AC-Based Topology Control Algorithms (TCA) – A PJM Historical Data Case Study

Evgeniy A. Goldis, Xiaoguang Li, Michael C. Caramanis, Aleksandr M. Rudkevich, Pablo A. Ruiz

***Abstract*—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. Our previous work 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. In control rooms, however, algorithms must rely on AC-based power flow tools to ensure feasibility in the physical network. Considering the computational time constraints that must be met in an operational setting, iterating between DC-based topology control algorithms and AC power flow validation of proposed topology control actions may become intractable in large systems. In this paper we present real system size computational results relying directly on AC-based topology control algorithms that we have developed. In particular, we discuss a case study on three historical weeks of PJM system data where AC-based topology control solutions are presented and compared to the corresponding DC-based solutions.**

INTRODUCTION

Although the co-optimization of generation dispatch and network topology can provide significant congestion cost savings, the computational complexity inherent in this Mixed Integer Linear Programming problem renders finding the optimal solution intractable for most real systems. This intractability issue has led to the investigation of a variety of heuristic algorithms [1]–[7] that focus on identifying a limited number of promising transmission lines to open/close. Successful heuristic algorithms are fast and provide near optimal congestion cost savings.

One application of topology control is for real-time markets. Real-time market tend to be cleared every five minutes with a 5 to 15 minute look ahead. The market clearing algorithms rely on a linearized AC model with shift factors and other parameters updated using state estimator data. To integrate topology control algorithms into the existing market process, the maximum admissible solution time is 5 minutes, which could make iterating between the DC and AC models impractical in large systems such as PJM. In this paper we report on the performance of algorithms similar to those previously proposed [4], [6], where AC rather than DC power flow equations are used. Unlike previously reported DC-based algorithm results [8], the AC-based algorithms do not rely on an approximate system state representation. It models both real and reactive power flows, losses and bus voltage magnitudes and angles, and it relies on linearization to achieve the requisite computational speed in the optimization problem. In the context of real-time market, each solution must be provided by the topology control process within five minutes. The evidence reported here re-affirms that topology control algorithms (TCA) can reduce congestion costs and provide novel congestion control options. In addition, it shows that TCA can be implemented in a control room environment that requires computational performance as well as AC power flow accuracy, which we henceforth refer to as AC-feasibility.

The rest of this paper is organized as follows. Section I summarizes the historical PJM data used and the AC-based TCA formulation. Section II presents computational results for the selected historical weeks and section III provides concluding remarks.

The work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000223 and NSF EFRI grant 1038230.

P. A. Ruiz (paruiz@ieee.org) and X. Li (Xiao.Li@brattle.com) are with The Brattle Group, Cambridge, MA 02138; P. A. Ruiz, M. C. Caramanis (mcaraman@bu.edu), E. Goldis (evgeny@bu.edu) and X. Li are with Boston University, Boston, MA 02215; A. Rudkevich (arudkevich@negll.com) is with Newton Energy Group, Newton, MA 02458;

I. PJM MODEL DEVELOPMENT

This section summarizes the main features of the PJM dataset on which the performance of TCA is evaluated. The model calibration process and other details can be found in [8]. The results presented in this paper are based on 3 historical weeks of the PJM system in 2010. In collaboration with PJM, three representative weeks from the summer, winter and shoulder seasons were selected as a basis for estimating annual savings.

The DC as well as AC-based TCA models employed in this paper were formulated to accept the same dataset as the one employed in the actual PJM real-time market. We note below the average basic dataset characteristics:

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

The dataset includes power flows from the PJM state estimator, monitored transmission and contingency constraints, and economic generation and transmission data from the real-time markets. These data were used to create TCA inputs for each of the 168 hours in each representative week.

The DC-based TCA formulation that was used previously and whose results we compare to the AC-based TCA formulation relied on the following simplifying assumptions:

- Power flow equations are limited to real power only and bus voltage magnitudes are assumed to be at 1.0 per unit
- Losses are taken from the state estimator AC case and distributed among the loads. The distributions and loss magnitude are not adjusted with topology or dispatch changes
- Contingency analysis relies on the DC power flow approximation and ignores changes in reactive flows

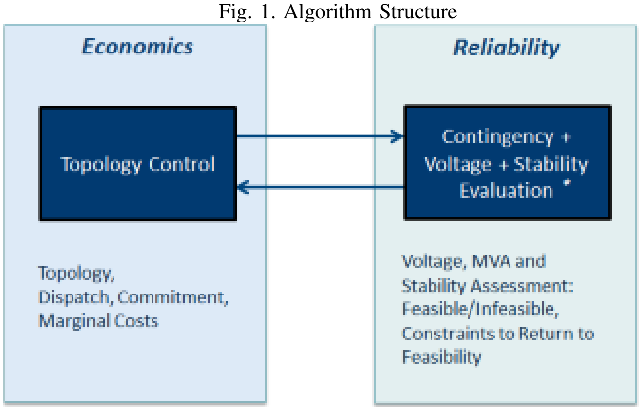
In this paper we modify our previous TCA formulation to incorporate AC power flow modeling. The OPF is solved using a linearized AC power flow formulation (see for example [9]) and contingency analysis also account for reactive flows. In contrast to the DC model, the AC TCA formulation represents both 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 TCA iteration. Compared to the DC model used in [8], the AC formulation guarantees AC feasibility at every step of the TCA, with sustainable impact on computation performance.

The iterative TCA formulation is summarized in the following 4 steps:

- Using heuristics in [4], [6] identify switchable line candidates for TC action. If good candidates are identified, proceed to the next step, otherwise skip to the last step
- Evaluate the benefits of switching the selected candidates on an AC model
- Evaluate 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.
- Repeat the previous steps until a stopping criterion is reached.
- 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 steps above

Fig. 1. Algorithm Structure



At each step in the Reliability assesment, 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. [1] 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.[2] 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.

II. Simulation Results

Based on computational results from the three representative weeks of 2010, the estimated annual savings in the PJM real-time market under 2010 conditions are estimated to be over \$100 million. Table I reports detailed weekly savings. The term *Cost of Congestion* represents the additional production cost that results from the generation re-dispatch required to avoid transmission line capacity violations, and, as such, it is the maximum conceivable savings that TC can achieve. More precisely, *Cost of Congestion* 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.

TABLE I
Summary of Savings achieved by TCA (millions of dollars)

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

Figures 2-4 compare the results above to savings found under the DC-based algorithms. The total cost of congestion estimated by the AC power flow model is smaller, primarily, due to the incorporation of marginal losses that were ignored in the DC model. The lossless transfer of power across large distances as modeled in the DC-OPF model underestimates costs and hence overestimates savings from dispatching distant low-cost generation. Since the cost of congestion in the DC OPF is estimated to be higher relative to the linearized AC OPF, total savings are evaluated to be lower by the AC power flow model. The relative cost of congestion savings, however, are similar. Moreover, the AC-based TCA switching solution is AC feasible, whereas the DC solution need not be.

Figures 5-7 compare the number of lines opened in the three 2010 weeks. The ramp-up trend in the first 24 hours of each figure is due to the incremental nature of the algorithm where each consecutive hour begins by inheriting the optimized

[1] While there are 20,000 lines total, they includes lines outside of PJM, lines connected in series, generation step up transformers, lower voltage facilities and other branches that are typically not explicitly monitored

[2] 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.

Fig. 2. Cost of Congestion

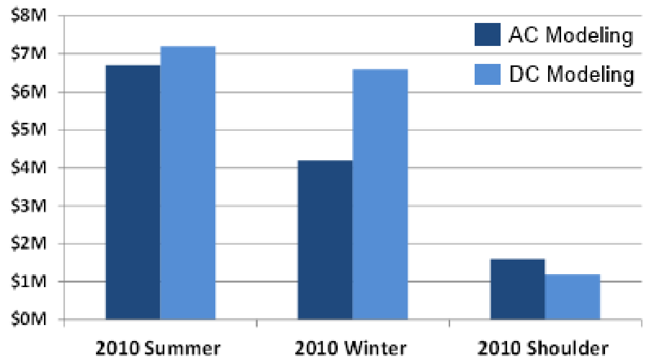


Fig. 3. Savings

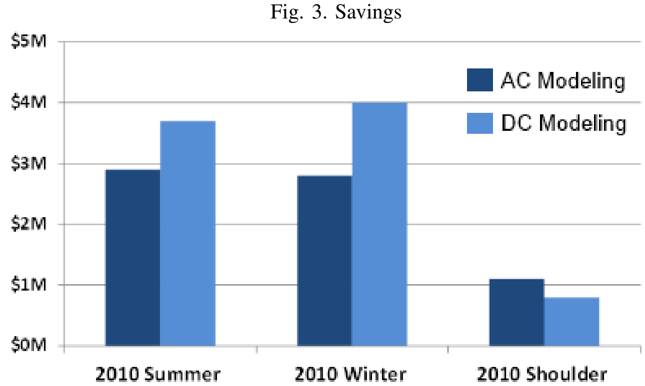


Fig. 4. % Savings Captured

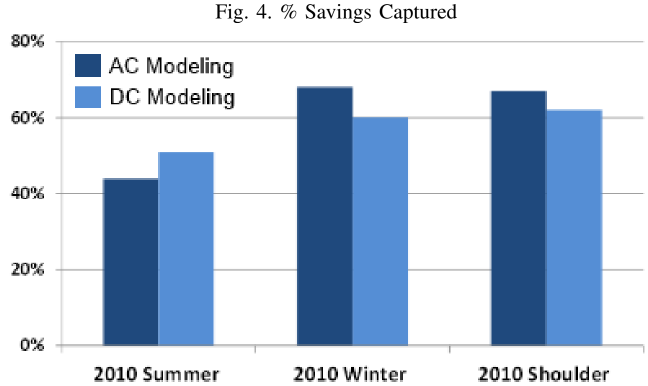


Fig. 5. Branches Open with TCA - 2010 Summer

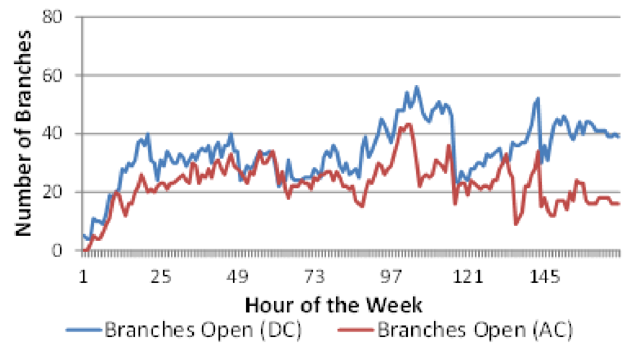


Fig. 6. Branches Open with TCA - 2010 Winter

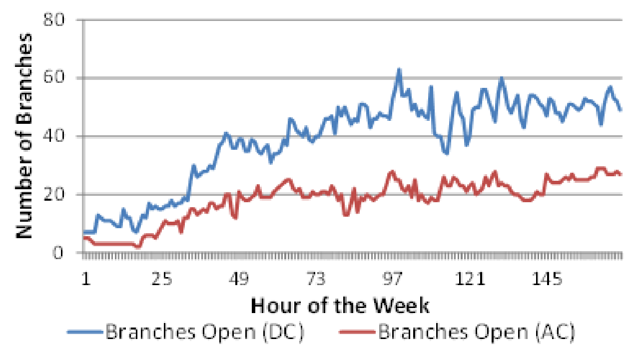
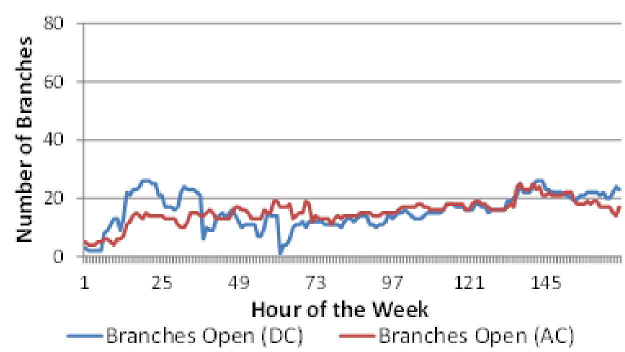


Fig. 7. Branches Open with TCA - 2010 Shoulder



topology of the previous hour. Since the first hour of the week does not inherit any opened lines, we observe that it takes about 24 hours for the number of lines opened to reach their "average" level. As shown in the figures, fewer lines are opened by the AC-based TCA during the higher load weeks (summer and winter). The main reason for this difference is the explicit modeling of marginal losses. Marginal losses increase as the system flows increase, which tends to happen under higher load conditions. With marginal loss modeling, the incremental cost savings of opening a branch has to be larger than the potential increments in costs due to losses increase. Lines associated with a high congestion-relieving marginal benefit in the lossless formulation may have an adverse impact on system losses. Thus, fewer branches are beneficial for opening under AC modeling. It is interesting to note that a similar effect was observed when losses were included in the DC-based TCA [10]. As shown in figure 4 and [10], the relative savings achieved by TCA are similar with and without loss modeling. In addition, opening fewer lines is clearly beneficial from an operations point of view. We also note that the AC-based TCA opens fewer lines than the DC-based TCA with loss modeling. This indicates that the AC-based TCA is usually constrained by the 5 minute computing time limit and analyzed fewer candidates.

Table II summarizes the frequency of branches switched open by the algorithm, classified by their nominal voltage level. In all three weeks, 56-59% of lines opened do not exceed 230 kV while 70% of all lines opened do not exceed 345 kV. Compared to the DC-based TCA results, in which over 80% of lines opened did not exceed 345 kV, the AC-based TCA opens a fewer percentage of low-voltage lines. Incorporating losses and reactive power appears to make it less desirable to open low-voltage lines.

TABLE II
SUMMARY OF LINE SWITCHINGS BY VOLTAGE LEVEL

Nominal kV	<200 kV	230 kV	345 kV	500 kV	765 kV
2010 Summer	35%	21%	14%	22%	8%
2010 Winter	36%	21%	20%	12%	10%
2010 Shoulder	16%	43%	14%	17%	10%

The general behavior of the branches switched are that lower voltage lines tend to stay open for longer strings of hours while higher voltage lines typically stay open for shorter periods. For branches below 230 kV, they make up 56-69% of the number of switching operations, but 67-75% of the hours in which branches are open. Conversely, at the 765 kV level, they represent 8-10% of the number of switching operations, but only 3-7% of the total number of hours in which branches are open. Higher voltage lines are generally opened over shorter periods that are associated with light load conditions.

Table III compares AC-based and DC-based TCA results in terms of some additional opening and closing statistics during the summer week. Again, we consistently observe fewer lines opened by the AC-based TCA with the median number of lines open at any given time trailing that of the DC-based TCA by about 10. In any given hour, however, both models open a small number of lines, with only one or two additional lines opened by the DC-based TCA. The winter week exhibits the same behavior as the summer week while the statistics for the shoulder week are almost identical among the AC and DC-based models (as shown in figure 7). In the shoulder season demand is lower, marginal losses have less impact, and the time constraint of five minutes is often not limiting the evaluation of promising switchable line candidates. Consequently, results between the AC and DC-based models are quite similar.

TABLE III
TOPOLOGY CHANGE STATISTICS SUMMARY - SUMMER WEEK

	AC | DC	AC | DC	AC | DC
percentile	Branches Open	Switched Open	Switched Close
Min	0 | 4	0 | 0	0 | 0
25%	18 | 28	0 | 1	1 | 1
Median	23 | 33	2 | 3	2 | 2
75%	27 | 40	4 | 5	3 | 4
Max	43 | 56	10 | 10	23 | 29

III. CONCLUSION

This paper demonstrates the applicability of TCA to real systems in a control room environment. By incorporating AC power flow modeling, we ensure AC feasible at every step of the TCA. In additional, we can accurately model branch MVA limits, and the inclusion of losses makes the TCA solutions more realistic. Compared to our previous work with DC-based TCA, the AC-based formulation is computationally more expensive. As a result, the AC-based TC algorithm tends to evaluate fewer candidate lines within the imposed five minute time constraint. Nevertheless, the results in this paper show that the relative savings captured by the AC-based TCA is substantial. In addition, the AC-based TCA opens fewer lines, which is more attractive to system operators and transmission owners from an implementation perspective. The evidence reported in [8] on the tractability of DC-based TCA in reducing congestion costs on a system the size of PJM is replicated here for the AC-based TCA, which additionally ensures the AC feasibility required for operational TC actions. In conclusion, this paper provides strong evidence to support the ability of TCA to be usefully employed in operations.

REFERENCES

[1] 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.

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] 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.

[7] M. Soroush and J. D. Fuller, "Accuracies of optimal transmission switching heuristics based on dcopf and acopf," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 924–932, Mar. 2014.

[8] E. A. Goldis, X. Li, M. C. Caramanis, B. Keshavamurthy, M. Patel, A. M. Rudkevich, and P. A. Ruiz, "Applicability of topology control algorithms (TCA) to a real-size power system," in *Proc. 51st Allerton Conf. on Communications, Control and Computing*, Monticello, IL, Oct. 2013, pp. 1349–1352.

[9] B. Wollenberg and A. Wood, *Power Generation, Operation and Control*, 2nd ed. New York, NY: John Wiley, 1996.

[10] E. A. Goldis, M. C. Caramanis, C. R. Philbrick, A. M. Rudkevich, and P. A. Ruiz, "Security-constrained MIP formulation of topology control using loss-adjusted shift factors," *2014 47th Hawaii International Conference on System Sciences*, vol. 0, pp. 2503–2509, 2014.