Transmission System Reconfiguration for Congestion Management Ensuring Transient and Voltage Stability

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***Abstract*—Transmission congestion management has been an important issue to power system operators and planners. As of the remedial/preventive actions, transmission reconfiguration has been employed to relieve congestion. In this paper, a methodology is proposed which optimally determines the system configuration to relieve congestion while respecting system security limits such as N-1 contingency criteria, voltage limits, voltage stability margin and transient stability. Most of these important criteria have been overlooked in the previous literature. The corresponding problem is solved using Benders decomposition method. The proposed methodology is evaluated using the IEEE 300-bus test system.**

***Index Terms*—Transmission congestion management, transmission reconfiguration, transient stability, voltage stability.**

I. Introduction

Electrical transmission systems are vital parts of power systems which provide paths between generations and loads. It is always desirable to transmit power through these paths without violating system security criteria. The transmittable power between two points in a network is confined by several security criteria such as voltage limits, lines thermal limits and stability limits. In the case that energy cannot be transmitted from one part to another part of a network due to restriction imposed by one or more of the mentioned criteria, congestion occurs [1].

In a congested system, the low-cost generation units may not be able to be fully dispatched which may even lead to higher energy prices compared to the uncongested system. This problem is typically handled by means of transmission congestion management schemes which are mostly based on conventional optimal power flow (OPF) minimizing functions such as: number of control actions, cost of re-dispatch, or deviations between pre- and post-dispatch systems [2],[3].

One of the important and suitable solutions for congestion management is the optimal network reconfiguration which has been employed by system operators, mostly based on engineering knowledge and experience. From time to time, the network operators change the network topology in order to enhance system security. The network switching actions are classified into two main categories: opening/closing branches and substation switching [4].

In order to show the effect of transmission switching on the total generation cost (TGC), an illustrative example is given here. Consider the 3-bus system shown in Fig. 1(a). All the lines have the same admittance (y) and the power flow limits through the lines are 400, 50 and 400 MW for Lines 1-2, 1-3 and 2-3, respectively. The supply bid prices (SBP) are also given in the figure. A DCOPF solution for this system is reported in Fig. 1(a). The system configuration does not allow the low-cost generator to be further dispatched and hence, the generation cost has reached \$27,500/hr. Now, assume that Line 1-3 is disconnected. The DC optimal power flow (DCOPF) results for this case are also calculated, as given in Fig. 1(b). The generation cost is reduced to \$8,000/hr (70.91% reduction) and Gen. 1 supplies the total demand. This illustrative example demonstrates the remarkable impact of transmission switching (TS) on the generation cost. Nevertheless, transmission congestion may not always lead to higher nodal prices.

Some research work has been carried out on the application of switching for network reconfiguration. TS was first introduced in [5], in which it was used as a tool for preventive control actions. The authors in [6] have used corrective switching to relieve line overloading. In [7], DC load flow and line outage distribution factors are used to determine the line outage that would eliminate network congestions without making overloads in other parts of the system. The busbar reconfiguration is also utilized to solve the branch overload problem in [8]. The z-matrix method is employed in [9] for finding the most influential lines to be switched off-line to resolve overloading problems. In [10], a sensitivity matrix is used to find the line(s) switching which has the largest impact on overloaded line(s); however, it is not always possible to open the proposed lines without violating system operation criteria. A discrete optimization algorithm has been employed in [11] to find optimal switching actions which alleviate overloads while avoiding potential over/under voltage

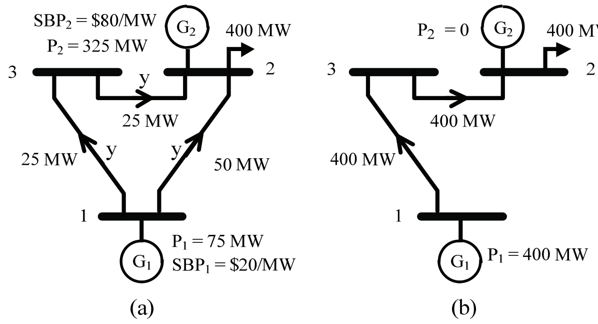

Figure 1. The 3-bus test system: (a) DCOPF results; (b) DCOPF results after Line 1-2 outage.

conditions. The authors in [12] have proposed a method which uses analytical equivalence of corrective switching for a systematic search to enhance system security.

Reference [13] provides a comprehensive review about the concept of corrective switching actions. The authors in [14] have proposed an approach based on DCOPF which utilizes TS in order to remove congestion. They have also considered $N-1$ line outage contingency criterion where the problem is formulated as a mixed-integer linear programming problem [15]. The application of TS in transmission expansion planning is also shown in [16] where switching action is employed as a powerful tool for maintaining system security and decreasing the operation cost. However, they have not examined the impact of switching on neither important system variables, such as bus voltage magnitudes and transmission losses, nor system security, such as transient and voltage stability. A DCOPF followed by an ACOPF is used in [17] which alleviates congestion and takes into consideration the impacts of switching on AC criteria. Since the optimal TS is selected based on a DC model, it is very likely that the proposed line outage would not be feasible in an AC model. Hence, in this paper, an optimal TS based on an ACOPF is used which does not suffer from the mentioned shortcomings in [15], [16]. The optimal reconfiguration of transmission system considering voltage limits and $N-1$ security criterion has been studied in a recent publication [18]. In this paper, the importance of considering other system security limits in the framework of transmission reconfiguration is shown and a multi-stage optimization problem is formulated to address these issues. The act of opening a loaded transmission line would certainly be followed by transient oscillations in synchronous generators. The resulted rotor angle oscillations may not be well-damped in all cases and power system static analysis including power flow studies are not able to check system transient stability conditions. In addition, an intentional line outage might also cause voltage stability issues. Although the mentioned byproducts of any TS are of crucial importance, they have been overlooked by previous studies. In this paper, these criteria are examined when a switching action is proposed.

This paper is organized as follows: Section II provides a background on power system transient stability assessment and voltage stability limit. Section III describes the proposed method which is then evaluated in Section IV. Also, the obtained results are compared to those of previous literature in Section IV. Section V summarizes the main contributions of this work.

II. Background

A. Power System Transient Stability

Power systems dynamics are described using a set of differential-algebraic equations (DAEs) [19]. In order to avoid solving the DAEs, it is also possible to approximately assume a limit on bus voltage angles, which has usually been calculated off-line for a specific system configuration and load level:

$$\delta_i^{\min} \leq \delta_i \leq \delta_i^{\max} \quad , i = 1, \ldots, n. \tag{1}$$

However, this method is only an approximation and is not applicable when the configuration or operating point is changed. Therefore, the exact transient stability assessment in the time-domain is inevitable. For transient stability analysis in this paper, loads are modeled as constant impedances and the admittance matrix reduction technique is used to reduce the size of admittance matrix. The classical model of synchronous generator is used here to model the dynamic behavior of the machines, as follows:

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}(P_m - P_e) \tag{2}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{3}$$

where δ, ω are the rotor angle and speed, respectively; H is the machine inertial; P_m is the mechanical power and P_e is the electrical power calculated using the network algebraic equations. The trapezoidal rule of integration is used to solve the DAEs.

B. Power System Voltage Stability Margin

In some cases, especially after a contingency, it is possible that the transmission system would not be able to transmit power to supply the grid's demand, which eventually would lead to voltage collapse. This means that all bus voltage magnitudes rapidly decrease below desired values. A measure for evaluating the system voltage stability margin is the maximum loadability, which can be found using continuation power flow method. This method along with several solution approaches are described in [20]. The overall procedure is to stepwise increase the whole power system loads by a factor (λ) and continue this increment until no power flow solution exist and system undergoes voltage collapse. At this point, λ is the maximum loadability ($\lambda_{\max}$) associated with the voltage collapse point. In this paper, the predictor-corrector method is employed and the so-called P-V curves (voltage magnitude versus λ) are calculated to find the voltage stability margin.

In the continuation power flow formulation, the constant loads are replaced by:

$$P_L = P_L^0 + \lambda \Delta P \ , \ Q_L = Q_L^0 + \lambda \Delta Q \tag{4a}$$

$$P_G = P_G^0 + \lambda \Delta P \tag{4b}$$

in which P_L, Q_L are the load active and reactive power, respectively; P_G is the generator active power; ΔP is the small step in in the load/generation variation; The zero superscript indicates the initial values. By increasing λ by small steps, a new power flow solution is attained. A tangent predictor is then used to estimate next solution. The corrector calculates the correct solution using Newton-Raphson power flow computation method [20]. The process terminates when the tangent corrector is zero.

III. Proposed Approach

In this paper, optimal TS is formulated as a mixed integer programming problem in a similar way as described in [18]. Regarding the proposed method in [18], it is not practical to decide to open any transmission line(s) just based on system static studies. If a particular line is suddenly disconnected, the system generators undergo rotor angle oscillations which may result in transient instability. Besides, losing a transmission line, especially at peak demand, may reduce the system voltage stability limit ($\lambda_{\max}$). The raised challenges to the proposed optimal TS scheme in [18] are addressed in this paper.

The problem formulation and solution methodology using the Benders decomposition are fully described in [18] and due to lack of space are not reproduced here. In this study, two new stages are added to the formulation of the problem which ensure the transient stability and voltage stability. Overall procedure of the new formulation is described in Fig. 2.

A brief description of the Benders decomposition for present work is given here. The Master problem determines the candidate lines for switching and active power generation of each unit as well as bus voltage angles (Fig. 2, MIP results), which is a mixed-integer linear programming problem. Only line flow violations are considered in Master problem and, therefore, bus voltage violations and reactive power distribution are considered in Subproblem 1. Also, the $N-1$ contingency criteria is evaluated in Subproblem 2. Violations in the Subproblems can be addressed by readjusting the active power generations or modifying the switching actions. Violations in Subproblem 2, transient stability check or voltage stability check may also need adding a new constraint given in (5) which prevents reproducing the same set of switching actions in the next iterations. This new constraint is defined as

$$\sum_{i.j \in C} z_{ij} > 0 \tag{5}$$

where z_{ij} stands for the status of line i-j ("On"/"Off"), and C is the set of the last determined candidate lines for outage which is not acceptable. This means that z_{ij} (for $ij \in C$) cannot be zero simultaneously. This does not allow the program to reproduce the same combination of switching actions in the next iteration.

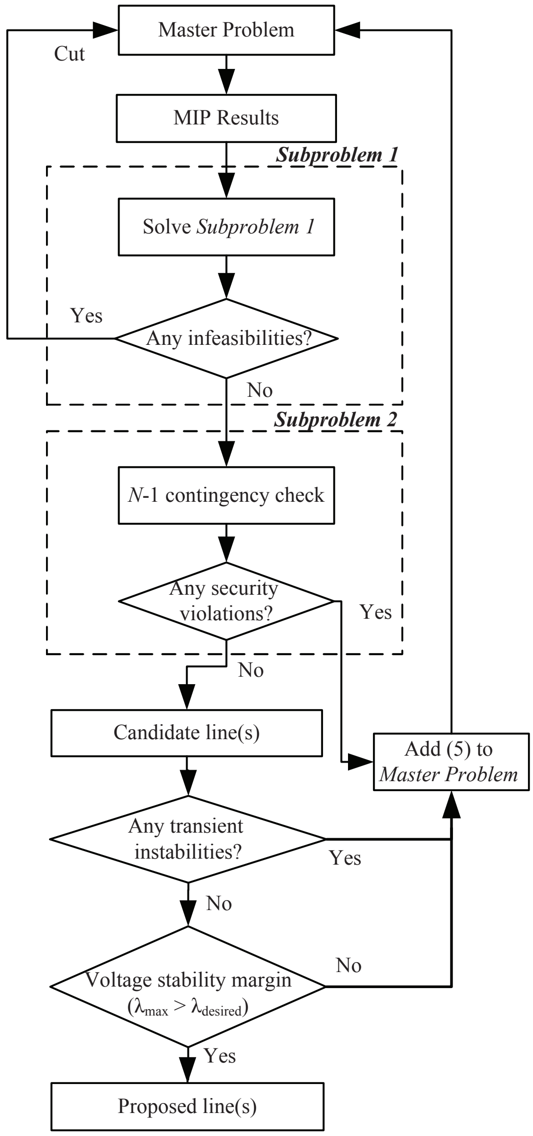

Figure 2. Block diagram representation of the proposed multi-stage algorithm using Benders Decomposition.

IV. Simulation Results

In order to show the applicability of the proposed method, the IEEE 300-bus test system is used. This system consists of 69 generators, 411 transmission lines, $23525.8 + j7788$ MVA loads. Load flow data for this system is available in [22]. Appropriate values for line flow limits are selected to make the system congested. The initial ACOPF indicates that Lines 216-116, 199-108 and 42-80 are congested with Lagrange multipliers (η) as \$31.34/MWh, \$72.26/MWh, and \$14.27/MWh, respectively. First, TS based on DCOPF as used in [14] and [21] is employed. Second, the optimal TS based on the proposed algorithm in this paper is used. All the formulations are implemented in GAMS environment [23].

1) DCOPF Method: Based on DCOPF method proposed in [14] and [21], the candidate switching actions are calculated and reported in Table I for different number of switching

Table I
OPTIMAL SWITCHING ACTIONS OBTAINED USING THE DCOPF METHOD ([14], [21]) FOR THE IEEE 300-BUS SYSTEM.

F	TGC ($/h)	C	η ($/MWh)		
			80-104	108-109	116-28
0	334382.3	-	13.20	49.78	40.18
1	321829.7	{116-28}	10.22	14.88	Open
2	318249.2	{116-28, 116-119}	4.70	0	Open
3	318084.0	{116-28, 116-119, 135-72}/{116-28, 116-119, 1-126}/etc	0	0.87	Open

Table II
OPTIMAL SWITCHING ACTIONS OBTAINED USING THE PROPOSED METHOD FOR THE IEEE 300-BUS SYSTEM.

F	TGC ($/h)	C	$\lambda_{\max}$	LMP ($/MWh)				Total Loss		η($/MWh)		
				min	max	μ	σ	P(MW)	Q(MVAR)	80-104	108-109	116-28
0	353687.8	-	1.38	10.0	41.2	20.6	4.95	591.9	6628.9	14.3	72.3	31.3
1	346785.2	{108-109}	1.31	10.2	29.7	19.2	2.7	518.3	6421.4	22.9	Open	16.7
2	342905.3	{108-109, 80-104}	1.25	10.2	23.3	19.0	1.78	483.4	6263.7	Open	Open	15.4
3	342855.1	{108-109, 80-104, 1-77}	1.21	10.2	23.3	19.0	1.77	480.6	6384.4	Open	Open	15.4

actions (F). For $F = 1$, the first proposed line is {116-28} which has reduced the objective by 3.75%. However, disconnection of this line would make the system transiently unstable, as shown in Fig. 3. Besides, Bus 28 has only two connections, namely 28-116 and 28-167. Therefore, loosing Line 28-116 would leave this bus with only one connection which is not acceptable from the viewpoint of system security. The proposed lines for $F = 2$ are also inapplicable because the first line, i.e. 28-116 is not acceptable. For $F = 3$, several sets of candidate lines with exactly the same objective values are found by changing the initial values. This means that all these actions would totally relieve the congestion and since no losses are assumed, the objective is the same for all these switching actions.

The minimum requirement for maximum loadability ($\lambda_{\max}$) is a parameter which is highly dependent on the system under study. For this test system, the minimum requirement for $\lambda_{\max}$ is assumed as 1.2 (20% loadability). With this assumption, some other switching actions proposed by the DCOPF method turn to be unacceptable. For example, {116-28, 116-119, 135-72} leads to $\lambda_{\max}$ = 1.08, as shown in Fig. 4.

As shown above, the suggested TS actions by the DCOPF method are not applicable when more realistic criteria are taken into account.

2) Proposed Method: Using the proposed method, applicable switching actions are determined and reported in Table II. The first switching action would reduce the objective by 1.95%, which is lower than the objective for the same value of F in DCOPF method. Observe that Line 116-28 is removed from the candidate lines by (5) because of violating the transient stability check. For $F = 2$, Line 80-104 is added to the first proposed line which would reduce the total generation cost (TGC) by 3.61%. Here, η_{80-104} and $\eta_{108-109}$ are reduced to zero and η_{116-28} has also been reduced from $31.34/MWh to $15.36/MWh (i.e. 51% reduction). This would also drastically decrease the congestion rent imposed to the market participants. The locational marginal price (LMP) variation over system buses has also been reduced after applying the switching actions. For instance, standard deviation of LMPs has been reduced from 4.95 to 1.77, i.e. 64.2% reduction. For $F = 3$, Line 1-77 is added to the previously identified lines. Here, the decrease in the objective is minor which is actually due to the reduction in active losses. Observe that, as opposed to the previous switching actions, the reactive losses have been increased and η_{116-28} has also been slightly increased. This means that there is no more switching actions that can relieve congestion without violating considered security criteria.

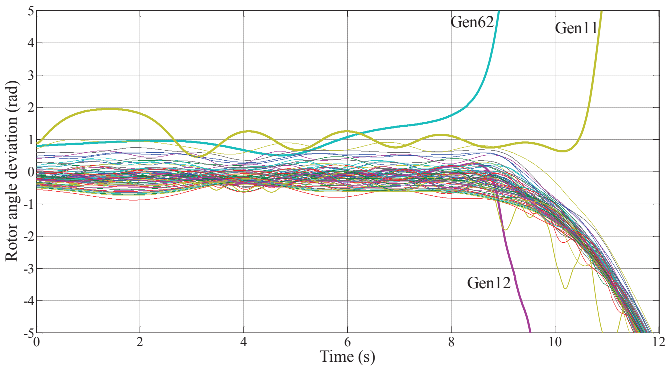

Figure 3. Rotor angle deviation for the IEEE 300-bus test system; Line 116-28 is disconnected at t = 0.

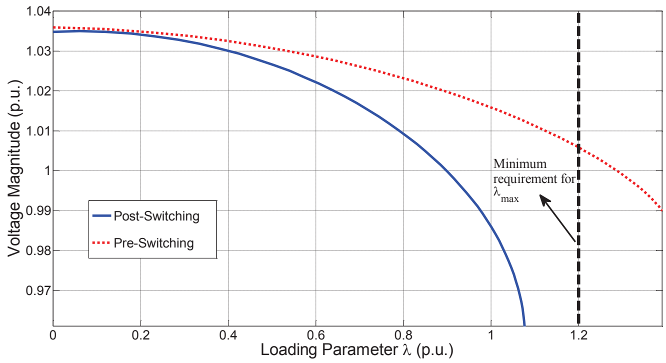

Figure 4. P-V curve for Bus 144 in the IEEE 300-bus system for pre- and post-switching systems; Lines 116-28, 116-119 and 135-72 are disconnected.

It should be noted that as a line is removed, $\lambda_{\max}$ is decreased. Here, a limit of 1.2 is assumed for the minimum value of $\lambda_{\max}$; thus the proposed lines for $F = 2$ and 3 are acceptable. Besides, for the proposed TS actions in Table II, the system shows stable transient behavior.

V. CONCLUSIONS

In the presented work, important issues regarding the opening of a transmission line such as power system transient stability, voltage stability, voltage security and $N-1$ contingency criteria are taken into account when proposing a switching action. The deficiencies of the previously proposed approaches for optimal reconfiguration and the superiority of the proposed method over those approaches were demonstrated using a test system. For instance, by using previously proposed switching methods in the literature, one may trigger first swing/multi swing transient instability.

The main contributions of this paper are summarized as follows:

- Transmission reconfiguration is used as an effective tool to reduce extra generation costs imposed due to transmission congestion or system losses.
- AC power flow constraints including voltage security and line flow limits are respected in the formulation.
- $N-1$ contingency criteria is respected for both pre- and post-switching systems.
- Power system transient stability is checked using time-domain simulations upon opening proposed transmission line(s).
- Voltage stability margin is computed for the post-switching system to ensure enough stability margin.

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