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Effect of Topology Control on System Reliability: TVA Test Case

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SUMMARY

Transmission assets are traditionally treated as static assets in power systems operational studies. Past research efforts have pointed out the advantages of treating the transmission network topology as a flexible asset; however, the flexibility in the transmission system is not fully modeled in existing operational tools (e.g., security constrained unit commitment, security constrained economic dispatch, contingency analysis). Although topology control (TC) is currently being used as a corrective mechanism to relieve violations in the system, the determination of the corrective actions are primarily determined based on ad-hoc methods. Most of the previous studies on TC are based on a DC framework and are tested on small systems. It is very important to test the switching solutions on an AC framework and on actual systems in order to get a real estimate of the actual benefits that could be obtained through TC. In this paper, an AC based N-1 contingency analysis is performed on the Tennessee Valley Authority (TVA) system. The fast decoupled power flow algorithm is used to solve the base case, the contingency case and to evaluate the switching solutions through a complete enumeration procedure. The objective of this research is to estimate the maximum reliability improvement that could be achieved through TC on an actual system by testing it on an AC setting. The TC actions on the TVA system are tested for its ability to reduce voltage violations as well as the thermal violations in the network at a post contingency stage. In the implemented approach, the generators are re-dispatched based on their available reserve capacity for generator contingencies unlike using the traditional assumption of a slack bus, where the loss of a generator is picked up by the slack bus. The results are promising and future work will analyse the effect of the switching solutions on the system stability.

KEYWORDS

Contingency analysis, Corrective topology control, Fast decoupled AC power flow, Transmission switching.

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I. INTRODUCTION

In most of the power system operation studies, the transmission system is considered as a static, uncontrollable asset. However, topology control is frequently used, as a corrective mechanism, to overcome operational issues such as to improve voltage profiles and for congestion management [1-3]. Past research efforts [4-6] have shown that it is possible to reduce losses and achieve economic savings with topology control (TC). It is demonstrated that cost savings could be achieved by co-optimizing transmission topology with generation dispatch [7]. In literature it has been reported that it is possible to achieve cost savings while satisfying N-1 reliability standard with TC [8]. Moreover, it is shown that TC can satisfy a robust N-1 standard while considering the demand side uncertainty [9]. TC is also proposed as a corrective mechanism for N-1 contingencies on a day-ahead framework [10] and for emergency applications with simultaneous contingencies in real-time framework [11].

However, in literature, most of the studies were carried out on small test systems and are based on a DC framework. The challenge is that the TC solutions have to be AC feasible and the system must remain stable with the implementation of the switching actions. A detailed review of AC optimal power flow is given in [12-14]. The active and the reactive power flows in the network are heavily dictated by the parameters of the transmission lines and the system loading. For instance, reactive power flows in the network will be predominant during low loading levels and this could potentially cause over voltages in specific areas of the system. Such situations could be overcome either by switching the shunt reactance in the area to absorb the excess reactive power or by varying the generator excitation or by switching a line out of service that was producing excess reactive power or a combination of all the three approaches. Alternatively, the flexible AC transmission system (FACTS) devices could also be installed in the system, which could change the parameters of the line and help alleviate the violations. Installation of the shunt elements or the FACTS devices in the system is expensive and it cannot be installed throughout the system. As far as the generation excitation control is concerned, the range of reactive power control that could be offered by a generator is limited due to restrictions on its operating limits. Moreover, the reactive power has a localized effect on the system and it does not travel far. Another approach is to employ TC, which provides an additional control over the flow of power; TC can also be used as a congestion management tool to alter power flows. The benefit of topology control is that it does not require the installation of additional expensive devices as TC could be implemented with the help of the circuit breakers which are already installed in the system. However, determining a good topology control solution is computationally challenging as the number of lines in an actual system are in range of few thousands and it is very difficult to choose one TC solution out of the many possible options.

Prior research efforts [15-20] have identified TC as a solution to relieve overloads and voltage violations; the work presented in this paper is an extension to this previous work. The objective of this research is to investigate the potential reliability improvement that could be obtained with TC for an actual large scale system in an AC setting. In this paper, an AC based N-1 contingency analysis is performed and TC is used as a tool to mitigate violations at a post contingency stage. A commercial-grade AC power flow tool [21], based on a fast decoupled power flow, is used to solve the AC power flow for the base case as well as for the contingency analysis. To demonstrate the benefits of implementing TC on an actual large scale system, a complete enumeration study for transmission switching is done to reduce the thermal flow violations and the voltage violations that result from the contingency analysis. Note that all the analysis is done on the system provided by the Tennessee Valley Authority (TVA) and the simulations are performed on an AC framework.

The rest of the paper is structured as follows; Section II describes the day-ahead scheduling procedure with and without topology control. The mathematical model and description for AC contingency analysis tool is presented in Section III. Numerical results associated with the TVA system are presented in Section IV. The conclusions and future work is presented in Section V.

II. PROCEDURE

A. Day-ahead scheduling process

The day-ahead scheduling process begins by solving a security-constrained unit commitment (SCUC) model, which incorporates proxy reserve requirements. SCUC is usually a deterministic model, which captures the transmission network via a direct current optimal power flow (DCOPF). While reserve requirements are used, a reliable solution is not guaranteed. Therefore, the operators need to check the result of SCUC (market model) to ensure reliability. If there are network violations in the base case or contingency analysis, then the process goes back to determine the energy schedule and base case power flow; while this iterative process can continue until a reliable solution is found, due to time constraints, it is frequently not the case that the resulting solution, produced by the market model itself, is reliable. MISO day-ahead scheduling procedure is presented in [22], which is shown in Fig. 1.

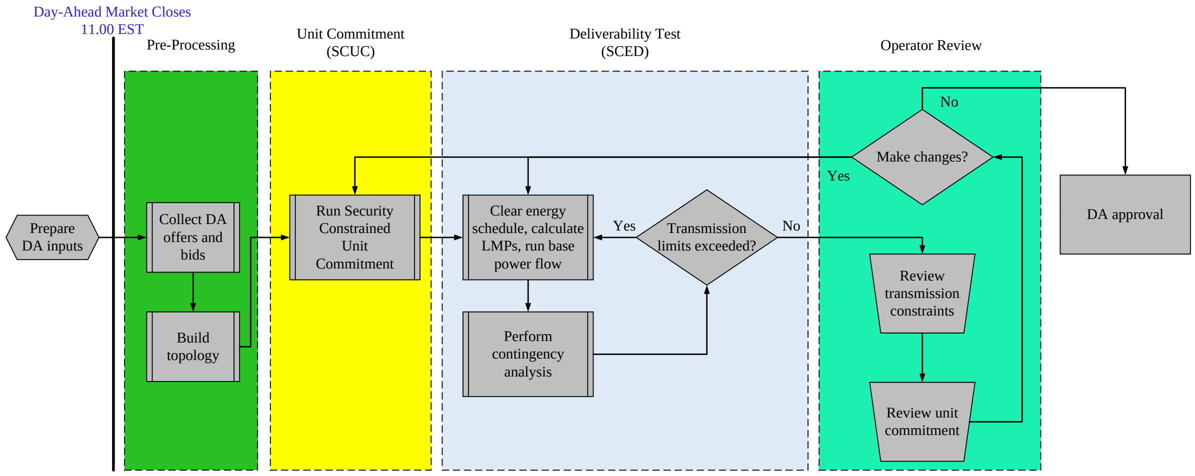


Fig. 1. MISO day-ahead market model [22].

B. Proposed day-ahead scheduling with corrective TC

By implementing topology control in the day-ahead scheduling process, there will be fewer post-contingency violations that the operator must correct in order to achieve N-1 reliability. Today, these corrections occur by either re-running the SCUC or SCED models or by implementing uneconomic adjustments outside of the market engine [23]. By utilizing TC, the operator can control power flow through the network in emergency conditions and avoid violations due to contingencies; as a result, there will be a reduction in the number of SCUC or SCED re-runs. The use of TC will also help to reduce the amount of costly uneconomic adjustments (out-of-market corrections). The proposed day-ahead scheduling process, with corrective TC, is shown in Fig. 2.

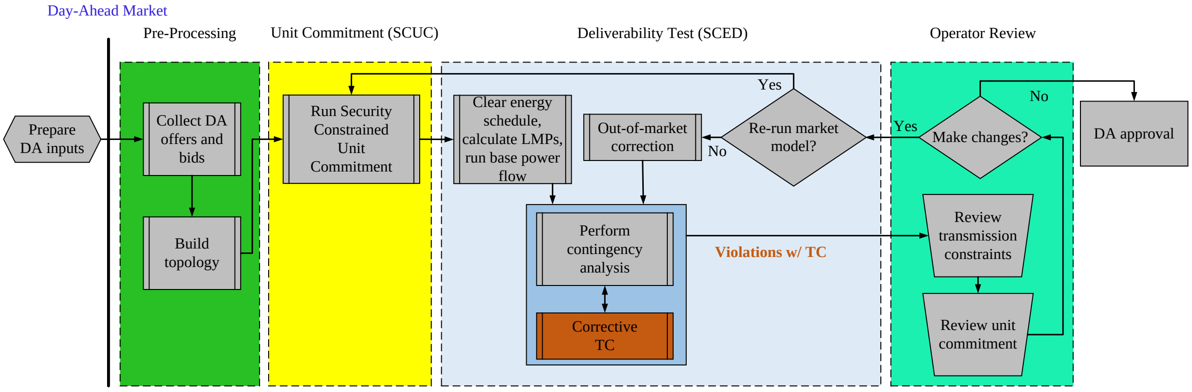


Fig. 2. Day-ahead scheduling with corrective TC

III. MODELING

In the pre-contingency condition, the power system operates without any voltage or flow violations; however, contingencies may cause flow violations and/or voltage violations in the system. Some of the contingencies may have a great impact on system security since they may cause severe violations. Transmission switching is one of the effective ways to handle this. In this paper, in order to find the best switching actions that reduce the violations, a complete enumeration of all possible switching actions is performed.

In a large scale system, there could be thousands of contingencies; however, not all contingencies are critical. Hence, only those contingencies which cause violations beyond a certain threshold are considered for this analysis. A complete enumeration is then performed to find the best switching solutions for the subset of contingencies that are critical as shown in Fig. 3. This procedure can be done offline to analyze all the possible beneficial switching actions corresponding to different contingencies. For this investigation, complete enumeration is simply used to conduct a holistic study of all potential single post-contingency corrective transmission topology control actions and to then analyze the potential improvement in post-contingency violations (or whether to study whether the system becomes worse off). Complete enumeration is not an algorithmic approach that we are proposing for implementation; instead, an optimization based method that intelligently searches for and finds a beneficial switching action very quickly is necessary. Such optimization algorithms are currently being developed and the presentation of those algorithms is left for future publications as this paper is merely presenting results corresponding to this holistic investigation of the impacts of post-contingency corrective transmission topology control.

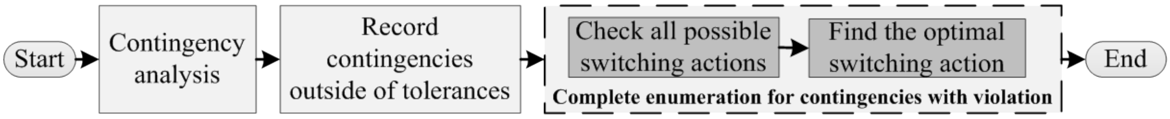


Fig. 3. Complete enumeration of transmission switching.

For the generator contingencies, the assumption that the loss of a generation will be picked up by the slack bus is improper and impractical. Hence, an available capacity-based generator participation factor (for the online generators) is used in this paper as shown in equations (1) and (2),

$$\Delta_{gc} = \frac{P_g^{\max} - P_g^0}{\sum_{\forall g, g \neq c} \left(P_g^{\max} - P_g^0 \right)} \tag{1}$$

$$P_{gc}^1 = P_g^0 + P_c \left(\Delta_{gc} \right) \tag{2}$$

where Δ_{gc} is the participation factor of unit g for contingency c, P_g^0 is the active power output of unit g in the pre-contingency state, $P_g^{\max}$ is the maximum power output that unit g can produce, P_c is the output of the generator that failed due to contingency c,and P_{gc}^1 is the active power output of unit g in the post-contingency state c. Note that this rule can be easily updated to incorporate ramp rates.

Note that all the procedures are carried out with the help of an open source tool [21], which is used to solve the AC power flow for the base case as well as for the contingency analysis. The tool does not have the capability to impose the reactive limits on generators and re-dispatch the generators for generator contingencies; however, the authors of the paper have written subroutines to include these functionalities in the tool.

IV. RESULTS

Corrective TC actions are tested on the TVA system over the data provided for three days (72 hours) of September 2012. The provided dataset is modified to model only the network that is within the TVA system. The network includes 1779 buses, 1708 transmission lines, 321 generators, 299 two-winding transformers, 98 three-winding transformers, and 178 switched shunts. Moreover, the tie line flows and power exchanges between the TVA system and the neighboring areas are also modeled.

First, a security constrained unit commitment (SCUC) model is solved for each day based on the load profile provided by TVA. The required out-of-market corrections (uneconomic adjustments) [23] have been performed on the SCUC solution to guarantee AC feasibility of the base case for all the 72 hours. An AC based N-1 contingency analysis is performed over the AC feasible test case for each hour, which includes a single contingency on lines, transformers or generators. The developed contingency analysis tool reports the voltage violations and the thermal flow violations in the system for the corresponding contingencies. Specific threshold values are considered individually for the voltage violations and the flow violations so that the corrective TC actions are performed only on those contingencies that exceed the specified threshold. This procedure ensures that corrective actions are not considered for negligible violations. The total line flow violation and total voltage violation for each contingency are considered as a metric for initiating corrective TC actions. The results for the N-1 contingency analysis are given in Table I and Table II; note that the threshold for the total line flow violation and the total voltage violation are set to 2 MVA and 0.002 p.u. respectively.

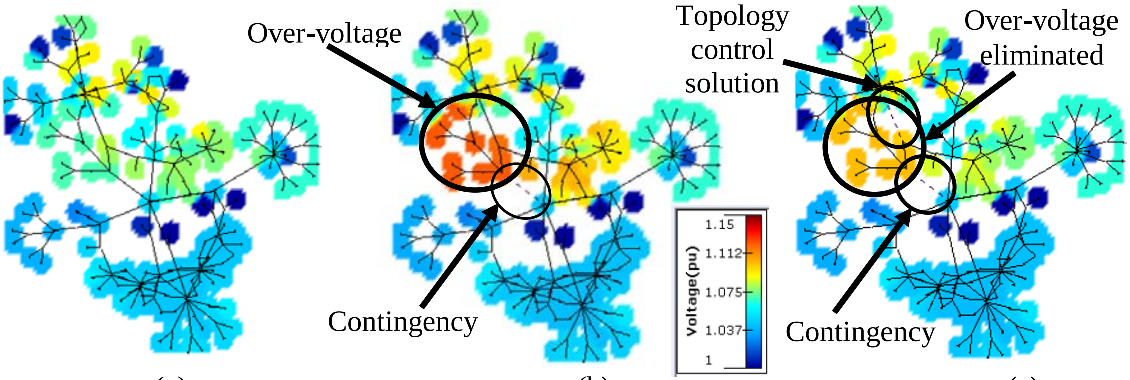
Table I. Results of day-ahead contingency analysis on the TVA system

	Transmission Contingencies	Generator Contingencies
Ave number of contingencies simulated per hour	1530	248
Ave number of non-converged contingencies per hour	1.9	0
Ave number of contingencies with violations per hour	20	64
Ave number of cont. with flow violations per hour	12.3	77
Ave number of cont. with voltage violation per hour	9.2	1.7
Ave number of line violations per contingency per hour	1.5	3.2
Ave number of bus voltage violation per contingency per hour	6.6	1.7

Table II. Cumulative results of day-ahead contingency analysis on the TVA system

	N-1 contingencies
Total number of contingencies with violation	5972
Total number of contingencies with flow violation	5363
Total number of contingencies with voltage violation	736
Ave flow violation on overloaded branches (MVA)	12
Ave voltage violation on buses with violation (p.u.)	0.04

Fig. 4 shows the voltage contour plots for the pre-contingency, contingency, and post-contingency states for a subsection of the TVA system for the worst case contingency in terms of voltage violations. All buses that have an overvoltage problem in the contingency state are the 500 kV buses. All the overvoltage problems are mitigated by implementing a single corrective switching action.



(a) (b) (c)

Fig. 4. Voltage levels in (a) pre-contingency, (b) contingency, and (c) post-contingency state for a sub-section of TVA system.

This particular pre-contingency state corresponds to a lightly loaded period, in which most of the 500 kV lines in this area are lightly loaded compared with its peak-load condition. In the contingency state, the reactive power available within the affected area is more than the requirement, which results in overvoltage in this area. Implementation of TC inherently reduces the excessive flow of reactive power into the affected area and helps to reduce the bus voltages to safe operating limits. Note that, in Fig. 4, for simplicity, only a subsection of the TVA system is shown.

The summary of results with the corrective TC (for a threshold of 2 MVA and 0.002 p.u.) are presented in Table III. From the results it is evident that both flow violations and voltage violations are reduced considerably with the application of corrective TC. Also, out of 5972 contingencies with violations, 17% (1017) of contingencies have no violations with corrective TC action. For these contingencies, TC is able to fully eliminate all the violations with a single transmission switching (post-contingency) solution. The TC solutions are analyzed for different thresholds on flow violations and voltage violations. Fig. 5 and Fig. 6 show the average voltage violation percentage improvement and the average flow violation percentage improvement for various threshold values respectively. In Fig. 5, it is observed that the effect of the MVA violation threshold on average voltage violation percentage improvement is not significant; however, a small increase in average voltage violation percentage improvement is observed with higher MVA threshold. Furthermore, the effect of voltage violation threshold on average voltage violation percentage improvement is roughly constant between 0.1 p.u. to1 p.u. thresholds. In Fig. 6, it is observed that the effect of the voltage violation threshold on the MVA percentage improvement is minimal. The effect of MVA threshold on MVA percentage improvement is considerable. Furthermore, the decrease in MVA percentage improvement from increase in MVA threshold is approximately linear between 10 MVA to 100 MVA thresholds.

Table III. Results of day-ahead contingency analysis for TVA system

Number of contingencies with violations outside of tolerance	5972
Percentage of contingencies where there is NO beneficial corrective switching action	7.3%
Worst case total branch flow violation (no voltage violation for this contingency, MVA)	646
Reduction in the worst case total branch flow violation with topology control	30%
Worst case total voltage violation (no MVA violation for this contingency, p.u.)	3.5
Reduction in the worst case total voltage violation with topology control	16.5%
Ave flow violation reduction per contingency	50%
Ave voltage violation reduction per contingency	53%
Percentage of contingencies with no violation with corrective TC	17%

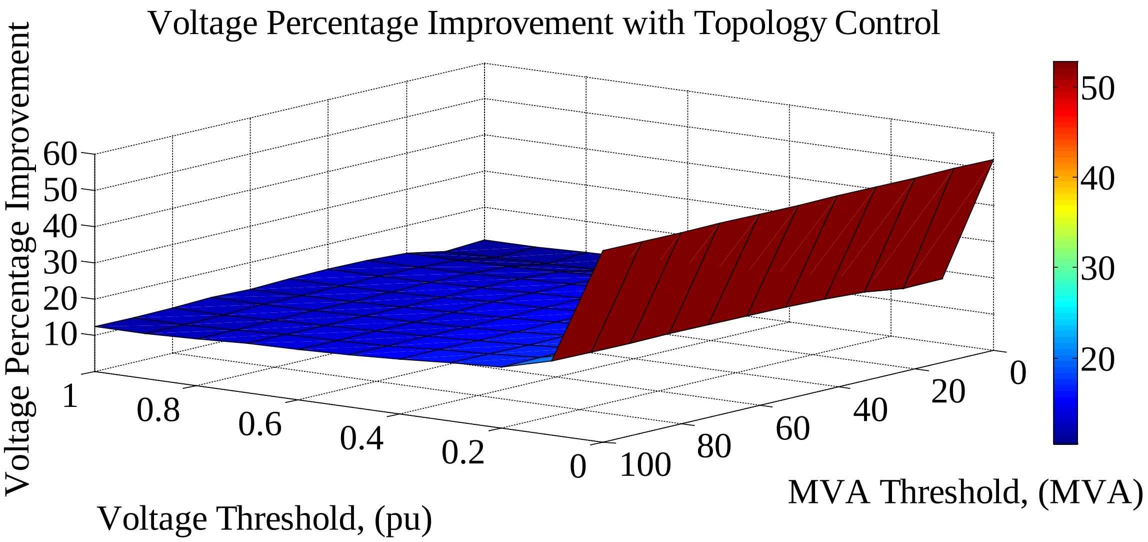


Fig. 5. Average voltage percentage improvement for various thresholds.

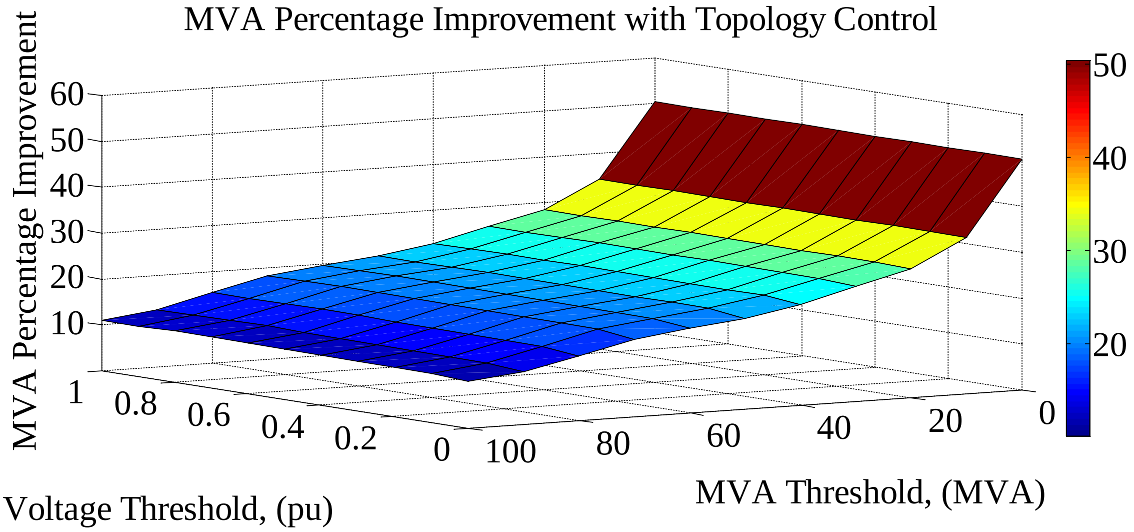


Fig 6. Average flow violation percentage improvement for various thresholds.

V. CONCLUSION AND FUTURE WORK

Today, in most of the power system operation studies, system topology is modeled as a fixed asset over which the operator does not have control. However, changing the system topology for short term benefits such as to respond to contingencies may have substantial benefits in terms of cost and operational flexibility. Numerical results, presented in this paper, demonstrate that 17% of the N-1 contingencies, which have violations, can be completely eliminated through corrective TC. Furthermore, only 7.3% of contingencies do not benefit due to corrective TC. These results project the benefits of TC on the system operations and emphasize the additional flexibility that TC could provide to the operator, which is presently absent.

Future work will involve studying the effect of topology control solution on system stability. Furthermore, it will also involve developing a methodology to determine the corrective TC actions instead of performing a complete enumeration, which would largely speed-up the computational performance.

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