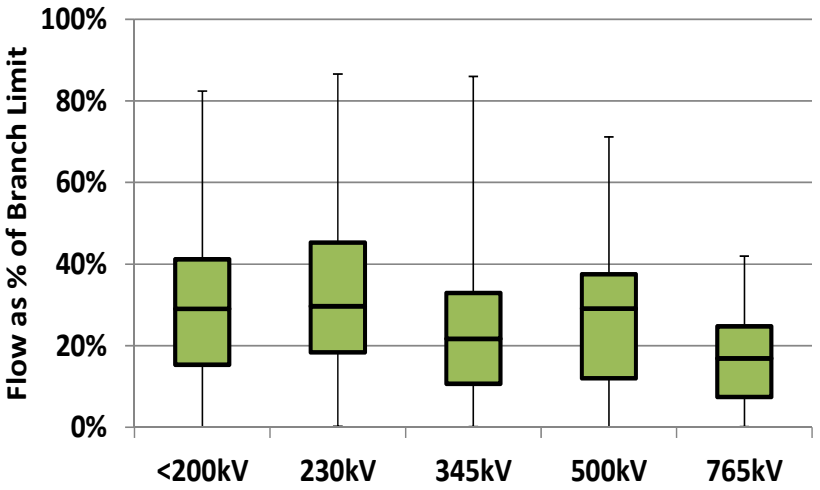


Flow on Breakers Switched Close



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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 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

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)

Next Steps

- Today, we are already able to perform economic analyses for customers looking to better understand the impact of topology control on their assets, within any transmission system, as we have done in cooperation with PJM
- A complete analysis of TCA's impact in PJM RT markets under high renewables levels will be available by Q1 2014
- By Q2 2014 we will be actively rolling out the capability to provide ISOs and RTOs an off-line advisory operations planning tool
- The TCA team is currently developing algorithms to co-optimize transmission topology with unit commitment, with initial results targeted for Q4 2014

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