A Data Mining Approach for Real-time Corrective Switching

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***Abstract*—Corrective transmission switching can improve the flexibility of power system. To avoid the computational complexity, a data mining approach for real-time corrective switching is proposed in this paper. A factorized expression that measures the approximate switching effects is first derived. The expression can be utilized to generate candidate transmission switching lists. Based on the factorized expression, an algorithm is proposed. The algorithm can be used to generate rank list of candidate switching actions. Since the algorithm bypasses the need to solve complex mixed integer optimization problems, it can provide candidate switching actions for real-time corrective control efficiently. The validity of the presented approach is demonstrated by tests conducted on IEEE RTS96 system.**

***Index Terms*—Power system, corrective switching, contingency, corrective control.**

I. Introduction

Transmission lines are, traditionally, regarded as uncontrollable static assets in power system operations. However, through actively controlling the topology of power system, the system can be more flexible. This idea has been explored by researchers since 1980s as a way to relieve abnormal conditions in a system when there are scheduled outages or unscheduled events [1], [2] and to reduce system loss [3], [4].

In recent studies, it has been shown that, with transmission switching, the cost of operating power systems can be significantly reduced [5], [6]. In these papers, the network topology is co-optimized with the generation dispatch. A mixed integer linear programming (MILP) is solved to provide system operators choices of dispatches as well as system topologies. In [7], security constraints enforcing N-1 reliability are also taken into consideration. In [8], network topology is also co-optimized with the unit comment while ensuring N-1 reliability. Instead of solving MILP, fast heuristics are proposed in [9], [10].

The flexibility provided by transmission switching can also be used to relieve overloads and voltage violations when contingency occurs beyond improving efficiency in operating the system. In contrast to other corrective control actions such as load shedding and switching in shunt, corrective transmission switching utilizes existing assets required by normal operating conditions, corrective transmission switching incurs no additional cost other than possible wear of the breakers which is typically small as compared to the potential benefits. In [11], the authors propose a new algorithm to find optimal line and bus-bar switching action for relieving both overloads and voltage violations. The algorithm is based on fast decoupled power flow with limited iterations. The switching actions effects are evaluated by a security margin index proposed in the paper. In [12], the authors investigate the application of a sensitivity based greedy algorithm to preform corrective switching. In [13], three corrective switching methodologies are presented and the formulation of robust corrective switching is provided. The solutions of the robust formulation can deal with any realizable load within the uncertainty set of loads.

In this paper, we proposed a data mining approach for real-time corrective switching. In our method, we assume that, based on previous experience of system operators and simulations, critical violations which might jeopardize the security of the system are predetermined. Candidate switching actions for different topologies are generated before a contingency occurs and are stored in the database. In real-time, when a contingency occurs and violations are observed, the information stored in the database is combined with real-time information measured from the system to obtain ranked switching actions. The algorithm is fast enough to be implemented in real-time since the proposed algorithm for generating candidate switching actions does not require the solution of any optimization problem. The method is tested on the IEEE RTS 96 system.

The paper is organized as follows. Section II presents real-time corrective switching methodologies and mathematical analysis for quantifying the effects of switching actions. Based on that analysis, a data mining approach for real-time corrective switching is proposed in section III. Section IV provides test results of the proposed method along with the analysis of the results and Section V concludes the paper.

II. METHDOLOGIES AND MATHEMATICAL ANALYSIS

Corrective switching can improve system flexibility and help reduce overloads and voltage violations. This paper proposes a data mining approach for corrective switching as a response to contingencies. In this section, the methodologies of corrective switching and the mathematical foundations of the proposed algorithm will be introduced.

A. *Real-time Corrective Switching Methedologies*

When contingencies occurs, overloads, voltage violations cascading failures or instability may appear in the system. System operators should take corrective control actions to deal with these problems. Corrective transmission switching is one of these corrective control actions. Figure 1 shows the timeline of corrective switching. Before contingency occurs, the system is in regular states and no violations can be observed. When a contingency occurs, the violations, power flow on each transmission line and voltage of each bus can be observed by the system operator. If there is a violation, the system will be in emergency state and all the variables which can be observed are available to be used in making decisions on what corrective control actions should be taken. While determining proper corrective control actions, AC feasibility and stability should be checked. After proper actions taking place, some violations might be relieved. But N-1 reliability may still be violated, so the system is still in emergency state. To restore the system to regular state, the contingency should be totally resolved or generation should be redispatched so that N-1 reliability is restored.

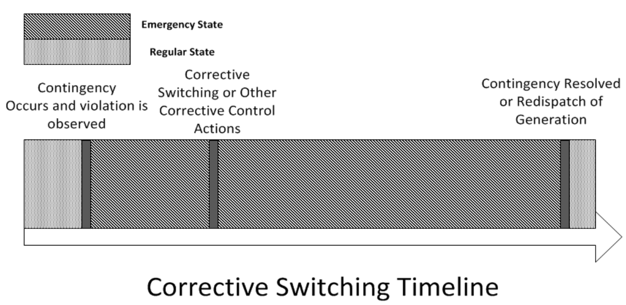

Figure 1. Corrective switching timeline

Corrective switching can be modeled as an optimization problem which if restricted to a single switching action can be expressed as:

$$\begin{aligned} &\max_{\mathbf{u}\in\mathbf{U}} f(\mathbf{x}) \\ &s.t.\ \mathbf{g}(\mathbf{x},\mathbf{u}) = 0 \\ &\quad \left\|\mathbf{u}-\mathbf{u}_0\right\| = 1 \\ &\quad \mathbf{x}\in\mathbf{X},\ \mathbf{u}\in\mathbf{U} \end{aligned} \tag{1}$$

In this formulation $\mathbf{x}$ is the vector of state variables and $\mathbf{u}$ is the vector of control variables. Vector $\mathbf{x}$ represents the flow on each line and voltage of each bus after corrective switching, and $\mathbf{u}$ is a vector of binary variables which represents the status of lines in the system. Vector $\mathbf{u}_0$ represents the status of lines before corrective switching. Set $\mathbf{X}$ contains all acceptable states after contingency occurs, and set $\mathbf{U}$ is a subset of B^n that contains all acceptable topology after contingency. Function $f:\mathbf{X}\rightarrow R$ measures the effects of corrective switching. The first constraint in (1) is the system power flow equation after switching a line. The second constraint in (1) represents that only one line can be switched each time. Solving problem (1), the operators can get a candidate switching solution $\mathbf{u}^*$. The operators should also check whether the solution will cause instability. If the system after switching is not stable, the system operators need to solve (1) again with $\mathbf{u}\in\mathbf{U}_1$ and $\mathbf{U}_1 = \mathbf{U}/\left\{\mathbf{u}^*\right\}$. Thus, when a contingency occurs, the operators may solve a sequence of Mixed Integer Programs (MIP) to get a feasible switching solution, which is computationally challenging in real-time for a realistic scale system. Hence other heuristic approaches are needed to obtain practically acceptable corrective switching solutions.

B. *Methematical Analysis*

Instead of solving a sequence of problem (1), an alternative approach is to create a rank list of candidate corrective switching solutions, and obtain real-time candidate corrective switching's through data mining. To do that, we need to understand how system configurations and operating points would affect the corrective switching actions.

Suppose there is a contingency and there are line flow violations or bus voltage violations in the system due to the contingency. The power flow equations for the system are:

$$0 = P_{gi} - P_{di} - U_i \sum_{j\in N_i} U_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right), \forall i\in N \tag{2}$$

$$0 = Q_{gi} - Q_{di} - U_i \sum_{j\in N_i} U_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right), \forall i\in N \tag{3}$$

where N denotes the set of buses and N_i denotes the set of buses that have direct connections with bus i. P_{gi}, P_{di}, Q_{gi} and Q_{di} are real power generation, real power consumption, reactive power generation and reactive power consumption on bus i, respectively. U_i is the voltage magnitude of bus i and θ_{ij} is the voltage angle difference between bus i and bus j. G_{ij} and B_{ij} are corresponding components from the system admittance matrix.

In each iteration of fast decoupled power flow, we have:

$$\Delta\theta = -B'^{-1}\Delta P \tag{4}$$

$$\Delta U = -B''^{-1}\Delta Q \tag{5}$$

where B'' is the imaginary part of the system admittance matrix. B' is the susceptance matrix whose terms are $\frac{1}{X_{ij}}$ where X_{ij} is the impedance of line ij. In (4) and (5), the B' and B'' matrices correspond to the system after switching of a candidate line. ΔP and ΔQ are the change of real power and reactive power injection at each bus. When line ij is switched, without loss of generality, assuming both bus i and bus j are PQ buses, ΔP and ΔQ can be expressed as:

$$\Delta P=\begin{bmatrix}\mathbf{0}\\P_{ij}\\\mathbf{0}\\-P_{ij}\\\mathbf{0}\end{bmatrix}\begin{matrix}\vdots\\i\\\vdots\\j\\\vdots\end{matrix}=M_{ij}P_{ij},\Delta Q=\begin{bmatrix}\mathbf{0}\\Q_{ij}\\\mathbf{0}\\-Q_{ij}\\\mathbf{0}\end{bmatrix}\begin{matrix}\vdots\\i\\\vdots\\j\\\vdots\end{matrix}=M_{ij}Q_{ij} \qquad (6)$$

where M_{ij} is defined as:

$$M_{ij}=\begin{bmatrix}\mathbf{0}\\1\\\mathbf{0}\\-1\\\mathbf{0}\end{bmatrix}\begin{matrix}\vdots\\i\\\vdots\\j\\\vdots\end{matrix} \qquad (7)$$

Suppose the susceptance matrices before switching off line ij are B_0' and B_0'', then B' and B'' can be expressed as:

$$\begin{aligned}B'&=B_0'-M_{ij}\frac{1}{X_{ij}}M_{ij}^T\\B''&=B_0''-M_{ij}B_{ij}M_{ij}^T\end{aligned} \qquad (8)$$

By matrix inversion lemma, we have:

$$\begin{aligned}B'^{-1}&=B_0'^{-1}+B_0'^{-1}M_{ij}\left(\frac{1}{X_{ij}}-M_{ij}^TB_0'^{-1}M_{ij}\right)M_{ij}^TB_0'^{-1}\\B''^{-1}&=B_0''^{-1}+B_0''^{-1}M_{ij}\left(B_{ij}-M_{ij}^TB_0''^{-1}M_{ij}\right)M_{ij}^TB_0''^{-1}\end{aligned} \qquad (9)$$

Using DC power flow we can get a linearized relation between $\Delta\theta_{mn}$ and ΔP_{mn} :

$$\Delta P_{mn}=X_{mn}^{-1}\Delta\theta_{mn}=X_{mn}^{-1}M_{mn}^T\Delta\theta \qquad (10)$$

Substituting (9) and (10) into (4) and (5) we will get the change of power flow on line mn and the voltage magnitude of bus k can be expressed as:

$$\begin{aligned}\Delta P_{mn}^{ij}&=-X_{mn}^{-1}M_{mn}^T\Big(B_0'^{-1}+B_0'^{-1}M_{ij}\Big(\frac{1}{X_{ij}}-\\&\quad M_{ij}^TB_0'^{-1}M_{ij}\Big)M_{ij}^TB_0'^{-1}\Big)M_{ij}P_{ij}\\&=h_P^{mn,ij}(\mathbf{u}_0)P_{ij}\\\Delta V_k^{ij}&=-\Big(B_0''^{-1}+B_0''^{-1}M_{ij}\Big(B_{ij}-\\&\quad M_{ij}^TB_0''^{-1}M_{ij}\Big)M_{ij}^TB_0''^{-1}\Big)M_{ij}Q_{ij}\\&=h_V^{k,ij}(\mathbf{u}_0)Q_{ij}\end{aligned} \qquad (11)$$

The approximation in (11) shows that the effect of switching one candidate line depends not only on the topology of the system, but also on the power flow of the switched line. However, the effect can be factorized. Assuming that from previous experience we are only concerned with a certain number of overloads and voltage violations, based on the factorization, we can generate lists that store $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ for overloads on line mn and voltage violations on bus k. The above information can be utilized together with real-time information to evaluate the effect of corrective switching. Note that $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ depend only on the topology. Violations are not necessarily required when calculating $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$. Moreover, the factorization is derived from the linear approximation. As shown in [11], such linear approximation can cause errors. Hence, we should generate $h_V^{k,ij}(\mathbf{u}_0)$ with operating conditions that are close to those with voltage violations. Usually, violations occur when system load is heavy. Thus, $h_V^{k,ij}(\mathbf{u}_0)$ should be generated with heavy loads. Moreover, the rank lists of $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ only represent the influence of the system configuration. To get the rank list of candidate switching actions, we also need the real-time flow information. To ensure that the best switching action is in the list, we should store enough candidate actions.

III. PROPOSED ALOGRITHM

In the proposed algorithm, we presume that for typical topologies the rank lists of $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ for concerned violations are stored in the database, which is available to the system operator when a contingency occurs. Moreover, the system operator could also get real-time line flow information in real-time. By (11), rank list of candidate switching actions could be obtained. Once the list is generated, AC feasibility and stability can be checked in a parallel to obtain a feasible switching action with best effect. The flow chart of the proposed algorithm is shown in Figure 2.

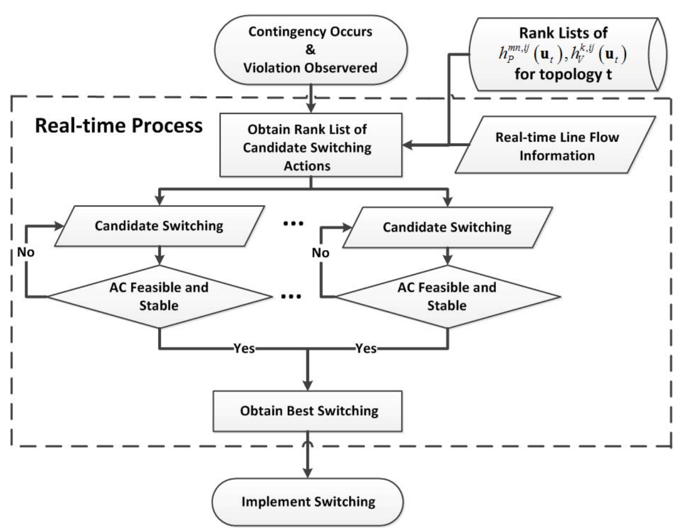

Figure 2. Flow chart for proposed algorithm.

IV. TEST RESULTS

The modified IEEE RTS96 test system is used to validate our algorithm. There are 73 buses, 121 branches and 33 generators in the system. In our study, MATPOWER [14] is used to solve power flows. In the study of line overloads, there is overload on line 31. In the study of voltage violations, there is voltage violation on bus 72. The rank lists of $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ are with respect to line 31 and bus 72. In both studies, four load profiles are created. Loads at each bus of different profiles are randomly drawn from a uniform distribution so that they vary from 90% to 110% of the corresponding base case value. Moreover, the total demand in each load profile ranges from 65% to 93% of the base case total demand. Load profile 1 has the smallest total demand and load profile 4 has the largest total demand. Different topologies are created by switching off lines in the system. There are 118 AC feasible topologies used in our test. Rank lists of $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ for 4 load profiles are compared with the rank lists of $h_P^{mn,ij}(\mathbf{u}_0)$ and $h_V^{k,ij}(\mathbf{u}_0)$ for the base case.

A. Results for Overloads

The top 10% of $h_P^{mn,ij}(\mathbf{u}_0)$ (12 switching actions) for 4 different load profiles with the same topology are presented in TABLE I. When a contingency occurs, and line 33 is switched off, the overload on line 31 will be totally relieved and no new violations will be introduced. This switching action is in the candidate switching actions list generated by all 4 load profiles. From the results, we can see that the rank lists are similar among different load profiles.

The effect of real-time corrective switching depends not only on the system configuration, but also on the flow of the line. What we need is the relatively large $h_P^{mn,ij}(\mathbf{u}_0)$, which can be combined with the real-time load flow to get a good switching action. Thus, the rank of $h_P^{mn,ij}(\mathbf{u}_0)$ for different switching action is not of our concern. Taking the top 10% of the lists as candidate switching actions, if the sets of candidate actions for different load profiles are similar to the set for the base case, we could use one of them to represent the set for that topology. In our study, we use Jaccard similarity as a metric. Jaccard similarity of set A and B is defined as:

$$J(A,B)=\frac{|A\cap B|}{|A\cup B|} \tag{12}$$

where $|\bullet|$ denotes the cardinality of a set. For 118 different topologies, the Jaccard similarities of candidate sets for 4 different load profiles with respect to the candidate set for base case are plotted in Figure 3. From Figure 3, we can see that the candidate switching actions for different load profiles are similar to those of the base case. The smallest Jaccard similarity of all is 0.6. That means, among all topologies, for different profiles, there are at most three candidate switching actions which are different from the candidate switching actions of the base case.

TABLE I. RANK LIST FOR OVERLOADS

Load Profile	Candidate Switching Actions
Base Case	**33**, 121, 119, 34, 35, 36, 32, 20, 26, 103, 23, 89
Load Profile 1	**33**, 121,119, 34, 35, 36, 32, 20, 26, 103, 23, 19
Load Profile 2	**33**, 121,119, 34, 35, 36, 32, 20, 26, 103, 23, 19
Load Profile 3	**33,** 121, 119, 34, 35, 36, 32, 20, 26, 93, 103, 23
Load Profile 4	**33**, 121, 119, 34, 35, 36, 32, 20, 26, 103, 23, 19

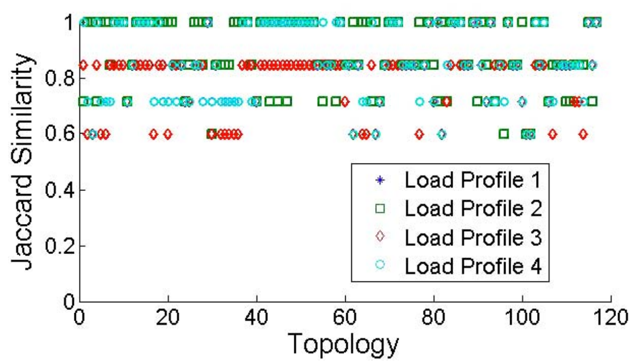

Figure 3. Jaccard similarity of candidate switching actions for different load profiles to relieve overloads.

B. Results for Voltage Violations

Rank lists of $h_V^{k,ij}(\mathbf{u}_0)$ for the same topology with 4 different load profiles are presented in TABLE II. Due to the error in the approximate expression for voltage, we store the top 20% candidate switching actions (24 switching actions) of each rank list.

TABLE II. RANK LIST FOR VOLTAGE VIOLATIONS

Load Profile	Candidate Switching Actions
Base Case	87, **109**, 31, 88, 92, 114, 115, 105, 106, 26, 89, 116, 117, 83. 7, 99, 32, 118, 30, 28, 29, 20, 27, 49
Load Profile1	87, 88, 69, 26, **109**, 99, 34, 30, 89, 114, 115, 7, 118, 116, 117, 92, 85, 49, 31, 105, 106, 32, 23, 21, 22
Load Profile 2	87, 26, 88, **109**, 99, 83, 34, 114, 115, 7, 116, 117, 31, 118, 30, 105, 106, 32, 89, 35, 36, 49, 85, 23
Load Profile 3	87, **109**, 88, 26, 114, 115, 31, 99, 7, 89, 116, 117, 105, 106, 118, 32, 30, 49, 34, 20, 27, 35, 36, 28
Load Profile 4	87, **109**, 31, 114, 115, 26, 88, 99, 106, 105, 116, 117, 7, 83, 89, 32, 92, 118, 30, 20, 28, 29, 27, 49

For the base case, the best corrective switching action is to switch off line 109. If line 109 is switched off, the voltage violation on bus 72 will be totally relieved and there will not be other violations. This switching action is contained in all the rank lists of four load profiles.

For 118 different topologies, the Jaccard similarities of candidate sets for 4 different load profiles with respect to the candidate sets for the base case are plotted in Figure 4. From the results, we can see that the Jaccard similarity gets higher when the load profile is more closed to the base case. For the top 24 switching actions of the base case and load profile 4, there are at most 3 different candidate switching actions.

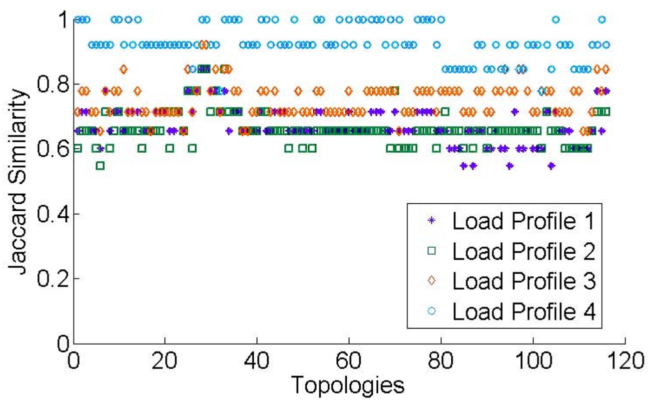

Figure 4. Jaccard similarity of candidate switching actions for different load profiles to relieve voltage violation.

V. CONCLUSIONS

Corrective transmission switching can utilize existing assets of power systems to relieve overloads and voltage violations caused by contingency without incurring additional costs. In this paper, a data mining approach for real-time corrective switching is presented. The algorithm is based on the factorization expression of approximate switching effects. Simulation results show that the factorization expression is more accurate for line overloads. Consequently we need to store more candidate actions for voltage violations than for line overloads. Future works may focus on confirming stability or finding a combination of corrective switching actions instead of single switching actions to relieve violations caused by contingencies. To conclude, the proposed algorithm can find acceptable corrective switching actions which can relieve overloads and voltage violations in an efficient manner.

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