A Data-Driven Heuristic for Corrective Transmission Switching

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***Abstract*— Utilizing flexibility of the transmission network has gained significant attention recently. Prior efforts have shown that various benefits could be achieved by appropriately changing the network topology. This paper focuses on the reliability gains that can be achieved through corrective transmission switching (CTS). A full AC contingency analysis is conducted to identify critical contingencies that would result in violations. CTS is employed on these critical contingencies to test for violation reductions. A data-driven heuristic is proposed in this paper to identify the candidate switching list. This heuristic, also referred to as enhanced data mining (EDM) approach, provides a static lookup table consisting of corrective switching solutions, which is fast and effective. The lookup table can be created through a straightforward data mining technique. Simulations on the TVA system demonstrate the effectiveness and efficiency of the proposed heuristic.**

***Index Terms*— Contingency analysis, corrective transmission switching, data mining, heuristic, large-scale power systems, lookup table, power system reliability.**

I. Introduction

The bulk power system operations are expected to be robust with self-healing capability and function at a relatively low cost. The full utilization of control of transmission network and optimization of transmission topology contributes significantly towards this goal. It is very unlikely that a fixed topology will be optimal for various system conditions. Network reconfiguration is a low cost option and a valuable approach to build a smarter and more flexible power grid [1]-[4].

Elements of the transmission network are traditionally treated as static fixed assets during short-term operations. These assets will always be in service, except for when it is under preventive maintenance and when it experiences a forced outage. Though it might be counter-intuitive that transmission switching (TS) will benefit the system, TS essentially leverages the flexibility of the grid and provides the operator an additional control option. The transmission network of a power system is built with redundancy in order to withstand potential contingencies. In general, TS provides more benefits for a heavily meshed network than a radial network.

Previous research efforts have demonstrated that TS is able to achieve a variety of benefits. TS can be used to reconfigure the system for enhancement of reliability [5]-[7], cost savings [8]-[11], congestion management [12], and increase of the do-not-exceed (DNE) limits [13]-[14], as well as a number of other objectives [15]-[17].

With voltage security and *N*-1 considered in the optimal transmission switching (OTS) problem, reduction in generation costs can still be obtained through transmission congestion management [18]. Stability is also a great concern for implementing TS. It is demonstrated in [19] that though the reduction in cost becomes less with extra dynamic constraints, cost saving can still be achieved with the application of TS.

In transmission and generation expansion planning, TS can enhance the system security and reduce the total cost including operating cost and investment cost [20]. TS can also be incorporated into the formulation of outage coordination problem for cost reduction [21]. Increase of system loading margin can be accomplished with additional flexibility provided by TS [22].

There is a concern on how TS would affect the energy markets since network reconfiguration would alter several market pricing signals. A number of studies were conducted [23]-[26] to examine this issue. For instance, an adaptive robust optimal transmission switching approach is proposed in [23] to deal with the uncertainty of net nodal electricity demands.

One difficulty of implementing TS is computational complexity. Previous efforts have been performed to develop efficient heuristics to reduce the computational burden for TS. Two prescreening methods are proposed in [27] to select a subset of switchable lines, which can achieve near optimal solution with significantly reduced solution time. An application of high performance computing to reduce solution time for TS is presented in [28].

Three heuristics are proposed in [1]-[2] to reduce computational complexity for corrective transmission switching (CTS). Numerical simulation demonstrates the effectiveness of the proposed CTS heuristics in terms of post-contingency violation reduction. Data mining (DM) method, one of the three heuristics, illustrated that the beneficial switching actions consist of a very limited subset of lines. The candidate list obtained from this regular DM approach contains the same set of switching actions for all critical contingencies identified. However, this would unnecessarily make the list lengthy and inefficient since the beneficial switching solutions for a contingency may provide little violation reduction caused by other contingencies.

Based on the authors' prior experience, a switching action that reduces violation for a contingency in one scenario may also provide benefits for the same contingency under a different scenario but may not provide any benefit for other contin-

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gencies. Inspired by this idea, a data-driven heuristic is proposed in this paper to investigate potential reduction in the length of the candidate list without compromising the performance of violation reduction achieved with CTS. The proposed heuristic is referred to as enhanced data mining (EDM) method to distinguish it from the regular DM method proposed in [1]-[2].

The proposed EDM heuristic is a static lookup table based approach. The switching list for each contingency is identified beforehand and it varies for different contingency. This list is much shorter than the list of DM, which results in much lesser solution time. The TVA system is used to validate the effectiveness of the proposed EDM approach in this paper. PJM switching solutions as listed in [29] indicates that the beneficial switching solutions for the same contingency would probably remain the same even if the load profile varies, which is consistent with the philosophy behind the proposed EDM heuristic.

The rest of this paper is organized as follows. Section II briefly explains the concepts of contingency analysis (CA) and corrective transmission switching and presents the methodology of the proposed EDM heuristic for the CTS application. Section III presents the results of CA and CTS for the TVA system. Finally, Section IV concludes the paper and Section V presents the potential future work.

II. Corrective Transmission Switching

Operating power system in a reliable way is of utmost importance. In real-time, CA is performed regularly, for instance, every one minute for PJM [30], every four minutes for MISO [31], and every five minutes for ERCOT [32] respectively. The goal of CA is to identify the critical contingencies. In this paper, a contingency that results in system violations is referred to as a critical contingency. The identified critical contingencies along with the associated violations will be reported to the system operators.

With all the information obtained from CA, corrective strategies for dealing with identified critical contingencies can be determined in advance. Thus, with pre-planned strategies, the system operators will be able to react to a critical contingency immediately after it occurs. Those corrective actions include generation re-dispatch, commitment of fast-start units, and load shedding. CTS is proposed as an additional control method for the operators to rely on.

The proposed CTS heuristic is based on a trial-and-error strategy. All switching actions in the candidate list will be examined one after another. After all the switching actions are scanned, the switching solution with the best performance will be reported.

For each critical contingency identified by CA, all candidate switching actions are examined for violation reduction. Two types of techniques can be used to determine the candidate switching list, static technique and dynamic technique. A dynamic technique will identify potential beneficial CTS solutions considering the operating state of the system in real-time. A static technique would create a lookup table consisting of potential beneficial CTS solutions offline, which is independent of the operating state of the system. One advantage of this static method is that the candidate list is available in advance. Extensive studies are conducted offline to determine the candidate list. Thus, in this approach the computational burden is completely shifted to offline studies and hence, it saves time during real-time operations. The proposed EDM heuristic, as a static technique, identifies the CTS candidate list offline, resulting in a lookup table which can be used in real-time to directly generate the candidate switching actions for handling critical contingencies.

The procedure for the EDM study in this paper consists of two stages. The first stage is to determine the candidate switching actions using historical data in the training set and the second stage is to investigate the performance of the EDM heuristic, with the candidate actions identified from stage 1, on different cases in the test set.

Stage 1: Determination of candidates list

To illustrate the methodology of the proposed EDM heuristic, it is assumed that multiple historical scenarios of the system conditions are available, which is reasonable and practical for real power systems. These scenarios form the training set for determining the static lookup table offline. The associated procedure is described below:

1) For each scenario, CA is conducted to identify the critical contingencies.
2) For each critical contingency identified in 1), complete enumeration (CE) of all possible switchable lines is performed to determine the best switching action.
3) By examining all historical scenarios, a lookup table consisting of beneficial switching solutions for the CTS application can then be created.

The lookup table contains the critical contingencies and the corresponding best CTS solutions identified from the scenarios in the training set.

Fig. 1 shows the flowchart of the proposed EDM heuristic for the CTS application. Historical scenarios are checked with CA. All critical contingencies with potential violations are sent to the CTS routine along with all possible solutions in the candidate list. After this process is completed, the best CTS solutions for the same contingency in different scenarios can then form the candidate switching list for the test cases that will be examined in stage 2.

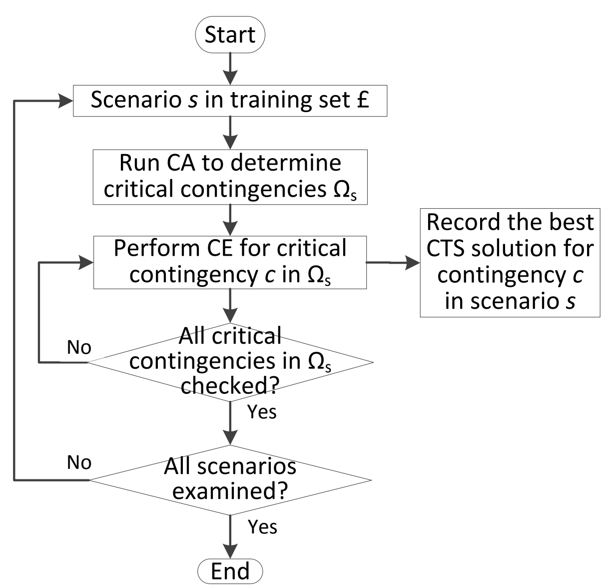

Fig. 1. Flowchart of the proposed EDM heuristic.

Stage 2: Performance of the proposed EDM heuristic

Stage 2 investigates the performance of the proposed EDM heuristic by examining the efficiency and effectiveness of the same CTS solutions, pre-determined for every critical contingency in stage 1, on cases that are different with the historical scenarios used in stage 1. To gauge the performance of the proposed EDM heuristic, CE and DM methods are also conducted in this stage. The results obtained from CE, as well as the results gained from DM method, are used only for comparison with the proposed EDM heuristic.

III. Case Studies

The computer platform used for all the studies presented in this paper is 64-bit Windows 7 Enterprise operating system with four Intel(R) Core(TM) i7-3770 CPUs of 3.40 GHz. OpenPA [33], an open source AC power flow package written in JAVA, is used as the power flow engine for all the simulations performed in this paper.

The TVA system is used to investigate the performance of the proposed heuristic in this paper. Three days or 72 hourly cases from TVA are used for this analysis. The detailed information can be found in [7]. In this paper, the first two days or 48 hours that represent the historical cases are used to determine the candidate switching list for each critical contingency identified on those cases, which corresponds to stage 1. Then, those pre-determined candidate lists are checked for the CTS performance on the remaining 24 cases in stage 2.

Analysis of simulation in stage 1

With CA conducted on the scenarios of day 1 and day 2 for the TVA system, 153 different critical contingencies are identified. CE is performed on all 48 scenarios to determine the best CTS solutions for each critical contingency. The best CTS solutions for the same contingency under various historical scenarios in the training set form the candidate list for that contingency.

Random variable α is defined as the number of cases for which the same contingency is identified as a critical contingency. Table I presents the statistics for this random variable. From this table, it is observed that most of the critical contingencies could cause violations for different system conditions corresponding to different historical cases. In other words, a contingency that causes violations in one scenario may also cause violations in other scenarios. The average number of scenarios that the same contingency will occur is 18.7 out of 48, corresponding to a probability of 39.0%.

Table I Statistics for random variables α and μ.

	max	min	median	average	std
α	43	1	20	18.7	11.1
μ	89.6%	2.1%	41.7%	39.0%	23.1%

Random variable μ is defined in (1).

$$\mu_c = \alpha_c / nT \tag{1}$$

where, α_c is number of cases where contingency c is identified as a critical contingency and nT is the total number of cases examined in this stage. nT is 48 in this paper. The statistics for μ is also presented in Table I. The maximum probability of the occurrence of the same contingency is as high as around 90%.

Fig. 2 shows the cumulative distribution function f of variable μ. It is observed that the probability of occurrence of a contingency, among 153 identified critical contingencies, is primarily in the range between 20% and 80%.

To verify the idea that the beneficial CTS solutions for a contingency will also provide violation reduction for the same contingency in a different scenario of the system, two random variables γ and β are proposed. Random variable γ denotes the number of scenarios where a beneficial CTS solution exists for a critical contingency. Then β, as defined in (2), denotes the probability that at least a beneficial CTS solution exists for an identified critical contingency.

$$\beta_c = \frac{\gamma_c}{\alpha_c} \times 100\% \tag{2}$$

where, the subscript c denotes critical contingency c.

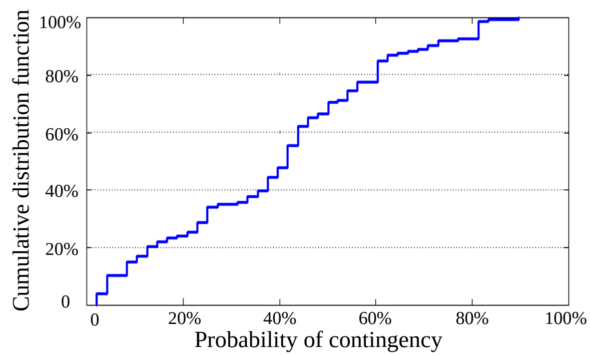

Fig. 2. Cumulative distribution function f of random variable μ.

Table II presents the statistics for random variable β. It shows that the probability of existence of beneficial CTS solutions for a critical contingency is extremely high. Even if 10% improvement is used as the tolerance for defining a beneficial switching action, on average, beneficial CTS solutions are still available to relieve violations caused by the same critical contingency for more than 80% of the scenarios.

Table II Statistics for random variable β.

Tolerance	max	Min	median	average	std
0	100%	0	100%	97.1%	13.84%
5%	100%	0	100%	86.6%	29.0%
10%	100%	0	100%	83.5%	31.3%

Random variable φ is defined as the number of switching actions in the candidate list for a critical contingency. Table III presents the statistics for this random variable. The candidate list obtained from the EDM method is extremely short. The average length is just around two, which implies that the added computational time per contingency due to CTS is just the solution time that is needed to perform two power flow simulations.

Table III Statistics for random variable φ.

Tolerance	max	min	median	average	Std
0	18	0	2	2.39	2.35
5%	6	0	1	1.66	0.99
10%	5	0	1	1.58	0.96

There are 153 numbers in the sample space for each random variable α, μ, γ, β, and φ since there were 153 critical contingencies identified in stage 1. Note that a heuristic using the candidate list without any tolerance for improvement is referred to as EDM1. Candidate list with a tolerance of 5% is referred to as EDM2, while the list for EDM3 corresponds to a tolerance of 10%.

Analysis of simulation in stage 2

Stage 2 aims to justify the proposed data-driven heuristic. Simulations were performed on the 24 hourly scenarios of day 3 for the TVA system to demonstrate the effectiveness of the proposed EDM approach.

In this stage, CA is first conducted on the 24 scenarios in the test set from day 3. Overall, 152 critical contingencies that would cause network violations are identified. Among those critical contingencies identified in stage 2, 128 contingencies, which correspond to 84.2% cases, are found in the critical contingency list identified from the 48 scenarios in the training set from day 1 and day 2. For each critical contingency in stage 2, only the beneficial switching actions identified in stage 1 for the corresponding contingencies are examined for the proposed EDM heuristic. The CE method and the regular DM methods are also conducted in order to compare and evaluate the performance of the EDM approach.

Table IV presents detailed statistics of the results obtained from DM, EDM, and CE methods respectively. The maximum, minimum, median, average, and standard deviation of the solution time per scenario for the different CTS methods is presented in Table IV. For both DM and EDM approaches, as the tolerance for defining beneficial CTS solutions is increased from 0% to 5%, the solutions time reduces by a large factor while the violation reductions stay almost the same. However, further increase in the tolerance from 5% to 10% only has a negligible effect on the reduction in solution time.

Average violation reduction in percentage is calculated as defined in [1] to quantify the benefits provided by the CTS scheme. Both voltage violation reduction and flow violation reduction are reported in Table IV. Both DM and EDM methods are proven to be very effective as they provide almost the same reduction in violations in comparison to the CE method. The violation reductions obtained by the proposed EDM heuristic is only around 1% lower than the DM and CE methods, while EDM achieves this result in much less solution time. EDM1 is around 20 times faster than DM1 and EDM3 is over 10 times faster than DM3. Moreover, EDM is over 200 times faster than the CE method. In conclusion, the proposed EDM heuristics provide near optimal solutions while adding the least overhead to the solution time for contingency analysis, which is very promising for real-time CTS applications.

Table IV Results for the third days' cases

	Solution time (s)					Violation Reduction	
Methods	max	min	median	average	std	Flow	Vm
DM1	464.2	22.1	208.7	219.5	161.4	39.77%	51.09%
DM2	225.9	11.0	103.6	108.3	79.5	39.77%	51.07%
DM3	200.7	9.7	90.9	96.1	70.8	39.76%	50.95%
EDM1	20.9	1.5	10.7	11.1	7.5	38.74%	50.24%
EDM2	18.0	1.4	9.1	9.6	6.5	38.73%	50.22%
EDM3	17.6	1.1	8.9	9.3	6.3	38.73%	50.03%
CE	9636.5	208.5	2003.5	2458.2	2316.9	39.77%	51.22%

Table V shows the average number of switching actions in the candidate list per contingency and the average solution time for the CTS routine per scenario. It is observed that the solution time is linearly correlated with the number of switching actions in the candidate list. Obviously, one reason why EDM is much faster than DM is that the candidate list of the proposed EDM approach is much shorter.

Table V Comparison among a variety of CTS methods

	CE	DM1	DM2	DM3	EDM1	EDM2	EDM3
nCTS	1528.9	145	64	55	2.4	1.7	1.6
T_1 (s)	2316.9	219.5	108.3	96.1	11.1	9.6	9.3

nCTS denotes the number of switching actions per contingency.
T_1 denotes the average solution time of CTS routine per scenario.

IV. Conclusions

Transmission switching has gained significant attention during the last decade. Prior research shows that utilization of the network flexibility could offer a variety of benefits for a wide range of applications. The same CTS solutions are found to be beneficial for the same contingency even if load profiles and system operating conditions vary. Therefore, a data-driven EDM heuristic is proposed in this paper to generate a static lookup table consisting of a list of CTS solutions for each critical contingency. Case studies demonstrate the usefulness of the proposed EDM approach, which is fast, effective, and straightforward to implement.

V. Future Work

One key assumption made in this paper is that the system topology is assumed to be fixed for all the scenarios. With this assumption, it is concluded that the CTS solutions for the same critical contingency contains a fixed set of a few lines even if the load profile varies. However, the CTS solutions from the pre-determined static lookup table may fail to provide expected performance in terms of violation reductions if network topology changes [34]. Therefore, future work should investigate how changes in topology affect the effectiveness of the proposed EDM heuristic.

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