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Case Analyses of Topology Control: The Software solution to Redirection of Power Flows to Reduce Constraints

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SUMMARY

Transmission topology control (line switching) is currently practiced with manual and ad-hoc based actions by ISO control room personnel who rely on a combination of past experience and a fixed data set of line openings linked to various congestion patterns. This paper presents the background to and case analyses of the application of Topology Control Algorithms (TCA) to historical cases in PJM. Specifically this paper provides evidence of the significant savings in operating costs that application of a topology optimization tool provides to system operators. The paper presents the results of multiple case analyses of the application of the optimization tool applied to contingency conditions on a realistic system size that are based directly on AC-based topology control algorithms. In particular, we discuss the results of a case study on three historical weeks of PJM system data and the results of analysis of a major contingency event also in PJM. While earlier work of the authors used sensitivity information from the solution of a DC economic dispatch problem to develop topology control algorithms that significantly improve the operators' ability to select promising lines to open/close, the current study demonstrates the feasibility of the use of tools / algorithms that are AC power flow based that meet the operating needs of system operators for both operational and computational time constraints.

KEYWORDS

Transmission Topology Control; Transmission Line Switching; Transmission Congestion Relief; PJM; AC Power Flow Analyses

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Background and Introduction

Prior to the development of the topology optimization tools reported in this paper, Topology Control (TC) or "line switching" had been applied by system operators based on their personal knowledge of the sensitivities of the transmission and generation system or based upon pre-programmed actions that responded to known system constraints. The advent of increased quantities of intermittent renewable generation technologies – specifically large scale wind and solar -- have placed increased demand on moving lower cost energy from often isolated locations across significant distances to the major load centers. At the same time, the loss of nuclear units and the impending reduction in base-load coal units has required a renewed focus on the interconnected grid and the need for bulk transmission that provides economically efficient delivery throughout major regions of the US and Europe.

Past planning and changes in patterns of both supply and demand have created a level of built-in system redundancy allowing for topology reconfigurations that can reliably route power around congested elements of the grid. Topology optimization tools enable RTOs and TOs to increase the transmission capability of the system by systematically identifying reconfiguration options that allow for the management of congestion; the response to contingency situations (eliminating overloads); and to accommodate / respond to maintenance outage requirements.

The critical computational improvement that has been implemented in the current work on topology optimization is that the developed tools have brought the heuristic logics of the "search engine" of Google or Bing to the identification of economically beneficial and reliable system reconfiguration alternatives in the power grid. It is this advantage that allows for the computational efficiencies reported.

This paper presents the logic and a series of case analyses of the significant economic value of the application of topology control. Based upon the development of a systematic approach employing a topology optimization tool it is possible to identify a finite number of topology control alternatives that will, for any specific system constraint condition, significantly improve the economic efficiency of the power system while continuing to meet all reliability requirements. In addition, the topology optimization tool described in the paper is able to operate in conjunction with market engines for security constrained dispatch and economic dispatch and it has equal applicability in the full range of utility time frames from planning to real time operations.[1]

The topology optimization tool is formulated based upon an AC power flow modeling structure. The OPF is solved using a linearized AC power flow formulation (see for example [9]). In contrast to a DC modeling structure, the AC formulation represents both real and reactive power flows as well as voltage magnitudes and angles at buses. Losses are calculated from the AC power flow solution and automatically updated at each iteration. Compared to the DC model used in [8], the AC formulation guarantees AC feasibility at every step, while assuring minimal impact on computation performance. These characteristics make application of the tool highly adaptable as an advisory tool in the system operations control room.

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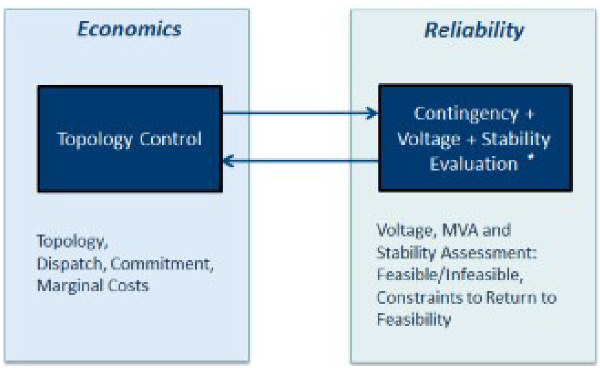
The iterative formulation is summarized in the following 5 steps:

1. Using the heuristics in [4], [6] identify switchable line candidates for topology control action. If good candidates are identified, proceed to the next step, otherwise skip to the last step
2. Evaluate the benefits of opening (or closing) the identified candidate breakers using the AC model;
3. Evaluate the flows of monitored facilities for all contingencies to verify that the post-switch-action topology is N-1 secure. The switching action is reverted if the security criterion is not met;
4. Repeat the previous steps until the stopping criterion is reached;
5. Specify the associated topology as final for the interval and proceed to the next interval (hourly intervals are used in the simulations in this paper).

Figure 1 depicts the iterative nature of the steps

Fig. 1. Topology Optimization Tool Structure



At each step in the Reliability assessment, all 3,500 branches are monitored in the contingency analysis. This is a comprehensive list of facilities that do not need to change with topology.[2] With the exception of transient and voltage stability, which are not assessed in this work, this algorithm ensures AC feasibility at each iteration described above.[3] By solving the AC power flow, we accurately capture losses as the topology changes and include these losses explicitly in the formulation employed by the TCA heuristics. Leveraging parallel computing options in performing the above steps, the proposed solution for each hour requires less than five minutes (it aligns with the five minute real-time market at PJM), and as shown in the next section performs similarly to the DC model in terms of line openings and congestion cost savings.

Case Study Results

The first set of results reported is based on analyses of three representative weeks in the PJM system in 2010. Table 1 presents the detailed weekly savings and Figure 2 presents graphically the savings for the three typical weeks. The term *Cost of Congestion* is defined as

[2] While there are 20,000 lines total, they include lines outside of PJM, lines connected in series, generation step up transformers, lower voltage facilities and other branches that are typically not explicitly monitored.
[3] The inclusion of stability evaluations is not expected to significantly reduce the potential TCA savings, given preliminary analyses and considering PJM system characteristics and the nature of usual system limitations.

the difference between generation production costs with the historical / non-modified topology and enforced transmission constraints and the production costs in the absence of transmission constraints. As such it is the maximum savings that could have been achieved through topology optimization. Stated differently, this is the cost of transmission constraints compared with the production cost had there been no constraints. As seen, the percent savings from application of the topology control tool ranged from a low of 44% in the summer week to 68% in the winter week. Using these three typical weeks as a sample for the full year, the level of savings forecast for 2010, had the topology optimization tool been used to minimize constraints, would have been over $100 million, a significant savings to consumers.

TABLE I
SUMMARY OF SAVINGS ACHIEVED BY TOPOLOGY OPTIMIZATION (MILLIONS OF DOLLARS)

Week	Cost of Congestion	Savings From Topology Optimization	% Savings Captured
2010 Summer	$6.7	$2.9	44%
2010 Winter	$4.2	$2.8	68%
2010 Shoulder	$1.6	$1.1	67%

Figure 2: Real Time Market Production Cost Savings

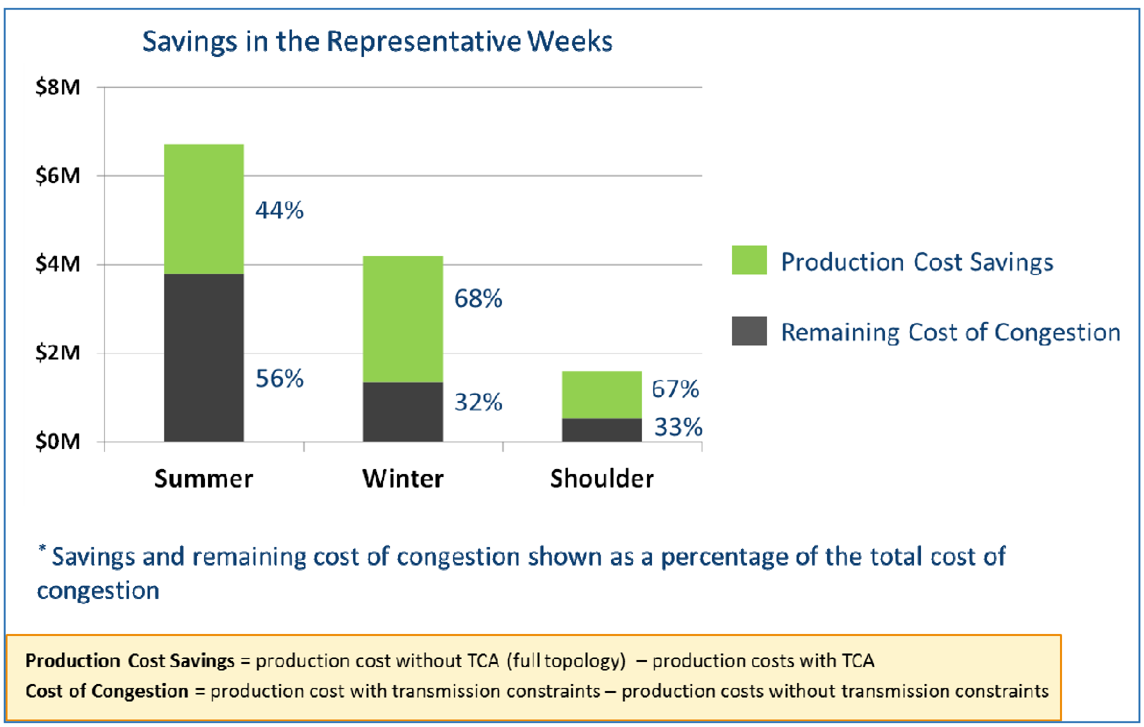


Figure 3 below indicates graphically the transfers between regions of PJM that occurred to achieve the savings shown in Table 1 and Figure 2. What is clear is that the topology optimization significantly increases the transfer capability within the PJM system moving lower cost energy generated in the west in an easterly direction.

Figure 3: Transfers between PJM with Topology Control in 2010 Average Conditions

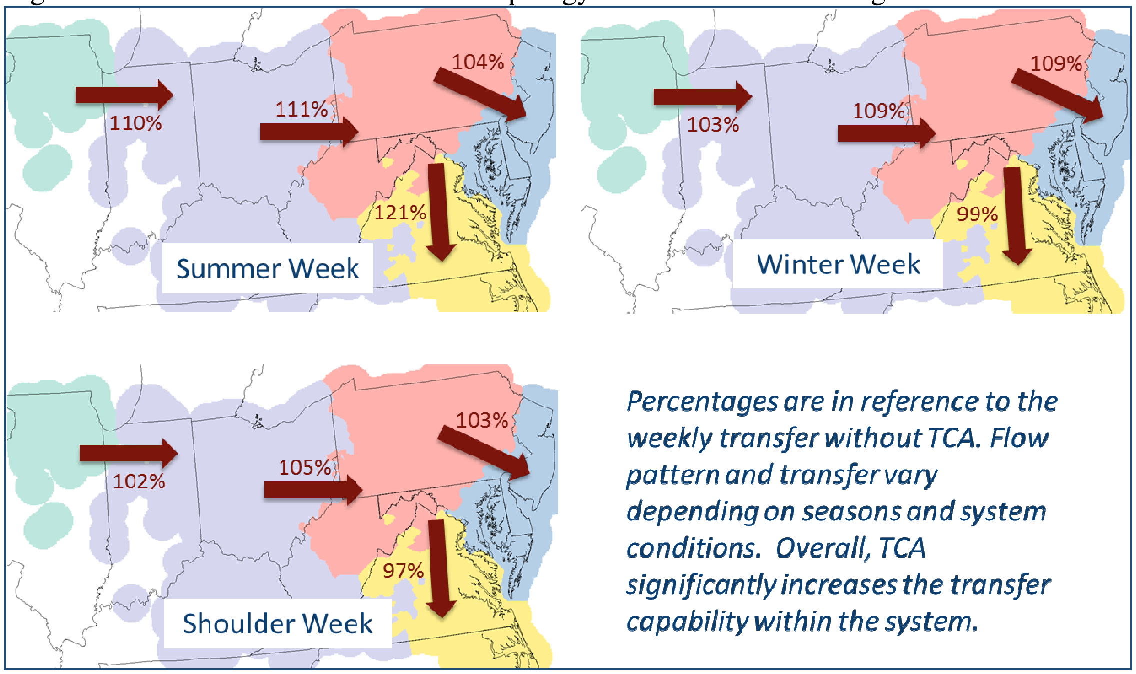
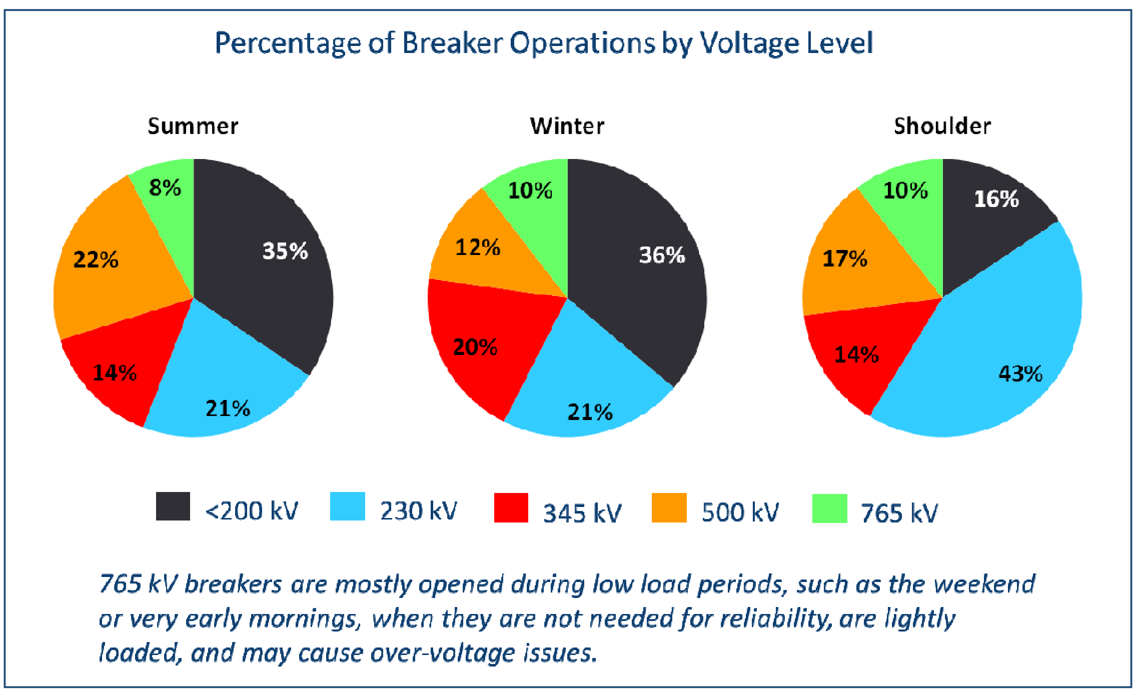


Figure 4 below indicates the percentage of breaker operations that were required by voltage level. As indicated, 765 kV breakers were generally opened only during low load periods.

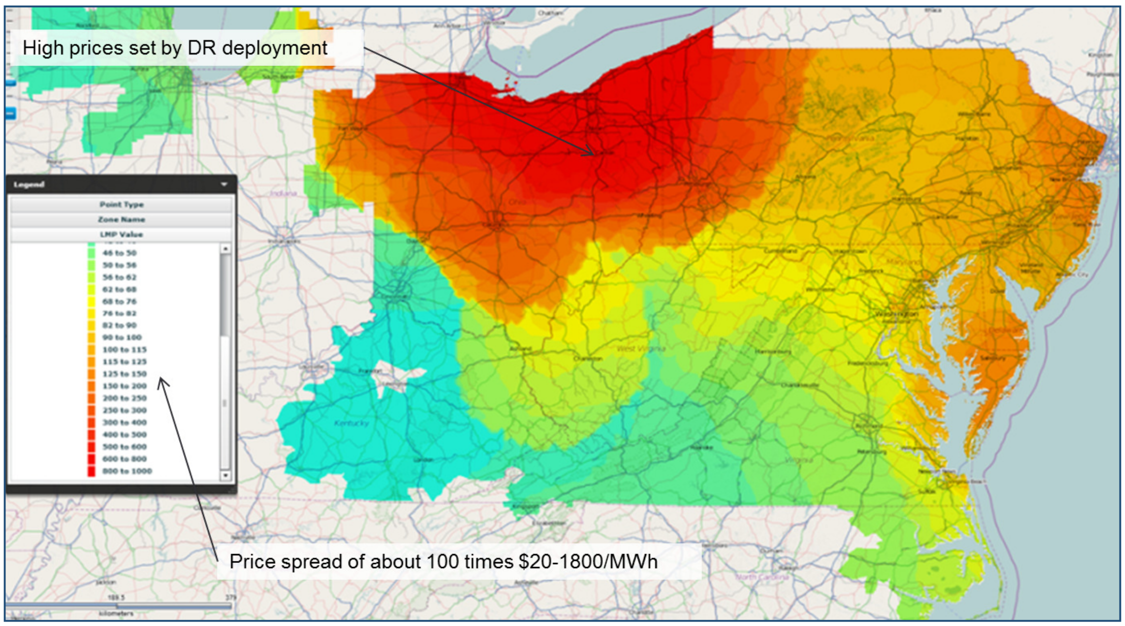
Figure 4: Breaker Operation by Voltage level in 2010 Average Conditions



The second case example of the use of topology optimization is specific to the events that occurred on July 15th 2013 in western PJM when the South Canton Transformer was severely congested with base case overloads. In addition, there were four 138 kV line post contingency overloads in the area as well. Further, there was 2700 MW of unplanned outages on the system. During this contingency, PJM deployed 650 MW of demand response that then set the highest of the prices.

Figure 5 shows the PJM Real Time Prices for the day for hour 15:30. The price spread for that time block, as indicated was from a low of \$20 to a high of \$1800 across PJM.

Figure 5: South Canton Overload Impact on PJM Spot Prices



We were asked to develop a case that could show the benefit / impact of the application of the topology optimization tool had it been applied to the contingency situation. Our analysis was undertaken after the event. Due to the extreme conditions for that day, the dispatch was kept the same as the initial EMS dispatch in order to capture any additional generation operation constraints not captured in the case. The results of the topology control were verified by the PJM operators to confirm that no reliability constraints would have been violated had our solution been implemented.

The result of the case analysis is that the proposed topology control, had it been implemented, would have been able to divert flow away from the transformer and fully relieve the base case and post contingency overloads in the area. In addition, the TC application would have reduced the required demand response deployment. This would have reduced customer discomfort along with reducing the cost incurred through the deployment of the DR. Finally, the voltage profiles with and without the topology control reconfiguration were similar.

Conclusion

Topology optimization / topology control represents a significant new tool for application to power systems real time operations as well as contingency planning. The case analyses have shown the magnitude of annual savings in operating costs that are possible with the application and the South Canton case has shown the ability to use topology control to relieve constraints in worst-case conditions.

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