Applicability of Topology Control Algorithms (TCA) to a Real-Size Power System

Evgeniy A. Goldis, Xiaoguang Li, Michael C. Caramanis, Bhavana Keshavamurthy, Mahendra Patel, Aleksandr M. Rudkevich, Pablo A. Ruiz

***Abstract*— Transmission topology control (line switching) is currently a manual operator intervention by power system operators implemented on an ad-hoc basis and relying on either the operators' previous experience or on a set of fixed procedures linking congestion with topology changes. While the co-optimization of network topology and generation resources has been shown to provide significant congestion cost reduction, the problem is intractable even for moderate-size systems. Our previous work developed near-optimal and tractable topology control algorithms (TCA) that employ sensitivity information extracted from a standard ED solution for a given starting topology to identify promising switch on or off line candidates. We have also developed shift-factor-based MILP TCAs that are more efficient while being consistent with ED algorithms adopted today by ISOs. This paper summarizes experience with and assessment of these methods on real-size intra-day market data based on three historical one-week periods of the PJM system.**

INTRODUCTION

In recent years, significant effort has been invested in developing topology control algorithms (TCA) that co-optimize electricity generation economic dispatch (ED) with the state (connectivity) of transmission network elements. Notable works have focused on production cost savings under economic dispatch [1]–[3] and unit commitment (UC) [4], [5]. TCA implementations on small systems support the achievability of significant congestion related production cost savings. However, to date, there is limited if any evidence that is based on large, real system implementations. The TCA problem is computationally hard. Even for a small IEEE 118-bus model, consideration of more than 24 switchable lines in a DC SCOPF MIP formulation results in intractable solution times. To bypass this intractability, a variety of heuristics are used, [2]–[4], [6]–[8] which cut the chase to the identification of a limited number of promising switch-off/on transmission lines. Work cited above provides evidence that heuristics are fast and still provide significant production cost savings. In this paper we report on the performance of our previously proposed heuristics [6], [8] developed and adapted further to handle a detailed operational model of the PJM system. More specifically, data we employed were based on three historical one-week periods of the PJM system. The contribution of this paper is the reconfirmation, this time on real system data, that employing a combination of heuristics can reduce the total costs of congestion by a significant fraction while observing computational performance requirements and security constraints.

The rest of this paper is organized as follows. Section I describes the historical PJM data used, the requisite model formulation effort, and the model input calibration process needed to capture the idiosyncrasies of historic operations. Section II discusses our general approach in applying TCA heuristics to identify promising switchable lines, to solve the hour-ahead problem and to validate the solution. Section III presents computational results for the selected historical weeks and section IV concludes.

I. PJM MODEL DEVELOPMENT AND CALIBRATION

The implementation of topology control algorithms (TCAs) on large realistic systems is an essential proof of the concept that dynamic Topology Control (TC) can provide significant cost savings in the operational time frame. To this end, we applied the TCAs on the PJM system using historical data from three weeks in 2010. In collaboration with PJM, one representative summer, winter and shoulder season week was selected to assist extrapolation to achievable annual savings estimates.

The PJM TCA models were developed to use the same dataset as the one employed in the actual PJM real-time market. This dataset includes:

- Operational powerflows from the PJM state estimator, saved every five minutes
- Generation economic and constraint data
- Generation units designated as must-run
- Constraints monitored by PJM and their respective limits
- Contingency list and set of monitored lines

Using the above data we created a model for every hour in the three representative weeks. The transmission model for each hour was based on a power flow snapshot instance taken during an actual five minute period in the middle of the hour. This snapshot was, in fact, a representative average for all the five minute intervals in that hour. All constraints, active contingencies and monitored facilities were mapped to each power flow snapshot. Most thermal generators were free to be dispatched to minimize total system-wide generation costs. All other units, including must-run units, had their dispatch levels fixed at their historical values.

The employed models are an approximation of the PJM system in two ways. First, reserve requirements were not modeled. However, since unit commitment was taken directly from the state estimator power flows, units needed to provide reserve are already committed. Hence, one may safely expect this approximation to have a minimal effect on the accuracy of the model. Second, transmission was modeled using a DC power flow model. Losses from the AC power flows were added to the DC powerflow but marginal loss models were not implemented and hence, changes in system losses resulting from transmission topology control were not captured. Finally, because we use a single power flow case for each hour, we refer to our model as hour-ahead. Nevertheless, aside from the approximations described above, the employment of a single power flow per hour, still replicates adequately the operation of PJM's real-time market.

The three 7x24 hourly models capture the salient characteristics of the 2010 PJM system by employing the following orders of magnitude:

- 13,000+ buses
- 500 dispatchable thermal generation units
- 20,000 branches (3,500 monitored branches)
- 6,000 single and multi-element contingencies

II. Heuristics in TCA

The employed TCAs are iterative and consist of four main steps:

- Using heuristics in [6], [8] identify good candidates for TC action to be followed by generation re-dispatch
- Perform DC contingency analysis; if violations are observed, include all requisite additional constraints and repeat previous step
- Evaluate final solution, specify the associated topology for the hourly model, and proceed to the next hour.

By leveraging parallel computing options in performing the steps above, each hourly model is solved in less than five minutes, and, as shown in the next section, it results in significant production cost savings.

III. Simulation Results

Based on computational results from the three representative weeks, the estimated annual savings in the PJM real-time market under 2010 conditions are over $100 million. Table I reports detailed weekly savings. The term *Cost of Congestion* represents the maximum possible savings that are conceivably achievable through TC. It is defined as the difference between generation production costs with the historical topology and enforced transmission constraints and the production costs in the absence of transmission constraints. The results are evidence that a timely implementation of TCA can capture a significant portion of the maximum possible savings.

TABLE I

Summary of Savings achieved by TCA (millions of dollars)

Week	Cost of Congestion	Savings From TCA	% Savings Obtained
2010 Summer	$7.2	$4.5	62%
2010 Winter	$6.6	$4.6	70%
2010 Shoulder	$1.2	$1.0	83%

In addition to production cost savings, other interesting TCA performance statistics relate to the tpye and number of transmission line switches. Table II shows the maximum and median number of lines opened/closed in each representative week. The median number of lines switched open in any particular hour range from two to five but can reach as high as twenty (column Switched Open). The algorithm closes a median number of two to five lines in each hour but this can also reach as high as twenty (column Switched Close). The Branches Open column reports the lines that are open at the end of an hour relative to the historical topology. Table II shows that the number of incremental line openings in any given hour is quite small and hence the number of switching action when transitioning from one hour to the next is also limited. Table III summarizes the frequency of branches switched opened by the algorithm, aggregated by nominal voltage level. Table III shows that in both summer and winter weeks, 70% of lines opened do not exceed 230kV. In all three weeks over 80% of lines opened do not exceed 345 kV. In the shoulder periods there is generally less congestion and therefore the algorithm has to open more of the higher voltage lines to attain the same level of production cost savings.

TABLE II

Summary of Line Openings and Closings by TCA

Week	Metric	Switched Open	Switched Closed	Branches Open
2010 Summer	Maximum	15	22	73
	Median	5	5	51
2010 Winter	Maximum	20	17	89
	Median	5	5	62
2010 Shoulder	Maximum	18	10	74
	Median	2	2	46

TABLE III

Summary of Line Switchings by Voltage Level

Nominal kV	¡200 kV	230 kV	345 kV	500 kV	765 kV
2010 Summer	46%	24%	14%	11%	5%
2010 Winter	51%	19%	15%	9%	6%
2010 Shoulder	33%	24%	25%	12%	6%

Tables IV and V elaborate for the summer week, the typical flow on the lines that the algorithm opened and closed, both in terms of absolute MW and as a percentage of the branch limit. Note that TCA switched lines at all the voltage levels, exhibit typically light loads. Opening lightly loaded lines is desirable as it reduces the amount of stress placed on breakers helping with maintenance costs. Winter and Shoulder weeks exhibit similar behaviors to the Summer week.

Figure 1 shows the trajectory of opened lines during a single week. Hours of the week are shown on the x-axis. Open branches are shown on the y-axis with bar lengths

Fig. 1. Pattern of Line Openings

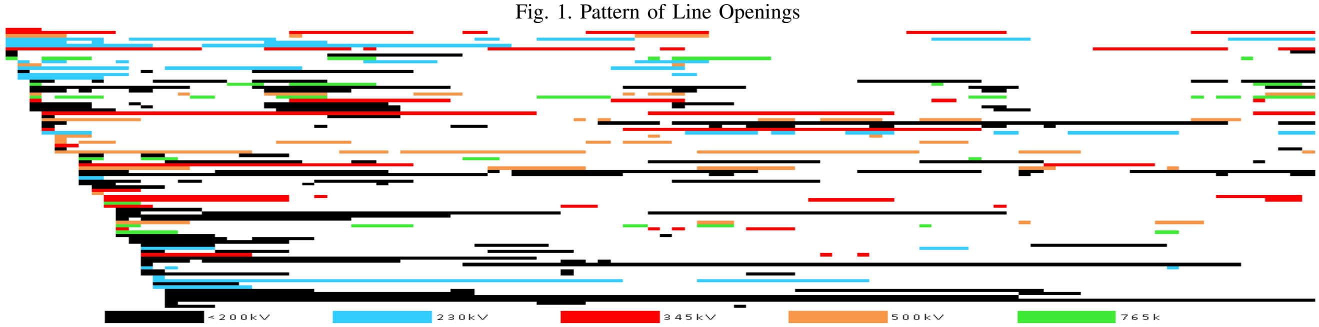


TABLE IV

TYPICAL FLOW ON OPENED LINES

Nominal kV	115kV	138kV	230kV	345kV	500kV	765kV
Median Flow (MW)	59	67	158	224	613	423
Median Flow (%)	29%	25%	23%	22%	23%	15%

TABLE V

TYPICAL FLOW ON CLOSED LINES

Nominal kV	115kV	138kV	230kV	345kV	500kV	765kV
Median Flow (MW)	70	99	199	250	613	462
Median Flow (%)	32%	32%	27%	24%	20%	16%

denoting the number of hours a line stays open. Branches are sorted by the hour in which they were first opened. This results in a diagonal pattern on the left side of the figure. We note that many branches were opened for an extended period before they were re-closed. This indicates that the algorithm choses fewer switching actions, which also reduces the stress on breakers and maintenance costs.

Figures 2 and 3 demonstrate TCA's ability to ameliorate constraints. In Figure 2, the large pie chart shows a particular constraint that was violated in the historical market data. Locational Marginal Price (LMP) contours present wide price variations indicating significant market splitting. Figure 3 shows the same system after 2 lines have been opened (opened lines are indicated by a circle with an "X"). The pie chart shows the particular constraint is no longer binding (98%), and the LMP contours show price seperation to have dissipated in the area. The original flow through the binding constraint is re-directed to alternative lines and overall system congestion is reduced.

IV. CONCLUSION

This paper demonstrates the applicability of TCA to large, real systems by evaluating hourly models of the PJM real-time market for 3 representative historical 2010 weeks. Subject to operational requirements, each hourly model was solved for a snapshot of the power flow taken from a 5 minute period within the hour, while satisfying contingency analysis.

Fig. 2. Congestion prior to Line Switching

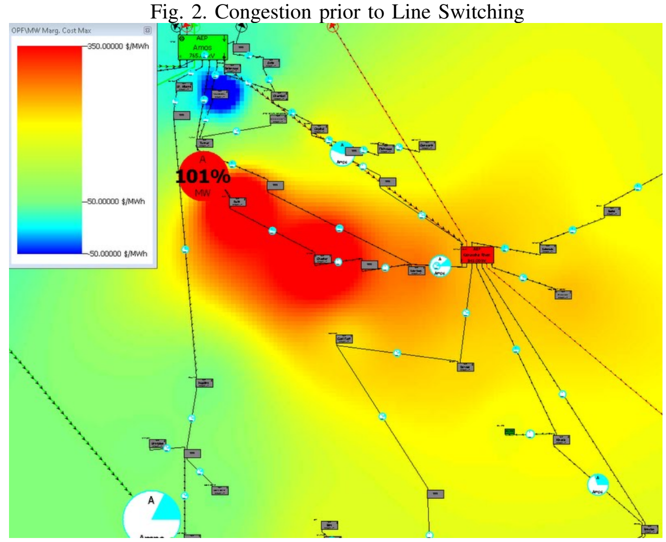
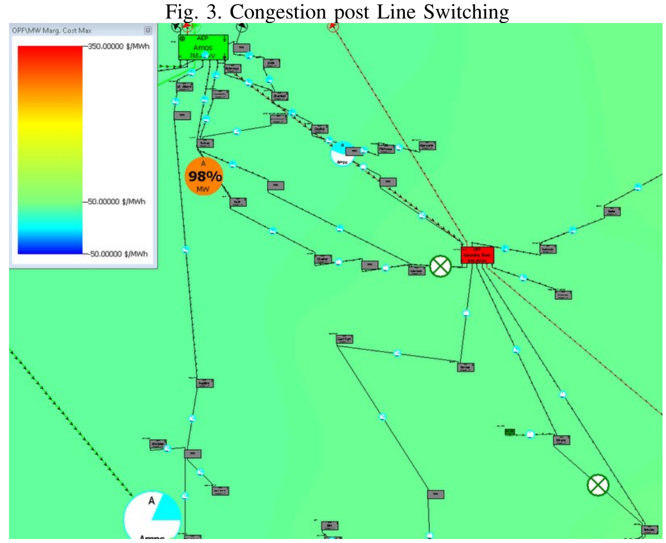


Fig. 3. Congestion post Line Switching



Based on the results from the 3 weekly runs, we offer the following conclusions.

- Topology control captures a significant portion of the maximum congestion cost savings. Extrapolation based

on the number of weeks in each season indicates a potential for over $100 million in production cost savings in the PJM real-time markets
- The net number of line openings in any given hour is modest as is the number of switching actions from one hour to the next.
- Over 80% of lines opened are 345 kV and below and the type of branches opened/closed are typically lightly loaded. Operating the breakers of such lightly loaded lines promises to reduce maintenance costs and stress on the breakers.
- Lines opened by the TCA are generally kept open for an extended period of time reducing breaker maintenance costs further.

Aside from continuing to improve the performance of our TCAs, future work will focus on incorporating operational criteria such as voltage and MVA flow constraints. We will also work on co-optimization of unit commitment and transmission topology.

REFERENCES

[1] R. O'Neill, R. Baldick, U. Helman, M. Rothkopf, and W. Stewart, "Dispatchable transmission in RTO markets," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 171–179, Feb. 2005.

[2] E. B. Fisher, R. P. O'Neill, and M. C. Ferris, "Optimal transmission switching," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1346–1355, Aug. 2008.

[3] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1577–1586, Aug. 2009.

[4] K. W. Hedman, M. C. Ferris, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with n-1 reliability," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1052–1063, May 2010.

[5] C. Liu, J. Wang, and J. Ostrowski, "Static security in multi-period transmission switching," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 1850–1858, 2012.

[6] P. A. Ruiz, J. M. Foster, A. Rudkevich, and M. C. Caramanis, "Tractable transmission topology control using sensitivity analysis," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1550–1559, Aug. 2012.

[7] J. D. Fuller, R. Ramasra, and A. Cha, "Fast heuristics for transmission-line switching," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1377–1386, Aug. 2012.

[8] P. A. Ruiz, A. M. Rudkevich, M. C. Caramanis, E. A. Goldis, E. Ntakou, and C. R. Philbrick, "Reduced MIP formulation for transmission topology control," in *Proc. 50th Allerton Conf. on Communications, Control and Computing*, Monticello, IL, Oct. 2012, pp. 1073–1079.