Real-Time Contingency Analysis with Corrective Transmission Switching

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***Abstract*— Transmission switching (TS) has gained significant attention recently. However, barriers still remain and must be overcome before the technology can be adopted by the industry. The state of the art challenges include AC feasibility, computational complexity, the ability to handle large-scale real power systems, and dynamic stability. This paper investigates these challenges by developing an AC corrective TS (CTS) based real-time contingency analysis (RTCA) tool that can handle large-scale systems within a reasonable time. The tool quickly proposes multiple high quality corrective switching actions for contingencies with potential violations. To reduce the computational complexity, three heuristic algorithms are proposed to generate a small set of candidate switching actions. Parallel computing is implemented to further speed up the solution time. Moreover, time-domain simulations are performed to check for dynamic stability of the proposed CTS solutions. The promising results, tested on the Tennessee Valley Authority (TVA) system and actual energy management system (EMS) snapshots from the PJM Interconnection (PJM) and the Electric Reliability Council of Texas (ERCOT), show that the tool effectively reduces post-contingency violations. It is concluded that CTS is ripe for industry adoption for RTCA application.**

***Index Terms*—Corrective transmission switching, energy management systems, high performance computing, large-scale power systems, power system operation, power system reliability, power system stability, real-time contingency analysis.**

I. INTRODUCTION

MAINTAINING a reliable power system is of utmost importance. The North American Electric Reliability Corporation (NERC) requires systems to withstand the loss of a single bulk element (*N*-1) [1]. While reserves are acquired, reliable operation is not always achieved. Real-time contingency analysis (RTCA) is frequently repeated for this purpose.

In the Midcontinent Independent System Operator (MISO) system, the RTCA package simulates more than 11,500 contingency scenarios every four minutes [2]. RTCA utilizes data from the state estimator and contingency analysis is performed by successively solving AC power flows. Line flow and bus voltage violations corresponding to different contingencies are determined [3] by analyzing the power flow results.

PJM Interconnection (PJM) runs AC real-time contingency analysis to identify the contingencies that cause violations in the system [4]. Approximately 6,000 contingencies are assessed every minute at PJM [4]. Although there is a list of all contingencies in PJM's database, not all contingencies in that list are evaluated at all times [5].

The Electric Reliability Council of Texas (ERCOT) uses a two-phase procedure to perform breaker-to-breaker contingency analysis [6]. A heuristic screening procedure is performed in the first phase to identify the most severe contingencies based on the post-contingency violations. Previously, ERCOT had approximately 3938 contingencies, including 2958 single branch contingencies, 375 double branch contingencies, and 605 generator contingencies, modeled in its system [7]. The RTCA in ERCOT executes every five minutes [7].

If a contingency with post-contingency violations is detected, appropriate actions will be taken to ensure reliable operations. These actions may include:

- Sending constraints to security-constrained economic dispatch to move away from a vulnerable state.
- Commitment of fast-start units to provide local reserves.
- Adjustment of transmission assets (e.g., transformer taps, switchable shunts, adjustment of flexible AC transmission systems (FACTS) devices).
- Transmission switching (TS) to enhance deliverability of reserves and reroute the network power flow.

Corrective transmission switching (CTS) is shown to be a viable solution for handling contingencies, which is also significantly cheaper than many alternatives [8]-[10]. CTS is already being used in normal and post-contingency operation, though to a very limited extent, at PJM [11]. Despite the vast body of literature that has been dedicated to TS over the last decade, important challenges remain for more systematic adoption of the technology. The challenges include the following: 1) computational complexity, 2) unknown or poor AC performance, 3) concerns regarding the stability of switching actions, 4) and limited insight on performance of the technology on actual large-scale power system data.

This paper closes an important gap in the literature by addressing these challenges for the RTCA application. An AC CTS-based RTCA tool, which is fast and works with actual power system data, is developed. The tool is tested on the Tennessee Valley Authority (TVA) system and actual energy management system (EMS) snapshots from PJM and ERCOT. High performance computing (HPC) is employed to improve computational efficiency. The results are very promising and show that CTS can provide significant reliability benefits by

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drastically reducing the potential post-contingency violations. This will translate into significant savings due to substantially reduced need for expensive reliability-motivated generation redispatch and commitment. The tool is able to handle the PJM system in about five minutes with a standard desktop. Furthermore, stability analysis is performed on selected cases to test the switching solutions are dynamically stable. To our knowledge, this paper is among the first comprehensive studies that addresses the state of the art challenges of CTS for RTCA with actual EMS data at this level of detail. Other recent work that considers base-case (not post-contingency corrective) switching actions for economic benefit has also examined the potential for transmission switching on large-scale test systems as well [12]-[13]. Other papers by the same authors have proposed novel ways to formulate the transmission switching problem with shift factors [14]-[17].

For this presented work, over 1.5 million contingencies are simulated on data from TVA, ERCOT, and PJM to analyze the effectiveness of CTS. The results show that 10%-33% of the contingencies with post-contingency violations would have no violations if a single CTS action is implemented. Substantial reductions in post-contingency violations are observed on 56%-83% of the cases. The solution times are suitable for real-time implementation. The computational efficiency is attained by using fast heuristics that require minimal additional computing. Overall, the results are promising and suggest that RTCA with CTS is ripe for industry adoption.

The rest of this paper is organized as follows. Section II presents a literature review on TS. Section III explains the concept of corrective TS. Section IV presents the algorithm and methodology. Section V describes the EMS data received and presents vanilla contingency analysis results. Typical RTCA without CTS is referred to as "vanilla contingency analysis." Section VI presents the results obtained from the RTCA CTS routine as well as the HPC and stability analysis results. Section VII is dedicated to provide insights as to why such simple algorithms are still preferred for this application. Finally, Section VIII concludes the paper.

II. Literature Review

Most existing operational protocols and software do not acknowledge the flexibility of transmission elements. A single network topology is likely sub-optimal for various operational states. Even though the flexibility in the transmission network is not modeled in optimal power flow, it is well known that system operators change the topology in practice [18]-[21].

Previous research has demonstrated that TS provides a variety of benefits including cost savings [22]-[24], active power loss reduction [25]-[26], thermal and voltage violation reduction [27]-[30], and enhancement of integration of renewable energy resources [31]. Furthermore, TS is shown to be beneficial in load shed recovery [32], enhancement of do-not-exceed limits [33]-[34], security and cost improvement in transmission and generation expansion planning [35], and potential cost saving in outage coordination [36].

It is illustrated in [37] that the optimal solution with TS will be at least as good as the solution obtained without TS. Co-optimization of unit commitment and TS is presented in [38]. Numerical studies show that the optimal network topology could be different for subsequent hours and that it is even possible to eliminate the need to commit additional generators as reserve deliverability is improved via TS. Tests conducted on the IEEE 118-bus test case demonstrate that 25% saving in system cost could be achieved by optimizing the transmission topology [39]. It is a general concern that TS may compromise the reliability of the system. However, [40] shows that 15% of the overall cost can be reduced via optimizing the transmission topology, while still maintaining *N*-1 reliability. Recent work has also focused on improving the formulation of the transmission switching problem, [41]-[42].

TS is a power flow control technology that can improve the transfer capability and reduce costs. The total congestion costs in the PJM system in 2013 increased by $147.9 million, which amounts to a 28% increase compared to the 2012 level of $529 million [43]. There is a great opportunity for efficiency improvement through TS and other power flow control technologies, such as FACTS devices [44]-[46]. A major advantage of TS is that it does not require sophisticated hardware, such as expensive FACTS. TS is a low cost power flow control technology that can significantly improve efficiency. All the promising findings described above indicate that TS is an efficient and low-cost technology for building a smarter and more flexible electric grid.

Due to computational complexity, as well as other concerns such as dynamic stability, implementation of TS has been very limited. Some system operators use TS as a corrective mechanism for improving voltage profiles and mitigating line overloads [19], [47]. TS is also being employed during planned outages, to make the transition smooth, and as a post-contingency corrective action [48]. California ISO (CAISO) is reported to perform TS on a seasonal basis and to relieve congestion in the system [19], [21], [49]. PJM has posted a list of potential switching solutions that may reduce or eliminate violations for normal and post-contingency situations [11], [50]. However, these switching actions are not guaranteed to always provide benefits because they are identified offline.

The major bottleneck to the implementation of TS is addressed by developing an RTCA tool with a very fast algorithm that identifies effectively corrective TS actions. Prior work on CTS focuses on approaches that do not conform to the modeling requirements or do not scale well. The majority of literature on this topic is based on small-scale test systems with DC power flow models.

While the developed RTCA tool with CTS is straightforward from an algorithmic sense, it is for that reason why the approach is ready to make an impact in industry; it is not only scalable but it is also highly effective and, thus, it bridges the gap between existing technologies and actual implementation. The contributions of this paper are the following:

1. The algorithms developed are extremely fast. In fact, they can handle a snapshot of PJM in about five minutes with a standard desktop. Parallel computing would further improve the solution time. Therefore, this paper effectively tackles the computational complexity of CTS.

2. AC power flows are solved to identify the switching action and to ensure that there is no ambiguity on the performance of the solution in an AC setting.

3. The tool is able to handle large-scale systems. The TVA system and actual snapshots from the EMS of PJM and ERCOT are used to test the tool.

4. Stability analysis is performed on a subset of cases using standard software (e.g., PSS/E).

This paper studies CTS with the details explained above and addresses the state of the art challenges of CTS. Therefore, the conclusions presented in this paper are more comprehensive compared to earlier studies while also showing that the proposed algorithm is both scalable and efficient. This paper elaborates on [51], presents the algorithm development, and provides detailed results obtained on the PJM, TVA, and ERCOT systems as well as stability analysis and high performance computing. Thus, this paper closes a significant gap in the literature by accomplishing the above-mentioned goals.

III. Concept of Corrective Switching

This section presents two examples to show how CTS can reduce post-contingency violations. Fig. 1 shows an example where CTS fully eliminates all voltage violations. This example is from the authors' prior work [30]. The network shown in Fig. 1 is a 500 kV portion of the TVA system for a lightly loaded period. In the pre-contingency state, the switching candidate produces reactive power, which travels through the contingency line. In the post-contingency state, there is an overvoltage problem since the contingency prevents the reactive power from leaving the area. By de-energizing the CTS solution, the reactive power produced decreases and the over voltage violations are then eliminated. Fig. 2 presents an example, which depicts how CTS can eliminate flow violations in the PJM system. In Fig. 2, bus 7 is the load pocket. A contingency on branch 1-5 overloads line 3-4. Switching line 2-3 relieves the overload and the power flow is rerouted to bus 7 through the external circuit.

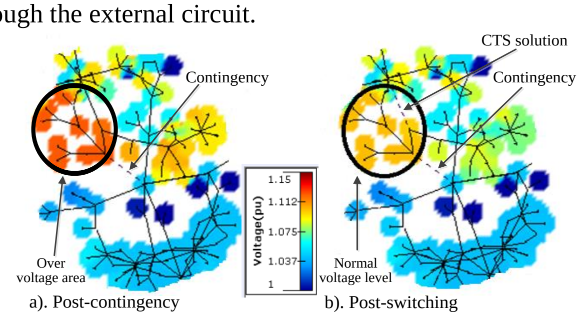

Fig. 1. An example of voltage violation fully eliminated by CTS; voltage contour plot.

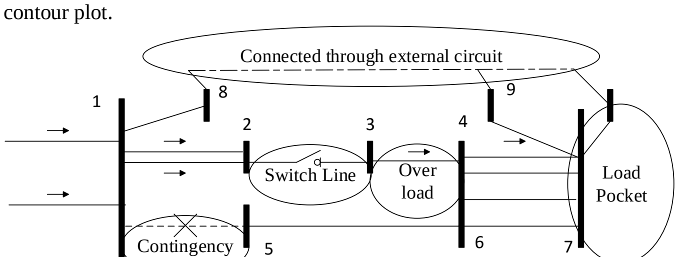

Fig. 2. Network diagram for CTS mechanism.

IV. Methodology and Algorithm

The procedure for RTCA with CTS is presented in Fig. 3. The normal operating state of the system, which consists of AC power flow information, is first fed into RTCA. Contingency analysis is then performed and the contingencies that would result in violations beyond a specific tolerance are identified. Violations less than the thresholds are ignored due to their insignificance. Only those contingencies with violations beyond the thresholds are sent to the CTS routine. Five switching candidates, which would eliminate or reduce the violations, are identified for each of those contingencies. Stability analysis, using a standard tool (e.g., PSS/E), is performed on selected CTS cases to test for dynamic stability.

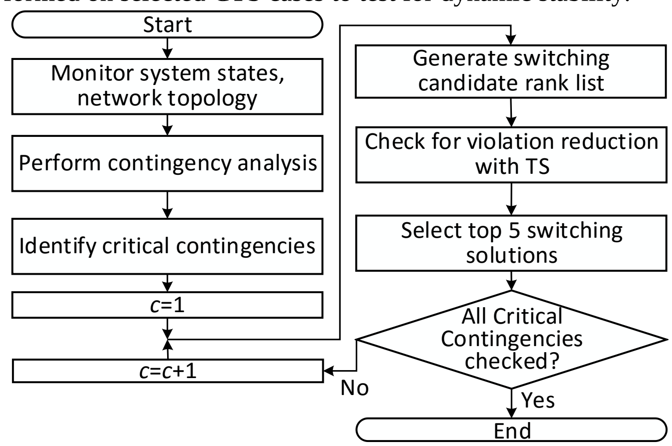

Fig. 3. Procedure for RTCA with CTS.

A. Contingency Analysis

RTCA is a well-known and essential function in modern energy management systems. RTCA does not involve any optimization and, hence, it does not enforce any constraint. The purpose of RTCA is to identify critical contingencies that could negatively affect the system reliability. This paper utilizes OpenPA [52], an open source decoupled AC power flow [53], as the power flow engine of the RTCA. The RTCA package developed in this paper adopts standard assumptions:

1. For transmission element contingencies, all generators' active power outputs remain at the pre-contingency level except for the generators at the slack bus(es).

2. For generator contingencies, participation factors, based on available capacity, are used to redispatch generation [30].

3. The faulty element is isolated using circuit breakers.

Operators have several options to maintain reliability after detection of a contingency with potential violations. The operator can move the dispatch away from the vulnerable state or commit additional units. These are common means of maintaining reliability. Note that reliability motivated commitments and redispatch create a significant economic burden. While such economic burdens are justifiable in order to prevent catastrophic blackouts, there are cheaper solutions.

CTS is shown to be an effective alternative to many preventive approaches. Not only is CTS effective, it is also drastically cheaper. CTS may completely eliminate the potential post-contingency violations or significantly reduce them. Thus, there will be substantially less need for expensive reliability-motivated commitments and redispatch. Taking everything into account, CTS provides reliability benefits, through which significant cost savings will be achieved.

Note that system operators do not model all potential *N*-1 events in RTCA. Various contingencies are not likely to cause violations based on the immediate system condition. To provide a comprehensive study, this paper simulates all potential *N*-1 events, excluding radial lines. The threshold for significance of voltage violations is assumed to be 0.005 p.u. and the threshold for thermal flow violation is set at 5 MVA. Both metrics are based on an aggregate level across the entire system. Voltage violations are recorded for values outside the range of 0.9 p.u. to 1.1 p.u. Transmission flow violations occur when the flow exceeds the emergency ratings. Buses and transmission assets below 70 kV are not monitored. This is consistent with existing practices in industry.

B. Heuristic Approaches for Computational Tractability

To reduce the computational complexity of the problem, three heuristics are proposed to generate a limited set of switching candidates. This fairly small subset of switchable elements includes quality solutions and also can be processed within a reasonable time, making the method suitable for real-time applications. The three heuristics, which are proposed in this paper to generate the ranked candidate switching list, are listed below. Complete enumeration (CE) is only used to gauge the performance of the heuristics.

- Closest branches to contingency element (CBCE).
- Closest branches to violation elements (CBVE).
- Data mining (DM).

Based on the authors' prior experience, it is observed that most of the beneficial switching solutions lie within a close vicinity of the contingency element and/or the violations. Based on this observation, two heuristic approaches, CBCE and CBVE, are developed. CBCE searches for the 100 closest branches to the contingency element. CBVE heuristic searches for the 100 closest branches to the elements with violations.

For transmission contingencies, it is found that the network violations occur on elements that are very close to the contingency. Hence, the lists of transmission switching candidates generated by both CBCE and CBVE would be similar. For generator contingencies, since the generators are redispatched, the violations may not be that close to the contingency. In this case, it is very likely that the CBVE method provides better CTS solutions when compared with the CBCE heuristic.

The distance of one element to another element, used by both CBCE and CBVE in this paper, is defined as the number of branches in the shortest path connecting these two elements. Therefore, neither the *electrical distance* [54]-[55] nor the *real distance (miles)* is involved in this metric; the proximity of two elements is only determined by the topological characteristics of the network. Suppose the contingent element is a line; all other transmission assets that are directly connected to either of the two contingent line's buses, they are given a distance of zero. When the distance is listed as being zero for a line, the shortest path does not traverse across any other transmission asset to reach that specified line whose distance is zero. Lines that have a distance of one are connected to the far end bus of lines that have a distance of zero (for the corresponding shortest path). This process repeats to generate distances based purely on a topological structure.

For the data mining technique, it was first observed that many switching solutions come from a common subset of transmission assets. The system cases are split into two sets: training and testing. Initially, complete enumeration of all the switchable branches is performed for each of the potential critical contingencies on the training set. The beneficial switching actions for each contingency in each scenario are identified and combined together. This combined list is a small subset of all switchable elements. The combination of the beneficial switching actions for the training set is considered as the switching candidate list for the test set. The basic assumption behind this method is that, even if operational conditions change, previously determined beneficial switching solutions should be at least top candidates considered for the switching action. To be more specific, the training set can be considered historical information while the test set will consist of snapshots in real-time.

Different tolerances for identifying beneficial solutions with the DM method can result in different candidate list lengths. Three DM methods with different thresholds are studied. They are referred to as DM1, DM2, and DM3. There is no minimum threshold used in DM1 for identifying the beneficial switching solutions, which makes the list very long. Only the switching actions that provide a violation reduction of more than 5% (10%) comprise the candidates for CTS in DM2 (DM3).

Apart from the heuristic methods, complete enumeration (CE) of all possible switching actions is also performed in order to estimate the best possible benefits that can be achieved with CTS. CE is obviously not a practical approach so it is merely used to confirm the optimal solution and to offer a basis for analysis of the quality of heuristic methods.

C. Metrics

Average violation reduction in percent is used to show the effectiveness of the method on an aggregate level:

$$P_{CTS} = \frac{1}{N_c}\sum_{c=1}^{N_c} \frac{(\Delta_{c0}-\Delta_{c1})}{\Delta_{c0}} * 100\% \quad (1)$$

where Δ_{c0} denotes the total violations after contingency c, Δ_{c1} denotes the total violations after corrective switching with contingency c still present, and N_c is the total number of critical contingencies identified.

Although the post-contingency violations may be reduced on an aggregate level by implementing a specific CTS action, it is important to analyze the impact of the switching action on individual elements. It is possible that a specific switching action, while reducing the overall violations, creates additional violations that did not exist before implementation of the CTS action. CTS may also increase the violation on one particular element, while reducing the overall violations. Therefore, solutions are checked for Pareto improvements (PI); the CTS solution provides a Pareto improvement when at least one post-contingency violation reduces without causing any additional violations on any other element of the system.

Depth is defined as the location of the identified beneficial CTS solution in the candidate list. Depth is proposed only as a metric to evaluate the efficiency of each heuristic. The average depth can be calculated as follows:

$$D_{CTS} = \frac{1}{M_c}\sum_{c=1}^{M_c} L_{CTS,c} \quad (2)$$

where $L_{CTS,c}$ denotes the rank list location of the beneficial CTS solution for contingency c and M_c is the number of critical contingencies for which a beneficial CTS solution exists.

D. N-1-1 Reliability

Meeting the *N*-1-1 reliability requirement is essential to ensure a reliable system. One major CTS concern is regaining *N*-1 reliability after the first contingency and the related CTS action. NERC's *N*-1-1 reliability criterion states that the system has to become *N*-1 reliable again within 30 minutes following the first contingency. In the case of a contingency leading to network violations, a corrective action is first implemented to relieve the violations and bring the system back to acceptable operational conditions in a short time. This paper proposes CTS as an effective corrective action at this initial step. Subsequently, remedial actions will be taken to regain *N*-1 reliability in post-switching situations. The remedial actions can include a mixture of generation redispatch, further CTS actions, and putting the switched CTS line back in service. This paper focuses on the CTS action taken right after the contingency; *N*-1-1 analysis is left for future work.

E. Impacts of Switching Solutions on Circuit Breakers

The proposed CTS scheme is intended to provide operators with additional corrective control actions that are very cheap and effective; the proposed CTS solution would be implemented only if the contingency occurs. The only associated cost of CTS is the impact on circuit breakers; ABB gave a presentation at PJM on circuit breaker health in relation to transmission switching [56]. Since the probability of the contingency is low, the CTS action would rarely need to be implemented. Additionally, there are many beneficial switching solutions that can be considered. Thus, the wear and tear on the circuit breaker due to CTS is minor.

F. Multiple Switching Solutions

Although switching multiple lines is theoretically possible and would provide more flexibility, we focus on single switching solutions based on industry feedback and we leave the investigation of multiple switching solutions to future work.

G. High Performance Computing

The nature of the CTS module within the developed RTCA is apt for parallel computing. Each switching candidate is independent of other candidates and, thus, can be assigned to an independent processor. The problem can be solved simultaneously with multiple threads by breaking it into independent sub-problems to speed up the computation. The parallel computing tool used is MPJ-Express [57], which is the message passing interface in JAVA.

H. Stability Analysis

Power system stability is of utmost importance. It has been defined as the ability of the system for a given initial operating state to regain a state of operating equilibrium after occurrence of a physical disturbance with system variables remaining bounded [58]. Maintaining dynamic stability is an essential requirement for secure operation of the power system. Power system instability has been reported to cause several major blackouts in the past, which emphasizes the need to focus more on the power system stability studies [59].

Contingencies, as well as switching actions, are generally associated with large changes to the operating steady-state equilibrium of the system. Since the focus of this paper is contingency analysis with CTS, stability analysis plays an important role in this work. Moreover, there is an overarching concern that CTS may introduce more vulnerability to the system leading to system instability. These important issues are addressed in this paper.

Two different methodologies are used to perform the time domain simulation for transmission contingencies and generator contingencies. In case of transmission contingencies, generation redisatch is not performed. The generators at the slack bus(es) are used to pick up the change in losses. However, generation redispatch based on the available capacity is implemented following a generator contingency.

For transmission contingencies, the base case power flow is run for the initial 2 seconds after which a transmission contingency is simulated. At t=20s, the CTS action is implemented and the simulation is terminated at t=40s. The time domain simulation is run for a total of 60 seconds for generator contingencies. The base case is run for the initial 2 seconds without any disturbance to the system. The generation contingency is simulated at t=2s and the generation redispatch associated with the particular contingency is implemented at t=20s. This is followed by the switching action, which is implemented at t=40s and the simulation is terminated at t=60s.

The rotor angle, frequency, and voltage stability are checked for selected switching actions. The relative rotor angles of all machines are monitored throughout the duration of the simulation to ensure that no single machine or group of machines swing away from the rest of the system and lose synchronism. If there is a relative rotor angle separation of any machine from the rest of the system such that it loses synchronism, the CTS action is categorized as unstable. The frequency of all the buses in the area of disturbance is monitored and it is checked that the frequency stays within the limits of $59.5Hz<f<60.5Hz$ [60]. For any bus in the system, if the frequency deviates beyond the specified threshold, the switching action is considered to be unstable. Similarly, a voltage threshold of $0.9<V<1.1$ [60] is used to ensure that the switching action does not cause voltage instability.

Note that the objective of performing stability studies in this paper is to check if the switching solution is stable, assuming the system remains stable after the contingency. Hence, the emphasis of this study is on the stability of CTS action, not the dynamics of the contingency itself.

V. EMS Data and Vanilla Contingency Analysis

Data is obtained from three reliability coordinators (RC): TVA, ERCOT, and PJM. The characteristics of the data are summarized in Table I.

TABLE I
DESCRIPTION OF THE ACTUAL SYSTEM DATA

System	Scenarios	Load (Real GW, Reactive GVAr)	Buses	Generators	Branches
TVA	72	~(24, 4)	~1.8k	~350	~2.3k
ERCOT	3	~(57, 8)	~6.4k	~700	~7.8k
PJM	167	~(139,22)	~15.5k	~2,800	~20.5k

Load profiles for 72 hours were obtained from TVA along with TVA's network information. Detailed information on TVA can be found in [30]. Security-constrained unit commitment (SCUC), which includes a DC optimal power flow, was run on the data to obtain 72 operating points for TVA. This SCUC solution was then used as a starting solution to obtain AC power flow base case solutions. If network violations are observed in the base case, out of market corrections [61] are made to obtain AC feasibility. This AC solution is the basis of the analysis for the TVA system conducted in this paper. TVA also provided actual operating conditions that were used to ensure the AC base cases resembled TVA operations. This approach was taken based on the available data from TVA.

The EMS data from ERCOT and PJM is directly used and all of the analysis is done on the original EMS snapshots with no modifications. EMS data for 167 hours, which correspond to a week in July 2013, was provided by PJM. ERCOT provided three snapshots of EMS data; these hours correspond to critical winter storms that led to operation difficulties.

Table II summarizes the results of this initial vanilla contingency analysis. The table shows that the original dispatch is vulnerable to a number of contingencies for all three systems. A full *N*-1 study is conducted and all contingencies with violations (beyond the specified threshold) are sent to the CTS routine. Table II shows that the percentage of contingencies with violations for TVA is larger than ERCOT and PJM. Moreover, the percentage of contingencies for which the violations are within the tolerance for TVA is also notably greater than ERCOT and PJM. The reason for such differences is that the TVA AC power flow base cases were created by the authors based on the data provided by TVA whereas ERCOT and PJM data came directly from their EMS. In real-time operations, the system operators perform adjustments that would make the operations less vulnerable to contingencies. Thus, there would naturally be a significant difference between the ERCOT and PJM actual EMS cases and the TVA cases that were created since the TVA data did not go through such a process.

It should be noted that system operators have ways to handle some of these contingencies via special protection schemes (SPS) [62], FACTS devices [44]-[45], [63], switchable shunts [64], transformer tap setting adjustment [64], or other corrective mechanisms. While such other preventive or corrective approaches can also be used instead of corrective transmission switching, the results clearly demonstrate the breadth and depth of corrective transmission switching. Corrective transmission switching is a practical and beneficial corrective action that should be added to the suite of existing corrective actions in use. This approach identifies CTS solutions in real-time, unlike offline techniques that are not guaranteed to work for all operating states.

TABLE II
OVERALL STATISTICS ON RTCA SIMULATIONS

System	# of Contingencies Simulated	# of Contingencies with Violations	# of Contingencies with Violations beyond Threshold
TVA	126,449	15,540	4,272
ERCOT	13,044	52	40
PJM	1,437,749	11,100	8,064

VI. CASE STUDIES

Different CTS strategies, including CBCE, CBVE, and DM, are implemented and the benefits obtained from each methodology are analyzed. Table III presents the overall statistics on the CTS simulations. All of the results presented in Table III correspond to the benefits obtained from the first best switching action as identified from the CBVE proximity search algorithm. A beneficial CTS solution may reduce the aggregate network violations without ensuring a Pareto improvement (PI); however, note that it is easy to select CTS solutions that only provide PI and the difference between enforcing a PI solution or not produce very similar results.

Table IV presents the average violation reduction with CTS as an average percentage. The metric is defined in Section IV.C. The average flow violation reductions are 40%, 53%, and 59% for TVA, ERCOT, and PJM respectively. Similarly, the bus voltage violation reductions on average are found to be 36%, 12%, and 20% for TVA, ERCOT, and PJM, respectively. Table IV shows that the violation reductions with and without consideration of Pareto improvement are not very different. This finding illustrates that the CTS actions identified in response to a specific violation almost never induces additional violations in the system. This is an important and interesting finding supported by evidence shown in Table IV.

TABLE III
OVERALL STATISTICS ON RTCA CTS SIMULATIONS

System	# of Contingencies Fully Eliminated	# of Contingencies with Partial Viol. Reduction	# of Contingencies with No Viol Reduction
TVA	427 (6 per hour)	3,535 (49 per hour)	310 (4 per hours)
ERCOT	6 (2 per hour)	27 (9 per hour)	7 (2 per hour)
PJM	2,684 (16 per hour)	4,554 (27 per hour)	826 (5 per hour)

TABLE IV
AVERAGE VIOLATION REDUCTION

System	Avg. Flow Violation Reduction		Avg. Voltage Violation Reduction	
	w/o PI	w/ PI	w/o PI	w/ PI
TVA	40.0%	40.0%	36.2%	35.6%
ERCOT	53.1%	49.3%	12.3%	12.3%
PJM	59.3%	59.0%	19.5%	19.3%

A. TVA System

For TVA, all heuristics (CBCE, CBVE, and DM) are implemented. Three DM approaches are constructed where the candidate switching actions for a particular day will be used to determine the beneficial CTS solutions for the other days.

Table V presents the results obtained from these CTS heuristics. Even though it is expected that the CBCE approach would perform similar to the CBVE, the reduction in violations obtained with both methods is found to be different for the TVA system. The majority of critical contingencies are generator contingencies for the TVA system, which involves generation redispatch from units spread across the system. With the redispatch, violations may not be close to the initial contingency. Hence, the effect of switching lines in the proximity of a contingency is different from the effects of switching a line in the proximity of a line that is overloaded. The results from CE are given to show the effectiveness of the different heuristics. The CBVE approach provides 40% reduction in flow violations in comparison with 40.8% reduction achieved by CE. However, the reduction in bus voltage violation with CBVE method is only 36.2% compared to 48.2% that is achieved with CE. CBVE takes only 6.8% of the time that CE takes; the results show that CBVE is fast and accurate. The data mining approach performs the best amongst the heuristics. All data mining methods provide similar violation reductions. The solution time for DM3 is significantly smaller. DM3 provides 26 times faster solutions with almost the same accuracy in comparison to CE. DM3 chooses the fewest candidate lines for its list, which is why it is the fastest. The solution times in Table V is with a single processor and does not involve parallel processing. Note that the solution time reported for CTS is averaged over all 72 hours and does not include the solution time required for performing the original RTCA. In order to be consistent, the solution time is reported in the same way through the remainder of this paper.

TABLE V
RESULTS FROM VARIOUS CTS METHODS ON THE TVA SYSTEM W/O HPC

TS Method	Avg. Solution time (s)	Avg. Flow Violation Reduction		Avg. Voltage Violation Reduction	
		w/o PI	w/ PI	w/o PI	w/ PI
CBCE	167	15.6%	15.0%	31.8%	30.9%
CBVE	178	40.0%	40.0%	36.2%	35.6%
DM1	202	40.6%	40.1%	48.1%	47.8%
DM2	107	40.5%	40.0%	48.1%	47.7%
DM3	98	40.5%	40.0%	48.0%	47.7%
CE	2585	40.8%	40.3%	48.2%	47.9%

Fig. 4 shows both flow violation reductions and voltage violation reductions associated to the five best CBVE switching actions, without enforcing a Pareto improvement. The average depth of the five best candidates is around 40 in the candidate list. It is found that the reduction in violation obtained with and without enforcing the solution to be a Pareto improvement is very similar for any of the approaches tested. This implies that the CTS solutions rarely cause additional violations while trying to reduce the original post-contingency violations. The figure shows that, as the rank of the switching candidate increases, the flow violation reduction drastically falls; however, the variation in voltage violation reduction is not so steep. It should be noted that these results are specific to the TVA system that is used for the analysis and a generalization cannot be made based on these results for other systems. The magnitude of congestion, as one of the determinants of the effectiveness of this technology, is drastically different from one system to another. Other factors such as reserve requirements, type of generators, and the topology of the network also play important roles in performance of CTS. Moreover, this analysis is conducted on the data corresponding to 3 days in September 2012; such results will vary throughout the year.

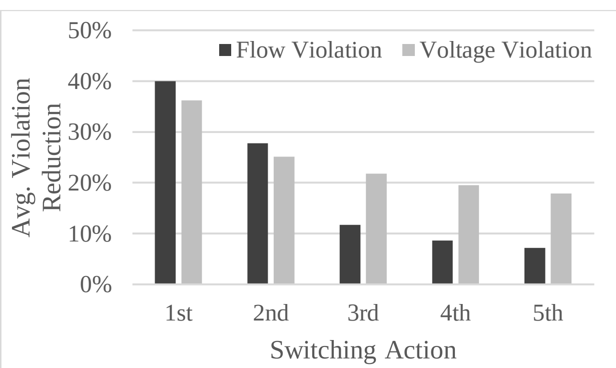

Fig. 4. Violation reductions with CTS actions on the TVA system.

B. ERCOT System

ERCOT provided three snapshots of their system. Two different heuristics, CBVE and CBCE, are used to identify the corrective switching actions to reduce the post-contingency violations. Complete enumeration of all the switching actions is also performed to find the upper bound of the benefits that can be obtained with CTS. Due to limited available data, data mining is not performed on the ERCOT system. Table VI lists the results of various transmission switching methods on the ERCOT system. It is found that both CBVE and CBCE methods provide similar benefits in terms of the reduction in voltage violations. However, CBVE results in 10% more reductions in flow violations. The reduction in violations achieved with both CBVE and CBCE heuristics are very similar to that achieved through complete enumeration, which confirms the efficiency of the heuristics. Note that both heuristics achieved such quality solutions 47 times faster than CE.

TABLE VI
RESULTS OF VARIOUS CTS METHODS ON ERCOT SYSTEM W/O HPC

TS methods	Avg. Solution time (s)	Avg. Flow Violation Reduction		Avg. Voltage Violation Reduction	
		w/o PI	w/ PI	w/o PI	w/ PI
CBCE	245	40.8%	37.7%	12.1%	12.1%
CBVE	244	53.1%	49.3%	12.3%	12.3%
CE	11,505	53.3%	49.3%	14.3%	14.3%

C. PJM System

The PJM system is the largest of the three systems used for the analysis. Hence, the computational time to run CTS-based RTCA on PJM is significantly longer compared to TVA and ERCOT. Therefore, all simulations on the PJM system are performed using HPC. For this specific section, 6 threads are only used and the computer platform is 64-bit Windows 7 Enterprise operating system, of which the processor is 3.40 GHz with four Intel(R) Core(TM) i7-3770 CPUs. The simulation is performed on the same machine that was used for the TVA and ERCOT systems, with the exception that ERCOT and TVA were solved sequentially with only 1 thread.

Similar to TVA and ERCOT, a vanilla contingency analysis is performed first to identify contingencies that would lead to violations. Similar to the ERCOT system, the two CTS heuristics, CBCE and CBVE, are used to form a rank list consisting of potential switching candidates for the PJM system. Note that the DM heuristic was not performed on the PJM system. The network branch and bus identifications varied across time periods; without PJM's data processing software, it was too difficult to match the data appropriately for the DM heuristic.

Table VII presents the statistics for violation reductions corresponding to the 5 best switching solutions with the CBVE heuristic. The percentage reduction in flow violations is found to be 59% and 46% for the first and the fifth best CTS actions respectively. However, in case of voltage violation reductions, it varies from 20% to 6% for the first and the fifth best switching actions. Note that the depth is relatively small and increases as the solutions become less beneficial, which demonstrates the effectiveness of the proposed heuristics. The results emphasize that quality solutions are found within the close vicinity of the elements with violations.

Table VIII presents the flow violation and voltage violation reductions for the top five switching candidates with the CBCE heuristic. All top 5 CTS solutions provide significant reductions in flow violation for the PJM system; only the top 3 CTS solutions provide voltage violation reductions above 10%. Table VIII also presents the statistics for distance. The average distance of the identified CTS solutions to the contingency element is around 1-2 for flow violations and about 3 for voltage violations.

The CTS results presented in Tables VII and VIII show that both heuristics perform equally well with respect to flow violation reductions, voltage violation reductions, and solution time on the PJM system.

TABLE VII
RESULTS OF THE 5 BEST SWITCHING ACTIONS ON PJM SYSTEM WITH CBVE

Candidate	Flow Violations				Voltage Violations			
	w/o PI		w/ PI		w/o PI		w/ PI	
	Avg. Reduc.	Depth	Avg. Reduc.	Depth	Avg. Reduc.	Depth	Avg. Reduc.	Depth
1st Best	59%	14.9	59%	15.4	20%	37.8	19%	38.6
2nd Best	58%	17.4	57%	17.7	15%	38.8	14%	39.1
3rd Best	53%	23.9	52%	24.7	12%	38.2	11%	38.9
4th Best	49%	27.5	49%	26.9	8%	40.9	8%	40.7
5th Best	46%	28.1	46%	28.4	6%	42.2	6%	42.4

TABLE VIII
STATISTICS OF THE 5 BEST SWITCHING ACTIONS ON THE PJM SYSTEM WITH CBCE HEURISTIC W/O PI

Candi-date	Avg. for Flow Violation			Avg. for Voltage Violation		
	Reduction	Depth	Distance	Reduction	Depth	Distance
1st Best	61.6%	18.2	1.36	19.1%	39.8	3.16
2nd Best	58.1%	21.9	1.55	14.2%	40.4	3.24
3rd Best	55.6%	26.6	1.90	10.9%	40.1	3.21
4th Best	49.3%	31.3	2.15	7.2%	41.6	3.34
5th Best	45.3%	31.3	2.15	5.9%	41.7	3.30

In order to estimate the quality of solutions obtained from the two CTS heuristics, complete enumeration of all possible switching actions is performed on 6 selected EMS snapshots. The hours represent sample data for peak, off-peak, and shoulder hours. Table IX presents the violation reductions and the corresponding computational time for the complete enumeration method as well as CBCE and CBVE heuristics. The results show that both the heuristic methods perform close to complete enumeration. The significant advantage of the heuristics is that the solution time to achieve such good quality CTS actions is 110 times faster than complete enumeration.

The results presented in Table IX confirm the effectiveness of the two heuristics to find quality solutions quickly. Furthermore, almost all of the CTS solutions make Pareto improvements and no significant difference was observed between the heuristics and CE in this sense.

Fig. 5 shows how the five candidates perform in one particular contingency case. This contingency resulted in the overload of only a single line. The best switching action provided a 100% reduction in violation while the fifth best CTS action provided 18% reduction. All five switching actions provide Pareto improvements. Fig. 6 presents an artificially created example that conceptually shows the case discussed in Fig. 5. There is power flow from bus 1 towards buses 6, 7, 10 and the rest of the system as seen in Fig. 6 (a). A contingency on the line connecting buses 4 and 6 creates a flow violation on the parallel path connecting buses 4 and 5 as shown in Fig. 6 (b). The top 5 switching actions identified by the CTS tool and the corresponding violation reductions for the first two CTS solutions on the overloaded line are presented in Fig. 6 (c) and (d) respectively. Note that the percentage loading on the lines presented in Fig. 6 (a) is based on the normal rating and the percentage loading in the rest of the post contingency cases are presented with respect to the emergency rating.

In another instance, a particular contingency caused an aggregate voltage violation of 0.4 pu spread across 17 buses. All of the top five switching actions fully eliminate the violations.

As described above, an important observation is that the results with and without Pareto improvement are very similar. Note that, for each contingency, only the five best switching candidates are proposed to the operator.

TABLE IX
RESULTS OF VARIOUS CTS METHODS ON PJM SYSTEM FOR SELECT HOURS

TS Method	Avg. Solution Time (s)	Avg. Flow Violation Reduction		Avg. Voltage Violation Reduction	
		w/o PI	w/ PI	w/o PI	w/ PI
CBCE	872	62.1%	61.0%	19.4%	19.4%
CBVE	875	59.4%	59.4%	19.4%	19.4%
CE	96922	62.5%	62.5%	21.0%	20.4%

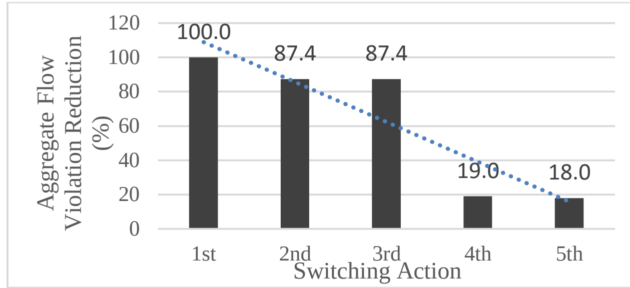

Fig. 5. Reduction in worst case flow violation corresponding to top 5 CTS actions on the PJM system.

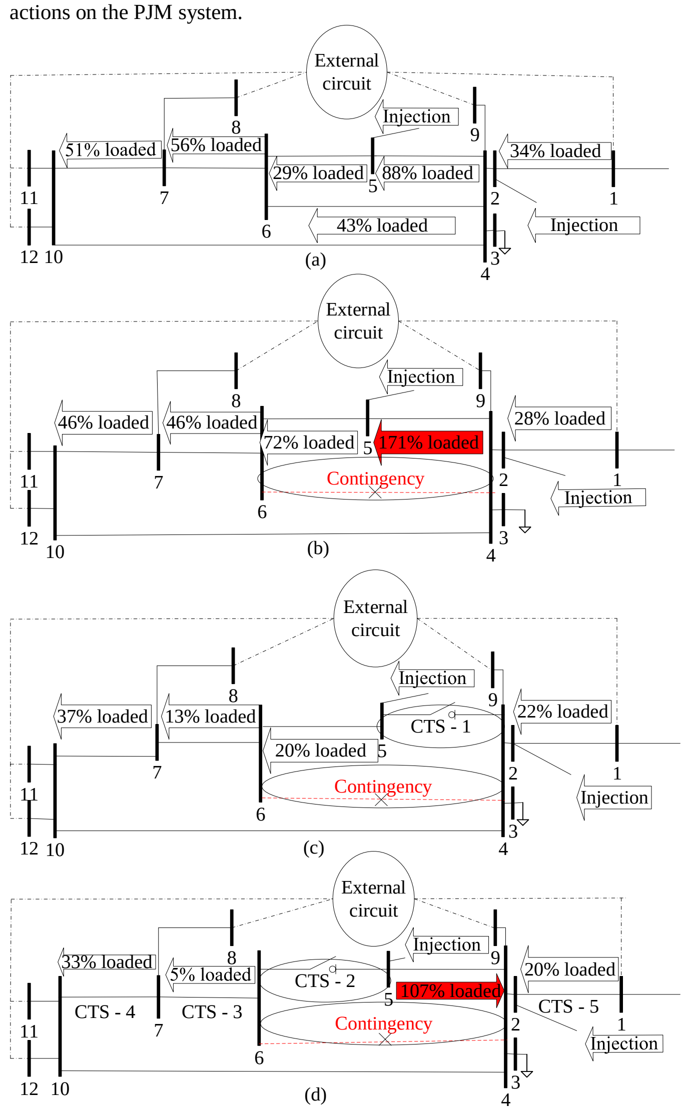

Fig. 6. An artificial example to represents the worst case flow violation. The performance of the top five CTS actions on the PJM system is shown: (a) Pre-contingency case, (b) Post-contingency case, (c) Post switching – candidate 1, (d) Post switching – candidate 2. The other candidates 3-5 are also shown, which resulted in violations of 7%, 57% and 58% respectively.

D. High Performance Computing

Computational complexity has been one of the factors inhibiting the application of optimization-based approaches for transmission switching. With the use of heuristics, the computational time presented in the previous section is substantially reduced for RTCA. Parallel computing can further improve the computational efficiency of the problem. The speedup is investigated for all the three systems with parallel computing. The hardware for parallel computing simulation is “cab” cluster at Lawrence Livermore National Laboratory (LLNL).

The variation in solution time in seconds for CTS with CBVE heuristic on the three large-scale systems, for different number of threads, is presented in Table X. It is observed that as the number of threads increased, the solution time decreases as expected. Up to 128 threads were used for vanilla contingency analysis. The solution time for RTCA on the TVA system comes down to 0.7s as compared to 49s for a sequential run with a single thread. The RTCA solution time for the ERCOT reduced to 10s from around 900s without parallel processing. For PJM, the solution time with 8 threads in parallel is almost half an hour and it decreases to about two minutes with 128 threads in parallel. The parallel efficiency of vanilla contingency analysis for the PJM system is presented in Fig. 7. Since the candidate list length for both CBVE and CBCE methods was chosen to be 100 elements, using more than 100 threads for CTS will not be beneficial, unless the power flow algorithm itself is parallelized. The results show that a computer cluster with only 100 processors can handle a snapshot of PJM data in less than two minutes on average.

Note that all the *N*-1 events are simulated for the analysis associated with Table X. System operators usually run their contingency analysis on a critical contingency list, which is a subset of all the *N*-1 contingencies. Thus, the computational time presented in Table X is expected to be reduced for actual implementation. The CTS time for PJM can be further reduced to well below a minute if the critical contingency list is available and only those contingencies are modeled.

TABLE X
AVERAGE SOLUTION TIME FOR RTCA AND CTS WITH DIFFERENT THREADS

RTCA				CTS			
# of Threads	TVA	ERCOT	PJM	# of Threads	TVA	ERCOT	PJM
1	49	899	NA	1	172	280	NA
2	25	455	NA	2	89	142	NA
4	13	231	NA	4	47	74	NA
8	6.9	123	1634	8	27	41	999
16	3.7	63	856	16	16	23	566
32	2.0	33	445	25	11	15	323
64	1.1	18	234	50	7.2	8.4	173
128	0.7	10	128	100	6.6	5.6	96

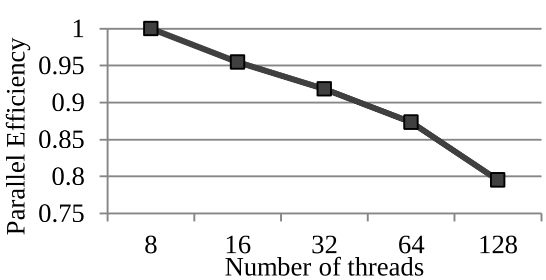

Fig. 7. Parallel efficiency of vanilla contingency analysis for the PJM system.

E. Stability Studies on the PJM system

The overall results obtained from the CTS heuristics are effective and efficient with respect to the quality of solutions and the solution time. The algorithms scale well for large-scale systems and all the analysis is done on an AC framework. However, the stability of the system following a switching action needs to be investigated. It is very essential to check the stability of CTS actions since unstable switching solutions would weaken the system rather than reducing the violations.

NERC requires system operators to have plans for loss of a second bulk element following an initial contingency (*N*-1-1). NERC specifically requires system operators to maintain dynamic stability following an *N*-1-1 event [65]. A CTS action following a contingency can be seen as an *N*-1-1 event, as a second element is being taken out of the system. Therefore, according to the NERC standard, it is required that the system maintains dynamic stability following a CTS action. After discussions with PJM, MISO, ERCOT, and ISONE, they confirm that stability for a single post-contingency switching action (after the system regains steady-state after the contingency) should not be a major hindrance to such a technology, which is one reason why PJM already implements this technology today, based on offline analysis [11]. While these arguments in support of CTS not being a primary concern for stability, nonetheless, it is important to analyze the impact on stability. Therefore, a limited number of switching solutions are tested for stability.

The dynamic data for the PJM system contains information about the different machine models in the system. Time domain simulation is performed using PSS/E to analyze the effect of the proposed CTS actions on the system stability. The stability studies are conducted on specific hours of the system spreading across the entire week of the PJM data. Those specific hours were chosen based on different loading conditions and the number of critical contingencies identified for that particular hour. Samples of peak, off peak, and shoulder hours are chosen along with the hour that have the maximum number of critical branch contingencies and the hour that has the maximum number of critical generator contingencies. Overall, the stability analysis is performed on 5 EMS snapshots with completely different system operating states.

Time domain simulations are performed on all contingencies that have violations for the selected hours. Stability analysis is conducted to examine if the proposed CTS solutions cause instability; in total, 284 contingencies, along with the CTS solutions, are analyzed. Overall, only 2 of the cases that were tested failed transient stability analysis. Fig. 8 presents the time domain simulation response for a branch contingency with CTS to relieve voltage violations in the system. Note that this particular contingency resulted in voltage violations on 17 buses with an aggregate violation of 0.4 pu. The CTS action completely eliminates those voltage violations. Fig. 9 represents the time domain simulation for a generator contingency that caused thermal flow violations. This particular contingency resulted in the maximum flow violation among all generator contingencies tested. The CTS action eliminates the flow violations completely.

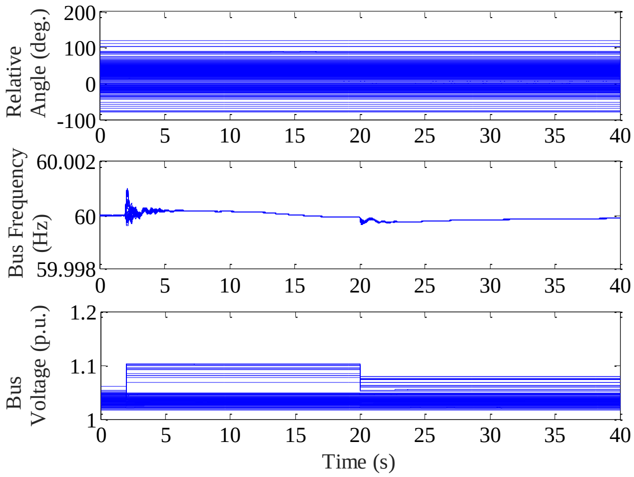

Fig. 8. Time domain simulation for a transmission contingency with CTS action on a lightly loaded hour on the PJM system.

Overall, more than 99% of the top switching candidates provide a stable solution, which is expected according to NERC standards and suggests that CTS is a viable corrective mechanism. Note that only 0.7% of the cases, which were tested, have a transient rotor angle stability issue associated with the switching action. These results are expected as PJM is reported to have limited concerns regarding transient stability for their system in its footprint [66]. PJM concludes that stability has yet to become a significant system limitation [66].

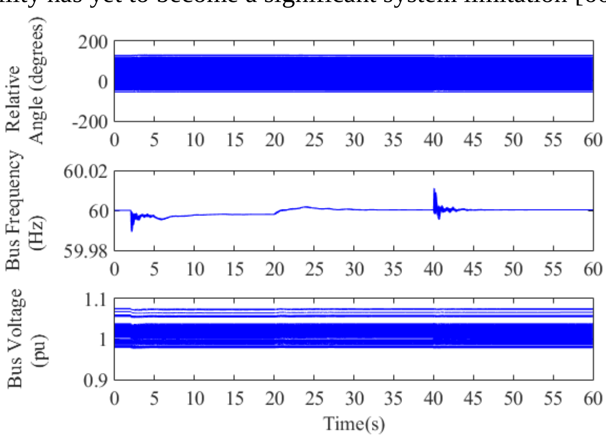

Fig. 9. Time domain simulation for a generator contingency with generation redispatch and CTS.

VII. Discussion on the Choice in the Algorithm

After analyzing the prior results, there are further insights that can be gained to understand why the CBCE and the CBVE methods are very fast but still very effective. The choice in what algorithm to implement was made after investigating various previously proposed approaches for transmission switching. While there have been some interesting advances recently in the realm for transmission switching, the following key issues dictated the preferred approach.

First, RTCA does not involve an optimization component today. RTCA relies on running power flows with predetermined assumptions (e.g., participation factors for generator contingencies) based on the system's anticipated response relative to the prior AC base case power flow solution from state estimation. RTCA, by itself, is an approximation since it leverages a past operating state to predict how the system will respond to a contingency for a future operating state that has yet to be realized while also making predetermined assumptions regarding the system response to this contingency. Just as it is apparent as to why RTCA is chosen to be very fast at producing good approximate solutions to advise operators regarding potential concerns, our algorithm is designed around that same straightforward philosophy.

Second, if the choice in the switching algorithm involves an optimization routine, the results from the RTCA tool need to be stored into a database. Then the data must be processed and the loaded into a separate tool to perform the optimization. That tool then must load a very large problem into its memory and conduct preprocessing followed by solving for then the optimal or a near-optimal solution (depending on the stopping criteria that are set). We found that this process was overly burdensome in terms of time for this application. With our proposed algorithm, we did not need to rely on any external optimization engine that required these procedures. The algorithm reads the required information regarding the contingency (location), refers to an offline rank list of corrective actions, and sends a command back to the AC power flow package to perform a new AC power flow calculation. By carefully choosing an algorithm that is well-suited for the time sensitive nature of RTCA, we are able to propose an approach that is very fast while also being very efficient. As can be seen by the results, the heuristic based algorithm performs very close to the optimal switching solution when you limit the corrective switching action to one switching action.

Third, the switching solution is limited to one action. We limited the switching solution to one action due to concerns regarding 1) stability of multiple switching actions in a post-contingency state, 2) the requirement for the system operator to initiate multiple switching actions, 3) the implication that multiple switching actions may have on regaining N-1, which is known as N-1-1, and 4) other practical considerations and limitations that are not represented in such steady-state power flow or optimization tools that are being leveraged. When you limit your corrective switching action to just one action, there is far less of a need for a complex optimization algorithm that will squeeze out that last drop of benefit at the expense of a much longer solution time. First off, the solution space is much smaller, small enough such that leveraging engineering insight as to what is a good switching candidate is sufficient to generate a very efficient heuristic. That engineering insight leverages the fact that a local control action is likely the best remedy for the violations caused by the contingency. This is the very basis for our algorithm. We choose lines that are within a close proximity to the issue.

For the ERCOT and the PJM results based directly on actual operations, the RTCA with CTS increases the solution time by a ratio of 30 to 60%, an increase in solution time that is easily handled. To combine that result with the heuristics' ability to perform close to optimality confirms the achievement for this particular application. Different applications of transmission switching are likely to rely on a different technique. Each application has its own unique requirements and characteristics, which makes it important to study those specific cases in order to choose the algorithm that best suites the needs of that situation.

VIII. Conclusions

Transmission switching is a low cost power flow control technology that would reduce the operational costs, improve system reliability, and enhance integration of intermittent renewable resources. Despite all these benefits, the industry adoption of the technology has been fairly limited due to the following barriers: computational complexity for large-scale systems, ambiguous AC performance, and stability concerns.

This paper comprehensively addresses the state of the art challenges of transmission switching for the application of RTCA. A multi-threaded AC-based RTCA package, which incorporates CTS as a corrective mechanism, is developed. When RTCA identifies a contingency with potential network violations, a separate routine finds effective CTS actions to relieve the violations. Thus, the need for reliability-motivated commitment and redispatch will be drastically reduced, which translates into reliability benefits and substantial cost savings.

The computational efficiency is achieved by using extremely powerful AC based heuristics along with parallel computing. The simple heuristics used for the CTS routine are able to find quality solutions very quickly. Local search algorithms around the contingency may not perform as well for generator contingencies due to the spatial distribution of redispatch and the resulting violations. Data mining methods may not perform well if the system condition changes significantly from the training data. Overall, the dynamic search around the violations shows the most promising performance. The results demonstrate the effectiveness of CTS based on its ability to reduce post-contingency violations in an AC setting. Moreover, stability analysis is performed to check the stability of the proposed CTS actions. A subset of CTS actions is analyzed and the results show that more than 99% of the CTS actions do not cause instability issues. The most important value of this paper is in finding algorithms that actually can enable CTS to work on large-scale systems, since not enough attention in literature is being given to the challenges that come up when dealing with large-scale data.

To conclude, the proposed technology is able to very quickly propose quality CTS solutions which provide the operators with an alternative option to alleviate post-contingency violations. The RTCA developed in this paper proposes multiple switching actions for each contingency. The operator has the choice to implement any of the solutions based on the associated violation reductions, Pareto performance, or stability concerns. The promising results on the real large-scale power systems (PJM, ERCOT, and TVA) with operational data show that corrective transmission switching is ripe for industry adoption for the real-time contingency analysis application.

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