Towards Smart Corrective Switching: Analysis and Advancement of PJM's Switching Solutions

P. Balasubramanian [1*], M. Sahraei-Ardakani [1], X. Li [1], and K. W. Hedman [1]

[1] Department of Electrical Computer and Energy Engineering, Arizona State University P.O. Box 875706, Tempe, AZ 85287-5706, USA
[*]pbalasu3@asu.edu

Abstract: Transmission switching, as a power flow control mechanism that can reduce costs and improve reliability, has gained a lot of attention during the last decade. Despite its benefits, industry adoption has been very limited due to its computational complexity, stability and AC performance concerns. PJM has published a list of corrective switching solutions to relieve actual and post-contingency network violations. The list is developed based on operators' prior knowledge and offline studies. This paper employs a fast AC-based real-time contingency analysis (RTCA) tool with corrective transmission switching (CTS) functionality to analyze PJM's switching solutions with actual PJM data. The results show that the RTCA CTS tool is almost always able to find solutions that perform better than, or equally as well as, PJM's solutions. The results also show that PJM's list identifies solutions for only 3% of the problematic contingencies with post-contingency violations over the course of one week. The RTCA CTS tool, however, is able to find corrective TS solutions for almost all the cases. The results suggest that CTS is ripe for industry adoption. The tool provides significant savings and would pave the road towards a smarter transmission network as an essential ingredient of the future smart grid.

1. Introduction

Transmission switching (TS), an effective power flow control technology, has recently received a lot of attention from academia and industry. The US Department of Energy (DOE) Advanced Research Projects Agency – Energy (ARPA-E) Green Electricity Network Integration (GENI) initiative has invested over forty million dollars in power flow control hardware and software technologies, including seven million for transmission switching [1]. It is well-known and acknowledged that the technology can reduce costs [2]-[5], improve system reliability [6]-[7], and enhance integration of intermittent renewable resources [8]. There is a large body of literature dedicated to different applications of transmission switching as well as methods for identifying switching actions. In spite of the acknowledgement of the benefits of the technology, industry adoption has been very limited. Among others, computational complexity, AC feasibility, and stability are the main challenges that need to be addressed before the employment of the technology. These issues are discussed in detail in the next section.

The Pennsylvania New Jersey Maryland (PJM) Interconnection is a leader in employing transmission switching and has identified and published a list of switching solutions for the purpose of thermal limit violation (overloads) and voltage control [9]. These solutions are proposed for actual and post-contingency situations based on operators' knowledge and offline studies. A real-time study of the solution is needed before it can be implemented, to ensure the actual effectiveness of the solution. PJM acknowledges that transmission switching is a *fast* and *cheap* alternative to other corrective actions such as generation redispatch [9].

An inherent drawback of PJM's approach is that it does not acknowledge the varying nature of the system conditions and proposes offline solutions to problems that are inherently dependent on system states. PJM's switching solutions are also limited in number since they have been identified offline. Therefore, many situations, for which viable TS solutions exist, are overlooked. This leaves a lot of room for efficiency gains through more effective employment of TS. This paper takes a natural step forward by employing a fast and effective AC TS-based real time contingency analysis (RTCA) package. This online tool proposes five different corrective transmission switching (CTS) candidates for each contingency with potential post-contingency violations. The tool was employed to study PJM's switching solution and analyze their effectiveness. The study was carried out on actual snapshots from PJM's energy management system (EMS).

The results show that the tool employed in this paper was able to identify PJM's solutions for the majority of the cases as one of the beneficial candidates. It often was able to find solutions that were not identified by PJM, but performed better by further reducing potential post-contingency violations. There were also instances that the RTCA CTS tool was able to eliminate significant thermal limit violations with a single switching action, while the solution was not identified by PJM.

This paper contributes to the existing literature by analyzing the most advanced industry practice of TS, PJM's switching solutions. The paper also takes a natural step forward by employing an RTCA CTS tool, which harnesses the flexibility of transmission elements while taking into account the system operating states. The RTCA CTS tool employs a simple heuristic that is straightforward to implement, easily parallelizable, fast, AC-based, and able to handle large-scale systems such as PJM. The heuristic provides very effective solutions that will significantly improve PJM's practice. The results show that improvements to the current industry practices, leading to significant benefits, are well within the reach of the existing technology. The paper, thus, closes an important gap between academic research and industry adoption of the technology.

The rest of this paper is organized as follows: Section II presents a comprehensive literature review on transmission switching and its state of the art challenges. Section III shows how the RTCA CTS tool is developed. PJM's switching solutions are analyzed in Section IV. Improvements beyond PJM's switching solutions are presented in Section V. Finally, Section VI concludes the paper.

2. Literature Review

2.1. Academic Literature

Transmission switching first gained attention as a corrective mechanism [10]-[15]. The idea since then has been extended to co-optimize the network topology alongside with generation dispatch in order to achieve economic gains [2]-[5], [16]-[17]. Despite the belief that economic benefits of TS comes at the cost of risking the reliability, it is shown that inclusion of TS in security-constrained unit commitment (SCUC) and security-constrained economic dispatch (SCED) would lower the system cost without jeopardizing reliability [5], [18]-[19]. A recent study [20] considers probabilistic reliability measures while analyzing economics of TS and concludes that savings can be achieved even by taking reliability costs into consideration.

In addition to power system operation problems such as SCUC and SCED, TS is shown to reduce the total planning cost in transmission expansion planning [21]. TS is also able to reduce the planning cost while enhancing integration of large-scale wind resources [22]. It is shown that TS can facilitate integration of intermittent renewable resources in various stages of power system operation [23]-[24]. Reference [25] discusses the operational challenges of increasing renewable generation in Europe and proposes TS as a cheap and viable solution. Such assistance in renewable generation would translate into economic benefits, due to reduced consumption of fossil fuels, as well as emission reductions.

As mentioned earlier, TS can also be used as a corrective mechanism in response to occurrence of contingencies. North American Electric Reliability Corporation (NERC) requires power systems to withstand the loss of a single bulk electric element [26], which is referred to as "*N*-1 reliability". Due to complexity of explicit modeling of *N*-1 contingency events in SCUC and SCED, proxy reserve requirements are used as the main reliability instrument in SCUC and SCED [27]. In addition to the reserve requirements, lead SCED solvers may include a very limited subset of contingency constraints. Thus, deliverability of the reserve is not guaranteed in all the potential post-contingency states [28]. To comply with NERC's *N*-1 reliability requirement, system operators continuously check the operating state of their system using RTCA. Out-of-market corrections (OMC), including reliability-motivated commitment and redispatch, are performed to ensure reliability [29]. Such OMC actions are expensive and should be performed in the pre-contingency stage to move the system to a reliable state. TS is an alternative to OMC actions that can enhance the deliverability of reserves and ensure system reliability [15]. Unlike OMC actions, TS can be performed only after the occurrence of the contingency at a very low cost [6]-[7], [30]. Corrective TS actions can be calculated offline using robust optimization to ensure feasibility under a variety of scenarios [6], [31], or online using fast heuristics [7], [32]-[33]. Previous research also shows that TS can be used to enhance do-not-exceed limits [34].

Despite all the benefits of TS, there remain barriers that prevent full adoption of the technology. These barriers include: 1) computational complexity, 2) ambiguity of AC performance, 3) limited knowledge of TS performance on large-scale systems, 4) stability concerns, 5) industry acceptance of something that is counterintuitive, 6) handling communication issues with transmission operators, and 7) financial issues such as FTR revenue adequacy problems [35].

The mathematical representation of optimal TS (OTS) for economic or reliability applications under DC set of assumptions is a mixed integer linear program [2], [6]. Each switchable transmission asset is represented by an integer variable. The complexity of such problem grows exponentially with the number of switchable transmission elements. Therefore, OTS is a computationally challenging problem for large-scale real power systems, given the existing computational capabilities. Reference [36] shows that the majority of TS benefits can be achieved by testing a very limited subset of switchable assets. Therefore, different heuristic methods are proposed to find TS actions quickly [37]-[41]. A parallel implementation of three TS heuristics is presented in [42].

Most of the algorithms developed for TS are based on DC power flow equations. It is not clear how such algorithms would perform under full AC power flow equations. A comparative analysis between optimal transmission switching in a DC setting and AC setting is presented in [43]. Reference [44] shows that the two heuristics developed based on DC [37] and AC optimal power flow (OPF) [38] do not perform well on the Polish system. Since DC models ignore voltage magnitudes, DC based TS methods may propose solutions that result in voltage collapse [45].

Another shortcoming of the literature on TS is limited studies on large-scale systems. The majority of the existing TS literature is on small scale test cases. Although OTS provides significant benefits in small scale systems, the performance of TS on large-scale real system is not clear. Recent studies suggest that TS can provide significant economic benefits in PJM [46]-[47] and reliability improvements in the Tennessee Valley Authority (TVA) [48]. More studies with real power system data are needed to draw comprehensive conclusions.

There is also a concern that TS may create stability issues [49] in power systems. Seasonal TS is proposed in response to such stability concerns [50] and other issues. However, as will be discussed late in this section, the industry already performs more frequent TS actions for a variety of reasons.

Overall, the academic literature has identified TS as a tool that can potentially offer significant benefits [51]. It is also an important flexible tool for the future smart grid [52]-[54].

2.2. Industry Practices

The Independent System Operator of New England (ISO-NE) allows switching a circuit breaker to relieve transmission constraints or in response to contingencies [55]. However, such TS actions are only allowed in well documented and well defined situations [55]. Thus, the operator's knowledge and offline studies are the basis of such remedial actions.

California ISO (CAISO) acknowledges TS for congestion relief [56]. In particular, [57] discusses how switching of a congested line relieves the congestion after loss of another line in CAISO territory. Pacific Gas and Electric also identifies TS as a tool that participating transmission owners use to reduce overloads [58]. The Electric Reliability Council of Texas (ERCOT) as well as the Midcontinent ISO (MISO) both acknowledge and allow TS as a corrective mechanism to reduce actual or potential post-contingency voltage issues and overloading of transmission facilities [59]-[60].

A NERC report shows that PJM switched multiple high voltage lines out of service to deal with overvoltage issues due to damages caused by Hurricane Sandy [61]. Other than specific events, PJM has a more systematic way of employing TS for reliability purposes. PJM has published a list of "switching solutions" in response to voltage issues, line or transformer overloads, or the occurrence of a contingency [9]. This seems to be the most advanced industry employment of TS technology. This paper develops an RTCA CTS tool that searches for TS solutions based on the system states in real-time and analyzes PJM's switching solutions using the developed tool. The paper shows that an RTCA CTS tool can offer significant improvements compared to the PJM switching solutions.

3. RTCA Corrective Transmission Switching

Fig. 1 shows a general RTCA package. System state information, including voltage magnitudes, voltage angles, injections, and power flow information, are sent to RTCA. ISOs also have a list of contingencies that they want to make sure their system can withstand. Not all the potential N-1 events are included in this list due to a variety of reasons such as existence of reliable corrective mechanisms, or insignificance of the contingency. In the case of a generator outage, the RTCA package adjusts the output of the remaining generation fleet to compensate for the lost generation, while the generation dispatch remains unchanged in the case of a transmission outage except that the generators at the slack bus adjust to compensate for the change in system losses. The contingencies are then simulated through an AC power flow solver.

This is a classic AC power flow problem with a set of *2N* equations with *4N* variables. At each node, two of the variables are known: net active injection and voltage magnitude for generation buses, net active and reactive injections for load buses, and voltage magnitude and angle for slack bus. The power flow problem can be solved using a method such as Newton-Raphson. OpenPA, an open source AC power flow tool [62], is used as the power flow solver in this paper.

The solution to the post-contingency AC power flow problem is checked for the following network constraints:

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{1}$$

$$|P_{mn} + jQ_{mn}| \leq S_k^{max} \tag{2}$$

$$|P_{nm} + jQ_{nm}| \leq S_k^{max} \tag{3}$$

Bus voltage limits are checked in (1) while (2) and (3) check whether the injections at the two ends of line k exceed the line's thermal capacity. If network violations are detected, special protection schemes (SPS), which are identified for that particular contingency, are tested. PJM's switching solutions [9] can be seen as a specific category of SPS. Here is an example of one switching solution identified by PJM [9]:

"To alleviate contingency overloads on the Tiltonsville-Windsor 138kV line, study and request APS/Duq to:

1. Open either the Lagonda CB or the Buffalo Jct CB at Windsor.
2. Open the West Bellair 345/138kV #1 Xfrmr (via the 138kV E & E2 CBs). If applicable, verify with AEP as a potential switching solution."

The example specifies two switching solutions to alleviate contingency overloads on a 138 KV line. One solution is to open one of two potential circuit breakers while the other solution requires switching a transformer out of service. The switching solutions or other SPSs can be tested by solving an AC power flow with another round of network violation checks. Note that all the network constraints should be checked again since the remedial action may be able to alleviate the original violations at the expense of causing network violations elsewhere.

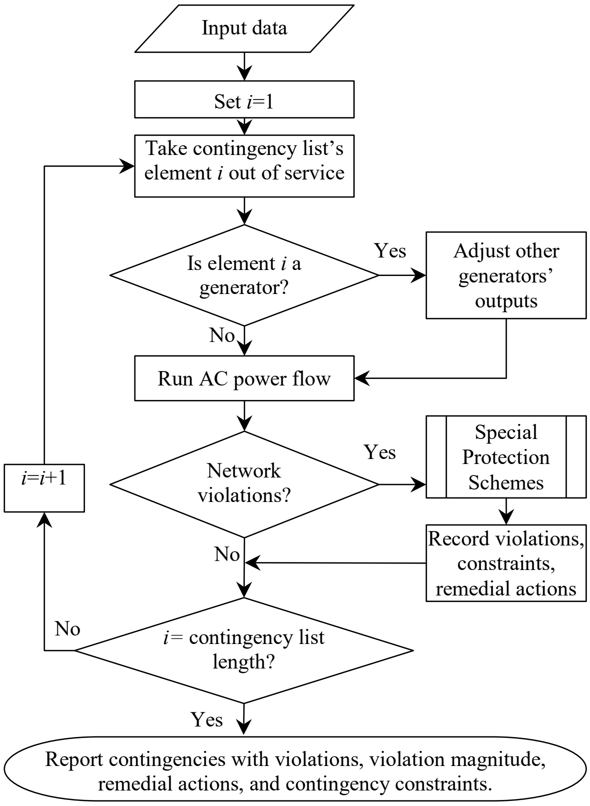

Fig. 1. *A general RTCA package that ISOs use.*

PJM's switching solutions are predetermined corrective actions that are tested for effectiveness in real-time. The approach employed in this paper, however, creates a list of switching candidates for each contingency with potential violations in real-time based on system operating states. The algorithm used in this paper simply creates a list that includes 100 closest lines to the contingency. Such a simple heuristic does not need any significant computational effort, which makes it faster and easier to implement in comparison to the existing TS heuristics [37]-[41]. Note that the closeness of a branch to the contingency element is defined based on the network topology. For instance, in the case of a branch contingency, the lines closest to the contingency element would be identified as follows: All the lines connected to the 'from' and/or 'to' bus of the contingency element will be selected as the closest switching candidates. Subsequently, the branches connected to the other end of these closest switching candidates, which were identified in the first step, will be included in the switching candidate list as the second set of closest transmission elements. This procedure is repeated until 100 closest lines to the contingency element are identified.

Note that the structure of the method is suitable for parallel computing. Each switching candidate can be sent to a separate processor for evaluation. The candidate with the best performance in terms of violation reductions will be selected for implementation.

Fig. 2 shows PJM's approach versus the corrective switching routine employed in this paper. Both of these routines can be employed as the SPS method shown in Fig. 1. The corrective TS routine shown in Fig. 2 is used as a basis to study the effectiveness of PJM's switching solutions.

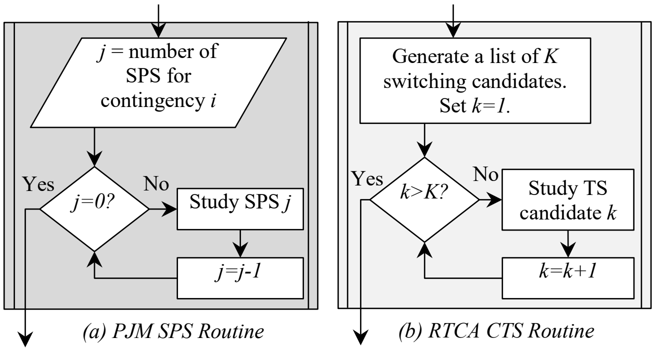

Fig. 2. *(a): PJM's SPS procedure; (b): the corrective TS routine employed in this paper.*

4. Overview of PJM Switching Solutions

This section summarizes PJM's publically available switching solutions. A map of PJM territory and its utility zones are shown in Fig. 3 [63]. Utility names and their abbreviations are presented in Table I. PJM has a total of 109 switching solutions that are posted on the PJM website [9]. Fig. 4 shows the distribution of these switching solutions in PJM's utilities zones. AEP has the largest number of such solutions followed by APS and Dominion. It is observed that one particular switching solution involves MISO, which shows that coordination between the neighboring regional transmission organizations can help alleviate network violations in some instances.

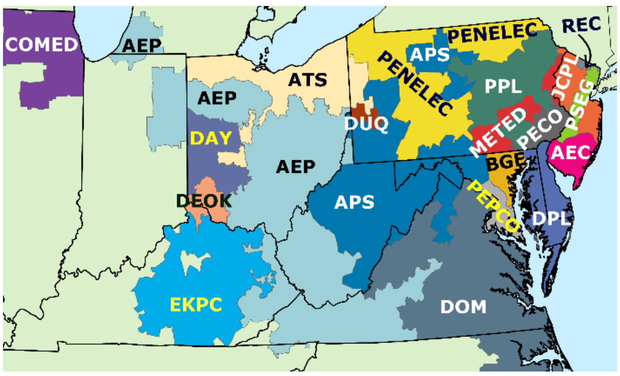

Fig. 3. *PJM's territory and its utility zones [63].*

These solutions are identified for different purposes such as voltage control and thermal overload. They are also intended for different stages like normal operation and post-contingency situations and are triggered based on different events such as occurrence of a contingency or detection of an overloaded transmission asset. These different characteristics of PJM's switching solutions are summarized in Fig. 5. The figure shows that only 2 out of 109 switching solutions are intended for voltage control and the rest are designed for thermal overload relief. In pre-contingency states, 67 switching solutions may be implemented, while 100 solutions exist for post-contingency states. Many of the solutions can be used both in normal operations (pre-contingency) and post-contingency. Finally, 21 switching solutions are triggered by a contingency while 94 of the solutions are triggered by detection of overloads. Likewise, there are switching solutions that are triggered both by overloads and contingencies.

Table 1 PJM utility names and abbreviations

Utility name	Abbr.	Utility name	Abbr.
Allegheny Power Systems	APS	Duquesne Light	DUQ
American Electric Power	AEP	East Kentucky Power Cooperative	EKPC
American Transmission system	ATS	Jersey Central Power and Light Company	JCPL
Atlantic City Electric Company	AECO	Metropolitan Edison Company	METED
Baltimore Gas and Electric Company	BGE	Philadelphia Electric Company	PECO
Commonwealth Edison Company	COMED	Pennsylvania Power and Light	PPL
Dayton Power and Light Company	DAY	Pennsylvania Electric Company	PENELEC
Duke Energy Ohio and Kentucky	DEOK	Potomac Electric Power Company	PEPCO
Delmarva Power and Light Company	DPL	Public Service Electric and Gas Company	PSEG
Dominion	DOM	Rockland Electric Company	RECO

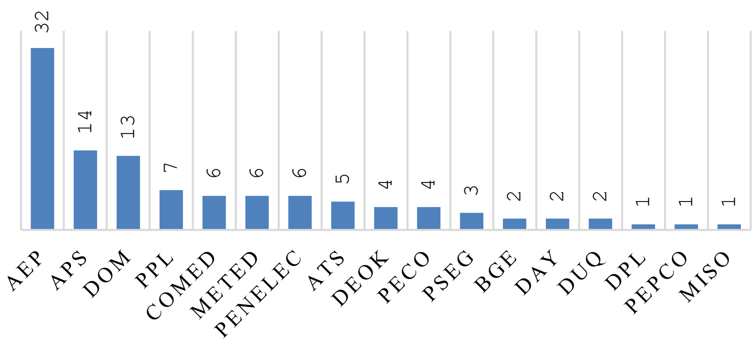

Fig. 4. *Number of switching solutions identified for each utility zone.*

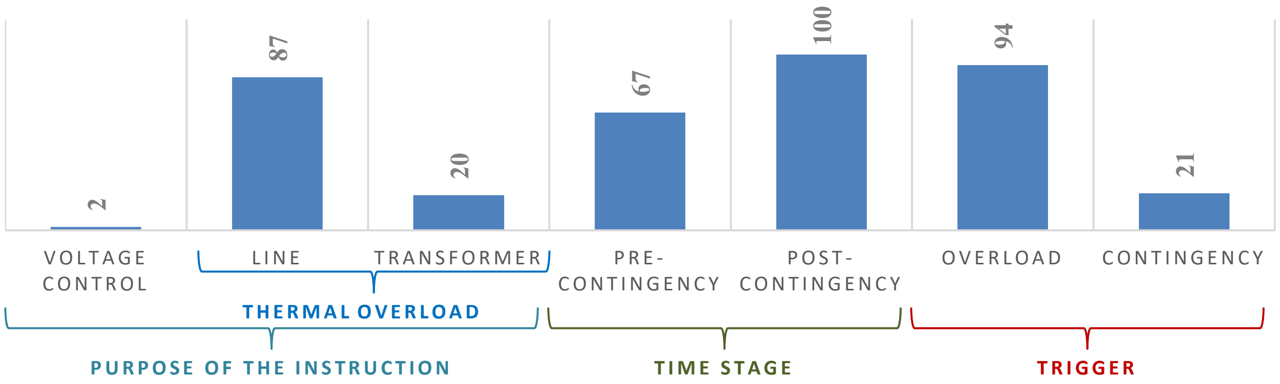

Fig. 5. *Summary of PJM switching solutions.*

5. Analysis of PJM Switching Solutions

The analysis presented in this paper is conducted on 167 actual snapshots from PJM's energy management system (EMS). The data represents 167 hours (one week) in July 2013. Each snapshot is sent to an RTCA with two different SPS routines: one simulating PJM's switching solutions (Fig. 2-a); and another RTCA with corrective TS routine (Fig. 2-b). There were 104 instances where one of the PJM's switching solutions was applicable. Each of such instances represent a single contingency in a particular hour that triggers one of PJM's switching solutions. Note that one solution may be triggered in multiple hours, i.e., the same contingency or post-contingency overload may happen in different hours. Those contingencies, for which a PJM switching solution exists, are also sent to the corrective switching routine of the RTCA CTS tool to compare the quality of solutions.

A conceptual example is presented in Fig. 6 to illustrate the mechanism by which the switching solutions relieve violations in the system. The figure shows two transformers in parallel that transfer power from one part of the network to the other. A contingency on one of the transformers would overload the other transformer. Switching the line that carries the power to these transformers, or switching the overloaded transformer itself would relieve the overload and reroute the power through other paths in the network. In fact, many of PJM's switching solutions involve switching parallel lines or transformers out of service.

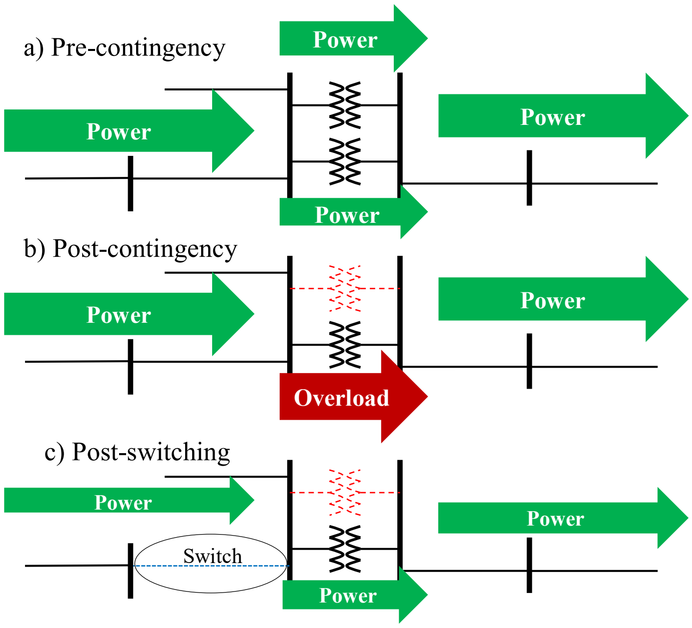

Fig. 6. *A conceptual example showing how post contingency corrective transmission switching can help reduce or eliminate network violations.*

Due to the sensitive nature of the data and by the request of PJM, actual network information is not presented in this paper. However, two artificial examples are presented in Fig. 7 and Fig. 8 that conceptually replicate two PJM cases. Fig. 7 compares the solution from the RTCA CTS tool with two available PJM solutions, while Fig. 8 presents a case for which PJM has not identified a switching solution; however, the RTCA CTS tool completely eliminates the violations in this case.

Fig. 7 (a) presents the pre-contingency case. In this particular example, power is injected through bus 4 that is transferred from the right part to the left part of the subsystem serving the loads in this subsystem and the external network. It is observed that there are two parallel paths from bus 1 serving the left part of the subsystem. Note that one branch connecting bus 1 to the external circuit is 83% loaded during normal operations. A contingency on the other branch forces more power to flow through this path resulting in 20% overload as shown in Fig. 7 (b). Two switching solutions are posted on the PJM website for this particular contingency. PJM suggests switching out one of the parallel lines connecting buses 1 and 2, which reduces the net injection from bus 4 to bus 1. It is found that the power flow into bus 2 reduces to 362 MVA and 364 MVA after corrective switching as shown in Fig. 7(c) and (d) respectively. The switching actions in turn reduce the violations to 13% and 14% as opposed to the original post-contingency violation of 20%. However, the RTCA CTS tool suggests removing the branch connecting buses 2 and 4, thereby significantly reducing the violations to only 4% as shown in Fig. 7 (e). It is clear from the figure that the RTCA CTS tool outperforms both of the PJM switching solutions in this particular example.

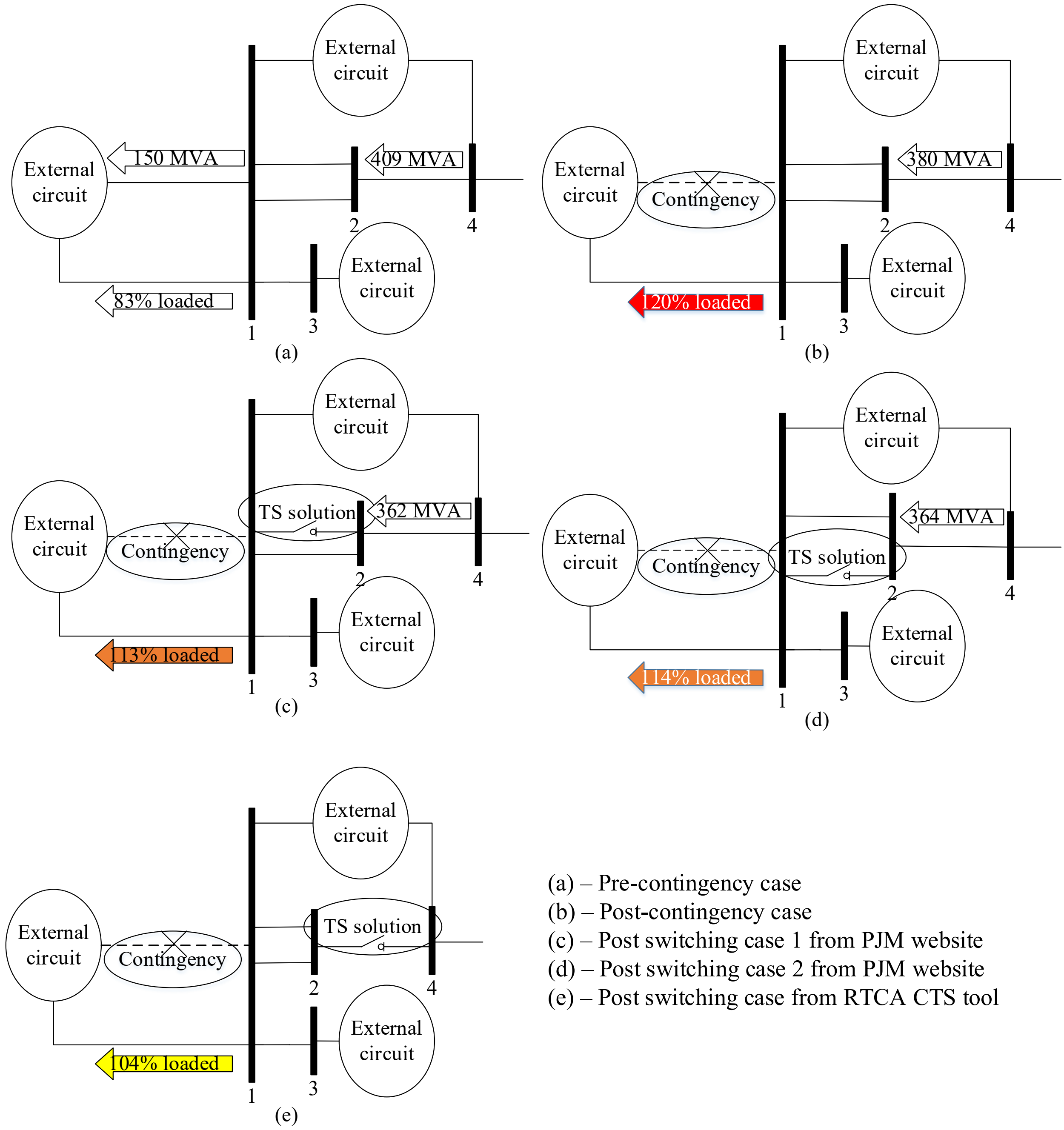

Fig. 7. *An artificially created example that conceptually illustrates a case in PJM system. For this case, both the PJM website and the RTCA CTS tool provide corrective transmission switching solutions that reduce network violations.*

Another detailed example is shown in Fig. 8. This example pertains to the case where the switching action provided by the RTCA CTS tool completely eliminates all the post-contingency violations in the system. The pre-contingency, post-contingency, and post-switching cases are shown in Fig. 8(a), Fig. 8(b), and Fig. 8(c), respectively. Note that no switching solution is posted on the PJM website for this particular case.

It is found that a contingency on branch 3 causes a flow violation of 100 MVA on branch 4 beyond its emergency rating. In the pre-contingency and post-contingency cases, the load in area A is partially served with the power transferred from area B through branches 1 and 7. However, the outage of branch 3 causes a severe overload on branch 4. The first switching solution identified for this operating state by the RTCA CTS tool is branch 1. By simply switching branch 1 out of service, the overloading issue is resolved. In the post-switching case, branch 1 is no longer available to transfer power through branch 7 to area A and through branches 2, 3, 4, and 5 to area D, which in turn reduces the loading on branch 4. Note that the load in area A and area D can still be served through the external circuits. Another interesting observation is that each of the top 4 candidates identified by the RTCA CTS tool namely branches 1, 5, 2, and 4, fully eliminates the violations for this case.

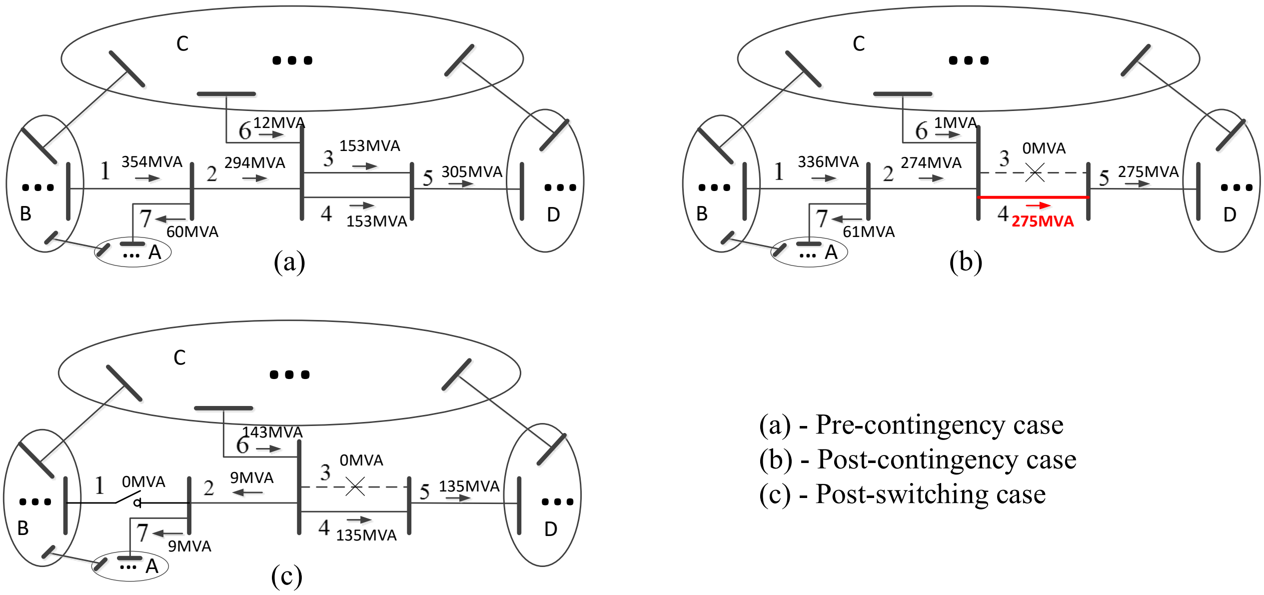

Fig. 8. *An artificially created example that conceptually illustrates a case in PJM system. In this case, only RTCA CTS tool provides corrective transmission switching solutions that eliminate network violations.*

Fig. 9(a) compares the performance of the two approaches. Performances are compared based on the ability to reduce post-contingency violations. Fig. 9(a) shows that 41% of the time, when a PJM switching solution exists, the RTCA CTS routine is able to find a solution that performs better than PJM's switching solution. It is found that 55% of the time, the two methods perform equally as well, i.e., either they find the exact same solution or the real-time RTCA CTS tool finds a different solution with the same quality as PJM's. Only 4% of the time does PJM suggest a solution that outperforms the RTCA CTS tool. The algorithm in the RTCA CTS tool is a very simple local search algorithm; the 4% of the cases correspond to situations where the preferred line to switch is not close to the violation. With larger candidate lists, the RTCA CTS tool can be further improved to ensure it always outperforms PJM. The RTCA CTS tool was able to eliminate 90% of the cases with post-contingency violations, while PJM's switching solutions only do so for 57% of the cases.

Fig. 9(b) shows the percentage of the cases where PJM's switching solution was among the five top candidates identified by the RTCA CTS tool. It also compares the performance of the two methods, when the RTCA CTS tool does not find PJM's switching solution. Fig. 9(b) shows that for more than half of the time, PJM's switching solution is identified among the RTCA CTS tool's top five candidates. In cases when this does not occur, the RTCA CTS tool often finds a solution that outperforms PJM's switching solution or performs equally as well. Although detailed information is not presented in the paper due to the sensitive nature of the data, the following observations were made:

1. Almost all the time, PJM's switching solution alleviates the violation it is intended to relieve.
2. PJM's solutions may in some instances create network violations elsewhere, which would make the switching solution invalid.
3. RTCA with corrective TS routine is able to identify those situations explained in 2 and, thus, it often outperforms PJM.
4. There are many contingencies that would lead to network violations for which PJM has either not identified or not published switching solutions.
5. RTCA with corrective TS routine is able to handle contingencies specified in 4 and propose quality corrective TS actions.

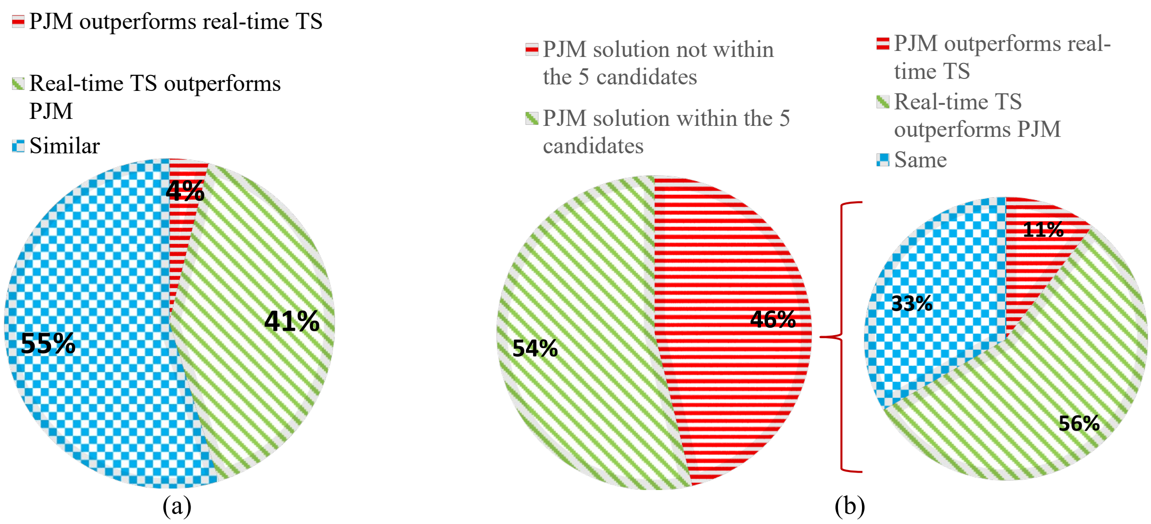

Fig. 9 (a). *Performance comparison of PJM switching solutions with RTCA CTS tool. Note that this graph only includes contingencies for which a PJM switching solution exists.* ***(b).*** *Left: percentage of the cases where the RTCA CTS tool was able to find PJM's switching solution among its five top candidates. Right: performance comparison of the two methods for the cases where the RTCA CTS tool was not able to find PJM's switching solution.*

6. Advancement of PJM's Switching Solutions

This section presents the results obtained by the RTCA CTS tool, which was described in Section III, and discusses different practical avenues to advance PJM's switching solutions.

ISOs today do not model all the potential N-1 contingencies in their RTCA package. There exists contingencies for which ISOs have enough reliable resources and, thus, they know such contingencies will not be problematic. However, since such information was not provided by PJM, all the potential N-1 contingencies, including all the generators and transmission elements above 70 KV, were simulated for the analysis presented here. This is roughly 3,862 contingencies for the 167 snapshots of the EMS data. On average, each hour of the data included 23 contingencies that would lead to network violations. Only for 2.7% of such cases has PJM identified a switching solution. All the results presented in the previous section corresponded to this 2.7% of potentially problematic cases. For the rest of the contingencies (97.3% of the cases), PJM is left with conventional means of dealing with a contingency: costly reliability-motivated commitments and redispatch. While PJM's existing practice of corrective TS does not provide a solution for the majority of the cases, the RTCA CTS tool always investigates the existence of such solution. It is found that the method is able to fully eliminate post-contingency violation in 69.8% of the cases. It is also able to reduce the violations in 30% of other cases, when full elimination of the violations is not possible. Only in 0.2% of the cases is the RTCA CTS tool not able to find any helpful solution. Such significant post-contingency violation reduction translates into significant cost savings due to reduced costly reliability-motivated commitments and redispatch. More details regarding the performance of the dynamic TS method is presented in [64]-[66].

It should be noted that the RTCA CTS tool presented in Fig. 2(b) is fully parallelizable. A separate thread can check the effectiveness of each switching candidate independently. The method also uses a full AC power flow and, thus, there is no loss of precision. Lawrence Livermore National Laboratory's 'Cab' cluster was used for analysing the speed up achieved with parallel processing. Table 2 provides the detailed specifications of the machine used for parallelization of the RTCA CTS tool. Note that the details presented in Table 2 are for a single node and the machines for all batch nodes are the same. The method presented here is able to handle a snapshot of PJM system in about ten minutes using only a single node. With more advanced desktop, with more nodes, the solution time could be further reduced. For instance, using a computer with 100 threads, one snapshot of the PJM system can be solved in about one minute and a half. More details are presented in [64]-[66].

Table 2 Computer specifications for parallel processing of the RTCA CTS heuristic

CPU	Intel Xeon E5-2670
CPU speed	2.6 GHz
Memory per node	32 GB
Operating system	TOSS 2.2 (Linux OS)
Number of physical cores	8
Number of threads	16
Max turbo frequency	20 GHz

Although PJM's switching solutions seem to be effective, they lack from one fundamental flaw: they ignore the dynamic nature of the system. Similar contingencies may result in different violations depending on the state of the system. Moreover, the same violations may be eliminated with different corrective TS actions in different system states. Therefore, a tool that acknowledges the dynamic nature of the system would naturally be more appropriate for identification of remedial actions. Another drawback of PJM's approach is that it depends heavily on prior knowledge or offline studies. Therefore, PJM has not yet identified switching solutions for the majority of problematic contingencies. Again, a real-time online tool, such as the RTCA CTS tool, would more appropriately identify corrective TS actions.

The results presented in this paper show that real-time corrective TS is ready for industry adoption. The industry can either use a dynamic tool like the one presented here, or use the tool in study mode, to identify more switching solutions.

7. Conclusions

This paper presented a comprehensive literature review on TS. The four main barriers for industry adoption of the technology were identified as: 1) computational complexity; 2) AC performance ambiguity; 3) difficulties in large-scale systems; and 4) stability concerns. The paper also summarized current limited industry practices of TS. To our knowledge, PJM's switching solutions seem to be the most advanced employment of the technology to date.

A fast AC based RTCA CTS tool was employed to analyze PJM's practice. It was shown that the tool was able to perform better than, or equally as well as, PJM's proposed solution most of the time. More than half of the time, the tool identified PJM's solution within its top five TS candidates. While PJM's switching solutions almost always were effective in handling the violation they were designed for, additional network violations were created in many instances. The RTCA CTS tool, however, was able to recognize such situations and, thus, proposed other TS solutions that did not suffer from such flaw.

It was discussed that PJM switching solutions, though may be effective, do not provide any TS solution for the majority of problematic contingencies. Therefore, the system operator has to rely on conventional costly reliability-motivated commitment and redispatch. However, a real-time tool such as the one employed in this paper would always investigate the existence of TS solutions.

The results presented in this paper demonstrate that the smart RTCA CTS tool is ready for industry adoption since it is innovative, fast, practical, and a cheap implementation of power flow control. Employment of such tools would bring significant savings and pave the road towards a smarter transmission network as an essential element of the future smart grid.

8. Acknowledgments

The authors would like to thank PJM interconnection for providing the data and insightful feedback throughout the project. The authors would also like to thank Advanced Research Projects Agency – Energy (ARPA-E) for funding this research under the Green Electricity Network Integration (GENI) program.

9. References

[1] ARPA-E GENI, [Online]. Available: http://www.arpa-e.energy.gov/?q=arpa-e-programs/geni.

[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-sensitivity analysis and extensions," IEEE Trans. Power Syst., vol. 23, no. 3, pp. 1469-1479, Aug. 2008.

[4] 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. 24, no. 3, pp. 1577-1586, Aug. 2009.

[5] 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.

[6] A. S. Korad and K. W. Hedman, "Robust corrective topology control for system reliability," IEEE Trans. Power Syst., vol. 28, no. 4, pp. 4042–4051, Nov. 2013.

[7] P. Balasubramanian and K. W. Hedman, "Real-time corrective switching in response to simultaneous contingencies," J. Energy Eng., vol. 14, no. 1, pp. 1-10, Feb. 2014.

[8] J. C. Villumsen, G. Brønmo, and A. B. Philpott, "Line capacity expansion and transmission switching in power systems with large-scale wind power," IEEE Trans. Power Syst., vol. 28, no. 2, pp. 731-729, May 2013.

[9] PJM, Switching solutions, [Online]. Available: http://www.pjm.com/markets-and-operations/etools/oasis/system-information/switching-solutions.aspx.

[10] A. A. Mazi, B. F. Wollenberg, and M. H. Hesse, "Corrective control of power system flows by line and bus-bar switching," IEEE Trans. Power Syst., vol. 1, no.3, pp. 258-264, Aug.1986.

[11] A. G. Bakirtzis and A. P. (Sakis) Meliopoulos, "Incorporation of switching operations in power system corrective control computations," IEEE Trans. Power Syst., vol. 2, no. 3, pp. 669-675, Aug. 1987.

[12] G. Schnyder and H. Glavitsch, "Integrated security control using an optimal power flow and switching concepts," IEEE Trans. Power Syst., vol. 3, no. 2, pp. 782-790, May 1988.

[13] G. Schnyder and H. Glavitsch, "Security enhancement using an optimal switching power flow," IEEE Trans. Power Syst., vol. 5, no. 2, pp. 674- 681, May 1990.

[14] J. G. Rolim. and L. J. B. Machado, "A study of the use of corrective switching in transmission systems," IEEE Trans. Power Syst., vol. 14, pp. 336-341, Feb. 1999.

[15] W. Shao and V. Vittal, "Corrective switching algorithm for relieving overloads and voltage violations," IEEE Trans. Power Syst., vol. 20, no. 4, pp. 1877-1885, Nov. 2005.

[16] C. Barrows and S. Blumsack, "Transmission switching in the RTS-96 test system," IEEE Trans. Power Syst., vol. 276, no. 2, pp. 1134-1135, May 2012.

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

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

[19] J. W. C. Zhang, "Optimal transmission switching considering probabilistic reliability," IEEE Trans. Power Syst., vol. 29, no. 2, pp. 974-975, Mar. 2014.

[20] P. Henneaux and D. S. Kirschen, “Probabilistic security analysis of optimal transmission switching,” IEEE Trans. Power Syst., vol. 31, no. 1, pp. 508-517, Mar. 2015.

[21] J. C. Villumsen and A. B. Philpott, “Investment in electricity networks with transmission switching,” European J. of Operational Res., vol. 222, no. 2, pp. 377–385, Oct. 2012.

[22] J. C. Villumsen, G. Brønmo, and A. B. Philpott, “Line capacity expansion and transmission switching in power systems with large-scale wind power,” IEEE Trans. Power Syst., vol. 28, no. 2, pp. 731–739, May 2013.

[23] F. Qiu and J. Wang, “Chance-constrained transmission switching with guaranteed wind power utilization,” IEEE Trans. Power Syst., vol. 30, no. 3, pp. 1270-1278, May 2015.

[24] C. Lueken, P. Carvalho, and J. Apt, “Distribution grid reconfiguration reduces power losses and helps integrate renewables,” Energ. Policy, vol. 48, pp. 260-273, Sep. 2012.

[25] J. Han and A. Papavasiliou, “Congestion management through topological corrections: a case study of Central Western Europe (CWE),” USAEE Working Paper No. 15-197, [Online]. Available at SSRN: http://ssrn.com/abstract=2551284

[26] NERC, “Standard TPL-002-0b – System performance following loss of a single bulk electric system element,” [Online]. Available: http://www.nerc.com/files/TPL-002-0b.pdf.

[27] E. H. Allen and M. Illic, “Reserve markets for power systems reliability,” IEEE Trans. Power Syst., vol. 15, no. 1, pp. 228-233, Feb. 2000.

[28] J. D. Lyon, K. W. Hedman, and M. Zhang, “Reserve requirements to efficiently manage intra-zonal congestion,” IEEE Trans. Power Syst., vol. 29, no. 1, pp. 251-258, Jan. 2014.

[29] Y. M. Al-Abdullah, M. Abdi-Khorsand, and K. W. Hedman, "The role of out-of-market corrections in day-ahead scheduling," IEEE Trans. Power Syst., vol. 3, no. 4, pp. 1937-1946, Jul. 2015.

[30] G. Ayala and A. Street, “Energy and reserve scheduling with post-contingency transmission switching,” Electric Power Systems Research, vol. 111, pp. 133-140, Jun. 2014.

[31] A. S. Korad, P. Balasubramanian, and K. W. Hedman, “Robust corrective topology control,” Handbook of Clean Energy Systems, Wiley, Jul. 2015.

[32] A. R. Escobedo, E. Moreno-Centeno, and K. W. Hedman, "Topology control for load shed recovery," IEEE Trans. Power Syst., vol. 29, no. 2, pp. 908-916, Mar. 2014.

[33] M. Li, P. Luh, L. Michel, Q. Zhao and X. Luo, "Corrective line switching with security constraints for the base and contingency cases," IEEE Trans. Power Syst., vol. 27, no. 1, pp. 125-133, Feb. 2012.

[34] A. S. Korad and K. W. Hedman, "Enhancement of do-not-exceed limits with robust corrective topology control," IEEE Trans. Power Syst., early access, Jul. 2015.

[35] K. Hedman, S. Oren, and R. P. O'Neill. "Optimal transmission switching: economic efficiency and market implications." J. Reg. Econ., vol. 40, no. 2, pp. 111-140, June 2011.

[36] C. Barrows and S. Blumsack, "Transmission switching in the RTS-96 test system," IEEE Trans. Power Syst., vol. 276, no. 2, pp. 1134-1135, May 2012.

[37] J. 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

[38] M. Soroush and J. 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.

[39] C. Liu, J. Wang, and J. Ostrowski, "Heuristic prescreening switchable branches in optimal transmission switching," IEEE Trans. Power Syst., vol. 27, no. 4, pp. 2289-2290, Nov. 2012.

[40] P. A. Ruiz, J. M. Foster, A. Rudkevich, and M. C. Caramanis. "On fast transmission topology control heuristics," IEEE PES General Meeting, Detroit, MI, Jul. 2011.

[41] 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.

[42] A. Papavasiliou, S. S. Oren, Z. Yang, P. Balasubramanian, and K. W. Hedman, "An application of high performance computing to transmission switching," IREP Symposium- Bulk Power System Dynamics and Control-IX, Rethymnon, Greece, Aug. 2013.

[43] T. Potluri and K. W. Hedman, "Impacts of topology control on the ACOPF," IEEE PES General Meeting, San Diego, CA, Jul. 2012.

[44] M. Sahraei-Ardakani, A. Korad, K. W. Hedman, P. Lipka, and S. Oren, “Performance of AC and DC based transmission switching heuristics on a large-scale polish system,” IEEE PES General Meeting, Jul. 2014.

[45] M. Khanabadi, H. Ghasemi, and M. Doostizadeh, “Optimal transmission switching considering voltage security and N-1 contingency analysis,” IEEE Trans. Power Syst., vol. 28, no. 1, pp. 542-550, Feb. 2013.

[46] 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 systems,” 51th Annual Allerton Conf., pp. 1349-1352, IL, USA, Oct. 2013.

[47] P. A. Ruiz, M. C. Caramanis, E. Goldis, B. Keshavamurthy, X. Li, M. Patel, C. R. Philbrick, A. M. Rudkevich, R. D. Tabors, and T. B. Tsuchida, “Transmission topology control for system efficiency: simulations on PJM real time markets,” IEEE PES General Meeting, 2013, Vancouver, BC, Canada.

[48] X. Li, P. Balasubramanian, M. Abdi-Khorsand, A. S. Korad, and K. W. Hedman, “Effect of topology control on system reliability: TVA test case,” CIGRE US National Committee Grid of the Future Symposium, Oct. 2014.

[49] G. M. Huang, W. Wang, and J. An, “Stability issues of smart grid transmission line switching,” 19th IFAC World Congress, pp. 24-29, Aug. 2014.

[50] M. Jabarnejad, J. Wang, and J. Valenzuela, “A decomposition for solving seasonal transmission switching,” IEEE Trans. Power Syst., vol. 30, no. 3, pp. 1203-1211, May 2015.

[51] A. B. Philpott, M. C. Ferris, and S. S. Oren, “Challenges and opportunities for optimization in electricity systems,” Math. Program. Ser. B, vol. 140, no. 2, pp. 235-237, Jun. 2013.

[52] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu and P. Zhang, "Smart transmission grid: vision and framework", IEEE Trans. Smart Grid, vol. 1, no. 2, Sept. 2010.

[53] K. W. Hedman, R. P. O’Neill, E. B. Fisher, S. S. Oren, “Smart flexible just-in-time transmission and flowgate bidding,” IEEE Trans. Power Syst., vol. 26, no. 1, pp. 93-102, Feb. 2011.

[54] G. T. Heydt, R. Ayyanar, K. Hedman, and V. Vittal, “Electric power and energy engineering: the first century,” Proceedings of IEEE, vol. 100, no. 2, pp. 1315-1328, May 2012.

[55] ISO New England, “Operating procedure No. 19 – transmission operations,” June 2015, [Online]. Available: http://www.iso-ne.com/rules_proceds/operating/isone/op19/op19_rto_final.pdf

[56] California ISO, “Transmission constraint relaxation parameter revision,” ISO draft final proposal, Nov. 2012, [Online]. Available: http://www.caiso.com/Documents/StrawProposal-TransmissionConstraintRelaxationParameterChange.pdf

[57] California ISO, “Minimum effective threshold report,” [Online]. Available: http://www.caiso.com/274c/274ce77df630.pdf.

[58] Pacific Gas and Electricity Company, “Comments of PG&E on contingency modeling enhancements proposal,” 2013, [Online]. Available: http://www.caiso.com/Documents/PGE-CommentsContingencyModelingEnhancements-RevisedStrawProposal.pdf .

[59] Electric Reliability Council of Texas, “ERCOT nodal protocols,” Jun. 2015, [Online]. Available: http://www.ercot.com/content/wcm/libraries/68125/June_25__2015_Nodal_Protocols.pdf

[60] Midcontinent Independent System Operator, “Regional transmission organization (RTO) reliability plan,” Jun. 2014, [Online]. Available: https://www.misoenergy.org/Library/Repository/Procedure/MISO%20Reliability%20Plan.pdf.

[61] North American Electric Reliability Corporation, “Hurricane Sandy event analysis report,” Jan. 2014, [Online]. Available: http://www.nerc.com/pa/rrm/ea/Oct2012HurricanSandyEvntAnlyssRprtDL/Hurricane_Sandy_EAR_20140312_Final.pdf

[62] IncSys, “Open source power apps and utilities,” [Online]. Available: https://github.com/powerdata/com.powerdata.openpa.

[63] PJM, “Zone map-corrected - PJM,” [Online]. Available: https://www.pjm.com/~/media/about-pjm/pjm-zones.ashx

[64] M. Sahraei-Ardakani, X. Li, P. Balasubramanian, K.W. Hedman, and M. Abdi-Khorsand, “Real-time contingency analysis with transmission switching on real power system data,” IEEE Trans. Power Syst., early access, Aug. 2015.

[65] X. Li, P. Balasubramanian, M. Sahraei-Ardakani, K. W. Hedman, and R. Podmore, “Real-time contingency analysis with corrective transmission switching—part I: methodology,” IEEE Trans. Power Syst., under review.

[66] X. Li, M. Sahraei-Ardakani, P. Balasubramanian, K. W. Hedman, and R. Podmore, “Real-time contingency analysis with corrective transmission switching —part II: results and discussion,” IEEE Trans. Power Syst., under review.