Topology Control Algorithms (TCA) Project Experience

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Agenda

Topology Control Algorithms (TCA)

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

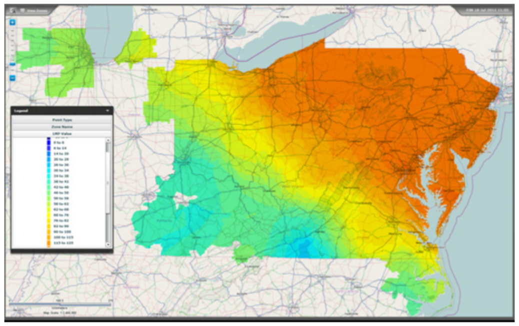
Topology Control Algorithms

Goals of controlling the transmission network topology:

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**

Timeframe: from operations planning up to real-time operations

PJM RT Markets LMP from 18-Jul-2013



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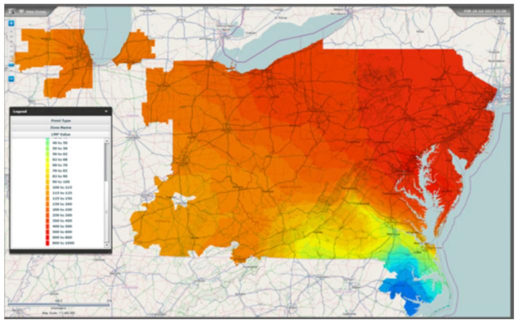

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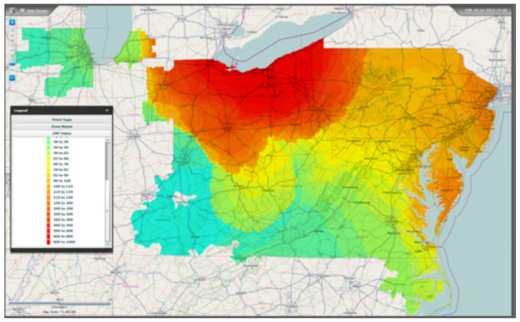

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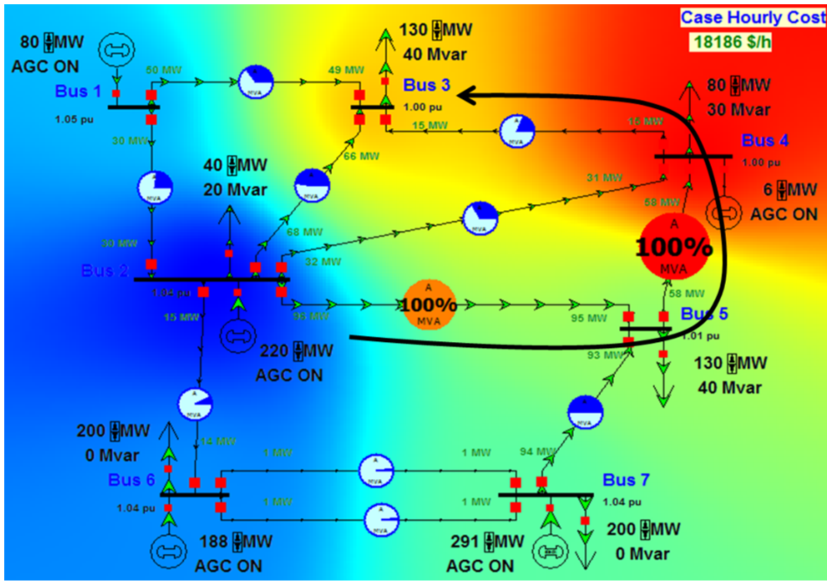
Illustration of Topology Control

7-bus Example Results



$40/MWh

$15/MWh

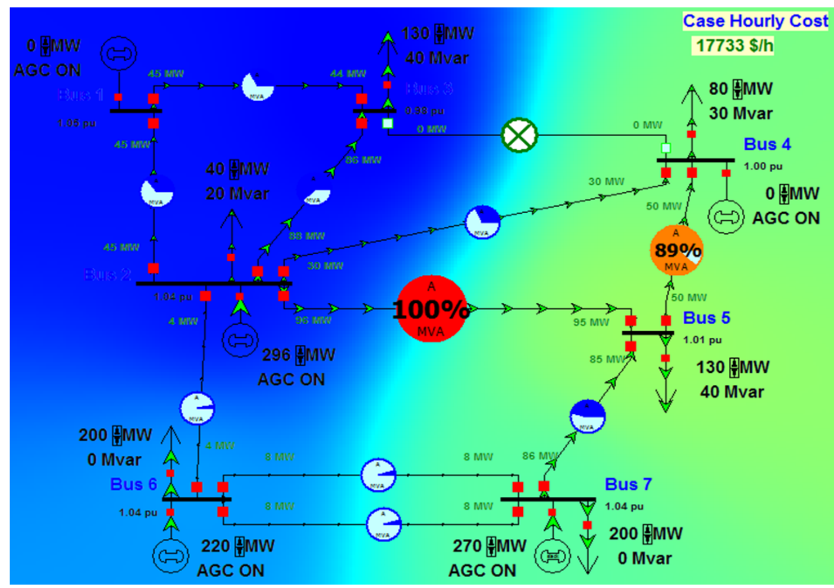
Hourly Cost

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

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, topology reconfigurations are developed manually using engineering judgment. There are no tools that provide quick identification of beneficial topology changes

Objectives and Focus

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 requirements, security constraints, transient stability and voltage criteria
- Impact evaluation: Economic, operations and renewable integration benefit

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 (“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

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

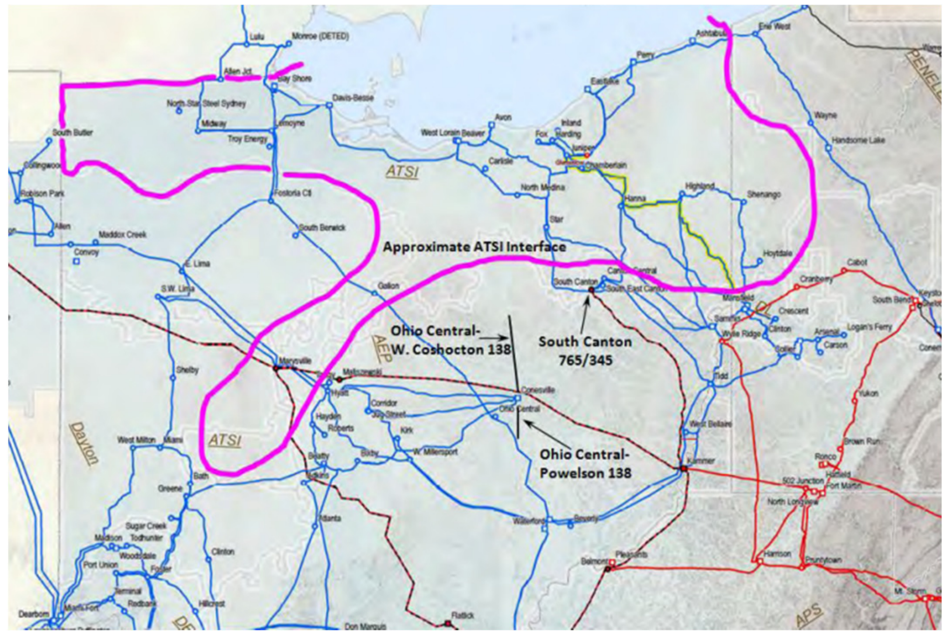
- The production or market Cost of Congestion (different from congestion rent) gives an upper bound on the maximum system-wide Production Cost Savings attainable with any transmission efficiency approach or technology

Estimated TCA impacts on PJM energy markets

- Market cost savings in excess of 50% of the cost of congestion
- Annual RT market cost reductions of over $100 million under 2010 conditions
- Average load LMP decrease leading to estimated annual energy payment reductions of over $1 billion (under 2010 conditions)
- These estimates are based on the weekly simulations

Detailed Feasibility Assessment

- It is hard to assess practical feasibility of new control technologies
  - Hypothetical scenarios where the system state is *very* different from what operations staff have experienced in the recent past
- Overload relief analysis
  - Facilitate assessment of TCA solutions operational feasibility
    - Only changes in system state from historical records are in topology
    - Fixed commitment, dispatch, load
  - Focused on recent events that mattered to system or market operators
    - Real or near overloads
    - High congestion

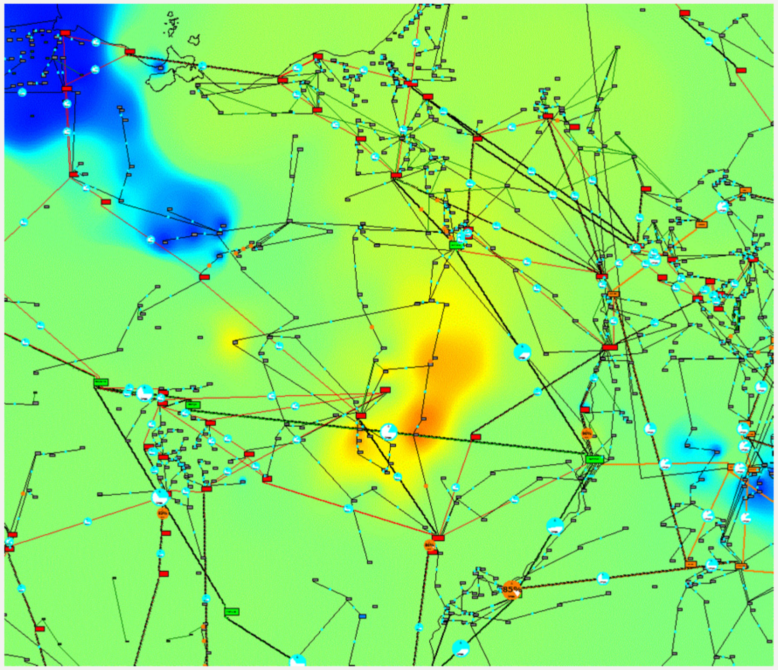


South Canton area (overloads in July 15-18, 2013)

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

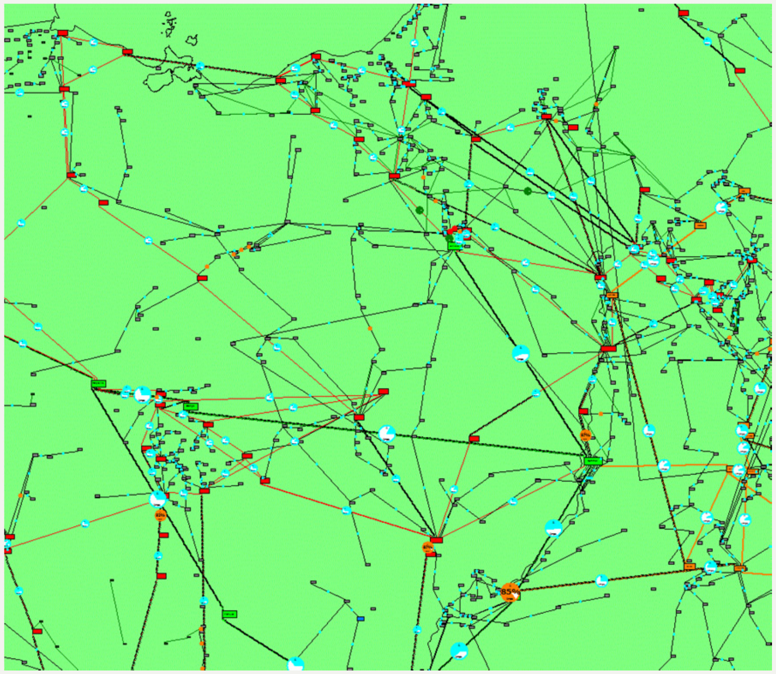
South Canton Potential Overload Relief

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

System Complexity

System operation is significantly more complex than an outsider would anticipate

- Time-varying processes: there are countless underlying processes that are time-varying, sometimes they are highly volatile
- Operator intervention: decision support tools usually do not capture all important phenomena (e.g., variability, uncertainty, forecast limitations), thus operators many times override their own tool recommendations
- Model dimensionality: accurate interconnected power system models may be extremely large; model simplifications can be made, but these have to be application-specific, and care has to be exercised
  - PJM Transmission reduced models: 15,000+ nodes
  - PJM Transmission breaker node model: ~100,000 nodes
  - Add sub-transmission and distribution detail: ~1,000,000 nodes?

Validation Efforts

Given system complexity, model development, benchmarking and validation is a tedious task

- It took us more effort than we would admit to develop, validate and adjust the PJM models until they resembled history closely enough
  - That was in spite of having the full collaboration of PJM, and having extensive power system and market model experience
- Issues that may require operator intervention are hard to model or even validate
  - Example: which constraint to enforce if there are multiple, semi-redundant constraints?
- It is extremely important to have operators review results in detail and provide feedback
- It may be needed to adjust or simplify experiments to ease validation
  - Example: TCA simulations with fixed dispatch

Commercial Software

Commercial software is extremely useful to perform standard support functions, but if applied to perform new functions, they may require significant customization

- No need to reinvent the wheel: commercial tool functionality can save significant efforts and allow the team to focus on the real innovations
  - Example: standard power flow or DC-OPF functions
- Commercial MIP solvers: black boxes whose performance does not always make sense
  - Heuristics used are based on a broad range of models, and there may be much better "tuning" to support power system problems
  - Pre-solve can be less effective than anticipated
    - Multi-period problems are solved 10x faster as a series of single-period problems even without inter-temporal constraints!
    - Leaving spurious variables can slow down solver significantly

Hardware Considerations

- Operations decision support applications have to run on hardware local to the RTO/utility (e.g., no SaaS), due to cybersecurity concerns
- Parallel processing can be effectively employed to perform embarrassingly parallelizable functions
  - Example: contingency analysis, branch and bound
- However, we have seen that single-threaded applications tend to take much longer (2x) in newer hardware systems with many cores than in older, lower cost systems with few cores
  - Increasing challenges in solving single-threaded problems in an IT world increasingly focused on multi-threaded applications

Team Composition

We really benefitted from the diverse skillset in our team, which is almost a requirement to be impactful in power system optimization efforts

- Fields: operations research, power system operations, planning and markets, data management, software development
- Institutions: academia and research community, software vendors, economic consulting, RTO
- RTO/Utility team members are crucial
  - They provide a practical perspective, deployment insights and invaluable review and validation
  - The amount of effort that RTO/utility team members dedicate, even if they do not conduct research, is very significant
  - The project has to be meaningful to the RTO, addressing current or expected challenges and priorities
- Large teams increase the administrative burden of a project…

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 simulations on detailed, full-scale RTO models:
  - Operations processes are very complex, with many time-varying phenomena, operator intervention and large system dimensionality
  - Model and results validation and technology feasibility assessment is a very involved task that benefits immensely from RTO/utility collaboration
  - Cross-disciplinary teams with both research and practical expertise, including highly committed RTO/utility staff, are key for a successful, impactful project outcome

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