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"Planning Reconfigurable Reactive Control for Voltage Stability Limited Power Systems"
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Reactive Power Control Planning to Increase Voltage Stability Margin

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***Abstract*—Voltage instability has been a cause of several recent major power outages worldwide. This paper presents a successive mixed integer programming (MIP) based method of reactive power control planning to increase voltage stability margin under a set of contingencies. The backward/forward search algorithm and voltage stability margin sensitivities are used to select candidate locations for switched shunt and series capacitors. Optimal locations and amounts of new reactive power controls are obtained by solving a sequence of mixed integer programming problems. The effectiveness of the method is illustrated using the New England 39 bus system. The results show that the method works satisfactorily to plan reactive power controls.**

Keywords-mixed integer programming (MIP); reactive power control planning; voltage stability margin

I. INTRODUCTION

Voltage instability is one of the major threats to power system operation [1]. Severe contingencies such as tripping of heavily loaded transmission lines or outage of large generating units can cause voltage instability when no new equilibrium of the power system exists (i.e. the voltage stability margin is negative) after contingencies. In face of the loss of equilibrium voltage instability, switched shunt and series capacitors are generally effective control candidates [1]-[3].

The potential for moderate contingencies often leads to small voltage stability margins [4]-[8]. We need to add more reactive power control devices to increase the voltage stability margin to be greater than a pre-specified value. The reactive power control planning problem can be formulated as follows: minimize the installation cost of reactive power control devices subject to voltage stability margin and/or transient voltage dip requirements under a set of contingencies.

In this paper, a method is presented for the reactive power control planning to increase post-contingency voltage stability margin. Mechanically switched shunt and series capacitors are used as the reactive power control means. Instead of considering only the most severe contingency or considering several contingencies sequentially [9] the proposed planning method considers multiple contingencies simultaneously. The backward/forward search algorithm with linear complexity is used to select candidate control locations. An initial mixed integer linear programming (MILP) formulation using voltage stability margin sensitivities is proposed to estimate reactive power control locations and amounts from the candidates. The objective function of the MILP is to minimize the total installation cost including fixed cost and variable cost of new controls while satisfying the voltage stability margin requirement under contingencies. A sequence of MILP with updated margin sensitivities is proposed to refine control amounts and/or locations from the initial MILP result until the voltage stability margin requirement is satisfied and there is no significant movement of the decision variables from the mixed integer programming (MIP) solution. The continuation power flow (CPF) program is utilized to check the true voltage stability margin after each MILP. This iterative process is required to account for system nonlinearities. The branch-and-bound and primal-dual interior-point methods [10] are used to solve the optimization problem. Because the optimization formulation is linear, it is fast, yet it provides good solutions for large-scale power systems compared with nonlinear optimization formulations.

The following assumptions are made in this paper:

- The system planner has identified a-priori lines where series compensation would create sub-synchronous resonance (SSR) risk and has eliminated those lines from the list of candidates.
- Voltage magnitude control is addressed as a refinement following identification of the reactive power resources necessary to satisfy the voltage stability margin requirements.

II. ALGORITHM OF REACTIVE POWER CONTROL PLANNING

The proposed reactive power control planning approach requires three stages: (1) select candidate control locations,

(2) use MIP to estimate control locations and amounts from stage 1 locations, and (3) use MIP with updated information to refine control amounts and/or locations from stage 2 locations and amounts. The overall procedure for the reactive power control planning is shown in Figure 1 which integrates the above mentioned steps.

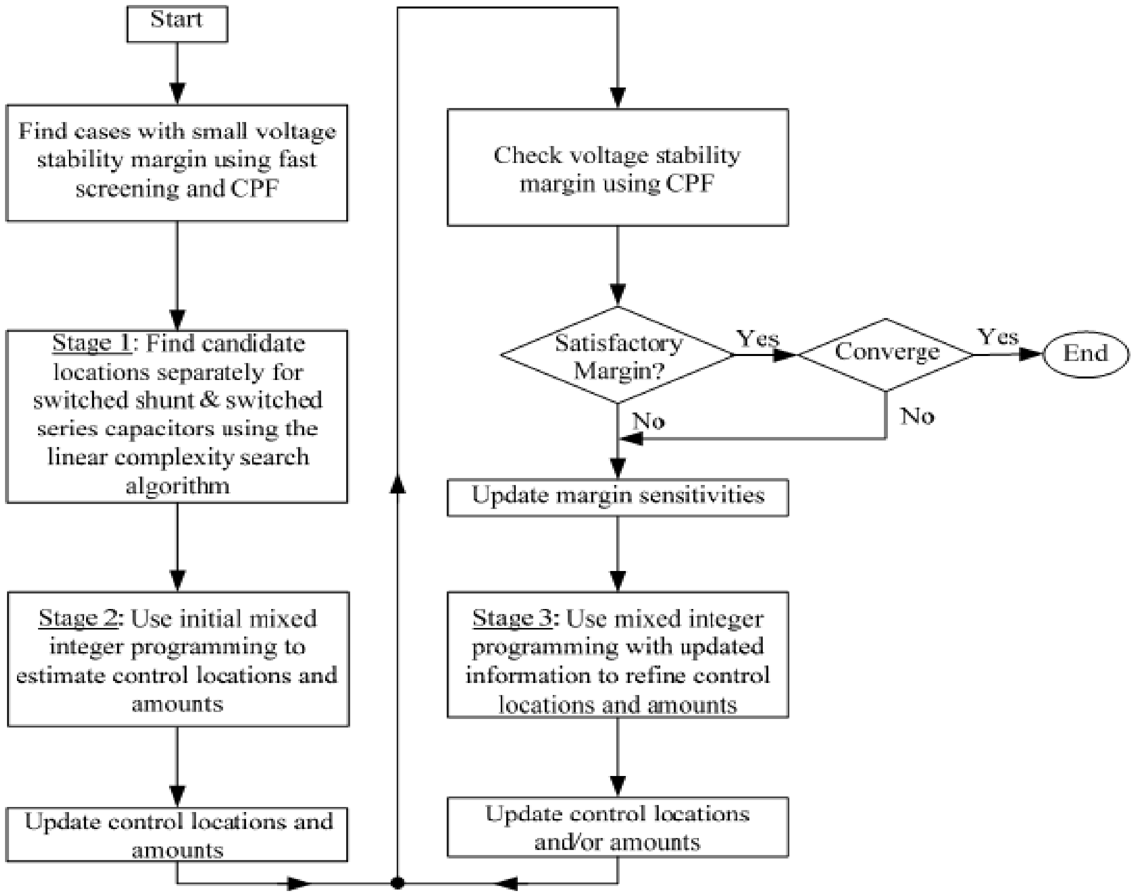

Figure 1. Flowchart for the reactive power control planning to increase voltage stability margin

A. *Selection of Candidate Control Locations*

The backward/forward search algorithm with linear complexity is used to find candidate locations separately for switched shunt and switched series capacitors under every contingency.

B. *Formulation of Initial Mixed Integer Programming*

In stage 1, we find the candidate locations for switched shunt and series capacitors separately. In this stage, we use a mixed integer programming (MIP) to estimate control locations and amounts from candidate control locations. The MIP minimizes the total control installation cost while increasing the voltage stability margin to a required percentage x for each concerned contingency.

minimize

$$J = \sum_{i\in\Omega_1}(C_{vi}B_i + C_{fi}q_i) + \sum_{j\in\Omega_2}(C_{vj}X_j + C_{fj}q_j) \qquad (1)$$

subject to

$$\sum_{i\in\Omega_1} S_i^{(k)}B_i^{(k)} + \sum_{j\in\Omega_2} S_j^{(k)}X_j^{(k)} + M^{(k)} \geq xP_{l0}, \forall k \qquad (2)$$

$$B_{i\min} \leq B_i^{(k)} \leq B_i, \forall k \qquad (3)$$

$$X_{j\min} \leq X_j^{(k)} \leq X_j, \forall k \qquad (4)$$

$$B_{i\min}q_i \leq B_i \leq B_{i\max}q_i \qquad (5)$$

$$X_{j\min}q_j \leq X_j \leq X_{j\max}q_j \qquad (6)$$

$$q_i, q_j = 0,1 \qquad (7)$$

The decision variables are $B_i^{(k)}, B_i, q_i, X_j^{(k)}, X_j,$ and q_j. Here,

- C_{fi} is fixed installation cost and C_{vi} is variable cost of mechanically switched shunt capacitors,
- C_{fj} is fixed installation cost and C_{vj} is variable cost of mechanically switched series capacitors,
- B_i is the size (susceptance) of the switched shunt capacitor at location i,
- X_j is the size (reactance) of the switched series capacitor at location j,

- $q_i = 1$ if location i is selected for reactive power control expansion, otherwise, $q_i = 0$ (the same to q_j),
- the superscript k represents the contingency under which there is insufficient voltage stability margin,
- Ω_1 is the set of candidate locations to install switched shunt capacitors,
- Ω_2 is the set of candidate locations to install switched series capacitors,
- $B_i^{(k)}$ is the size of the shunt capacitor to be switched on at location i under contingency k,
- $X_j^{(k)}$ is the size of the series capacitor to be switched on at location j under contingency k,
- $S_i^{(k)}$ is the sensitivity of the voltage stability margin with respect to the susceptance of the shunt capacitor at location i under contingency k,
- $S_j^{(k)}$ is the sensitivity of the voltage stability margin with respect to the reactance of the series capacitor at location j under contingency k,
- x is an arbitrarily specified voltage stability margin in percentage,
- P_{l0} is the forecasted system load,
- $M^{(k)}$ is the voltage stability margin under contingency k and without controls,
- $B_{i\min}$ is the minimum size of the switched shunt capacitor at location i,
- $B_{i\max}$ is the maximum size of the switched shunt capacitor at location i,
- $X_{j\min}$ is the minimum size of the switched series capacitor at location j, and
- $X_{j\max}$ is the maximum size of the switched series capacitor at location j.

Note that, we identify the minimum set of switched shunt and series capacitors to restore equilibrium points under severe contingencies using the successive MIP. We may then increase the voltage stability margin for these contingencies to the required value along with other contingencies having insufficient voltage stability margin. In order to minimize the total installation cost of switched shunt and series capacitors, the previously identified switched shunt and series capacitors can be utilized to increase the voltage stability margin for other contingencies. For example, if B_i amount of switched shunt capacitor is identified at location i and $B_i^{(k)}$ amount ($B_i^{(k)}$ can be zero under other contingencies) of switched shunt capacitor at location i needs to be switched on under contingency k to restore the equilibrium point, there will be no cost for using $B_i - B_i^{(k)}$ and no fixed cost for using $B_{i\max} - B_i$ to increase the voltage stability margin. Consequently, the fixed as well as variable cost for $B_i - B_i^{(k)}$ is set to be zero and the fixed cost for $B_{i\max} - B_i$ is set to be zero in the above MIP problem.

For k contingencies that have the voltage stability margin less than the required value and n selected candidate control locations, there are $n(k+2)$ decision variables and $k+3n+2kn$ constraints. The computational cost for solving the above mixed integer programming formulation is not high even for large-scale power systems. The branch-and-bound and primal-dual interior-point methods are used to solve this mixed integer programming problem.

The output of the mixed integer programming problem is the control locations and amounts for all k contingencies and the combined control location and amount. Then the network configuration is updated by switching in the controls under each contingency. After that, the voltage stability margin is recalculated using CPF to check if sufficient margin is achieved for each concerned contingency. This step is necessary because the voltage stability margin nonlinearly depends on control variables, and our mixed integer programming algorithm uses linear margin sensitivities to estimate the effect of variations of control variables on the voltage stability margin. As a result, there may be contingencies that have insufficient voltage stability margin after updating the network configuration according to results of the initial mixed integer programming problem. Also, the obtained solution may not be optimal after one iteration of MIP. The control locations and/or amounts are further refined by recomputing margin sensitivities (with updated network configuration) under each concerned contingency, and solving a second-stage successive MIP with updated information, as described in the next subsection.

C. *Formulation of MIP with Updated Information*

The successive MIP is formulated to minimize the total control installation cost subject to the constraint of the voltage stability margin requirement, as follows:

minimize

$$J = \sum_{i\in\Omega_1} (C_{vi}\overline{B}_i + C_{fi}\overline{q}_i) + \sum_{j\in\Omega_2} (C_{vj}\overline{X}_j + C_{fj}\overline{q}_j) \quad (8)$$

subject to

$$\begin{aligned} &\sum_{i\in\Omega_1} \overline{S}_i^{(k)} (\overline{B}_i^{(k)} - B_i^{(k)}) + \\ &\sum_{j\in\Omega_2} \overline{S}_j^{(k)} (\overline{X}_j^{(k)} - X_j^{(k)}) + \overline{M}^{(k)} \geq xP_{l0}, \forall k \end{aligned} \quad (9)$$

$$B_{i\min} \leq \overline{B}_i^{(k)} \leq \overline{B}_i, \forall k \quad (10)$$

$$X_{j\min} \le \overline{X}_j^{(k)} \le \overline{X}_j, \forall k \qquad (11)$$

$$B_{i\min}\overline{q}_i \le \overline{B}_i \le B_{i\max}\overline{q}_i \qquad (12)$$

$$X_{j\min}\overline{q}_j \le \overline{X}_j \le X_{j\max}\overline{q}_j \qquad (13)$$

$$\overline{q}_i, \overline{q}_j = 0,1 \qquad (14)$$

The decision variables are $\overline{B}_i^{(k)}, \overline{B}_i, \overline{q}_i, \overline{X}_j^{(k)}, \overline{X}_j$, and $\overline{q}_j$. Here,

- $\overline{B}_i$ is the new size of the switched shunt capacitor at location i,
- $\overline{X}_j$ is the new size of the switched series capacitor at location j,
- $\overline{q}_i$ and $\overline{q}_j$ are new binary control location variables,
- $\overline{S}_i^{(k)}$ is the updated sensitivity of the voltage stability margin with respect to the susceptance of the shunt capacitor at location i under contingency k,
- $\overline{S}_j^{(k)}$ is the updated sensitivity of the voltage stability margin with respect to the reactance of the series capacitor at location j under contingency k,
- $\overline{B}_i^{(k)}$ is the new size of the switched shunt capacitor at location i under contingency k,
- $\overline{X}_j^{(k)}$ is the new size of the switched series capacitor at location j under contingency k, and
- $\overline{M}^{(k)}$ is the updated voltage stability margin under contingency k.

The above successive MIP will end until all concerned contingencies have satisfactory voltage stability margin and there is no significant movement of the decision variables from the previous MIP solution.

III. Numerical Results

The proposed method has been applied to the New England 39-bus system shown in Figure 2. In the simulations, the following conditions are implemented unless stated otherwise:

- Loads are modeled as constant power;
- In computing voltage stability margin, the power factor of the load bus remains constant when the load increases, and load and generation increase are proportional to their base case value;
- The system MVA base is 100;
- Required voltage stability margin is assumed to be 10%;
- The parameter values adopted in the optimization problem are given in Table Ⅰ.

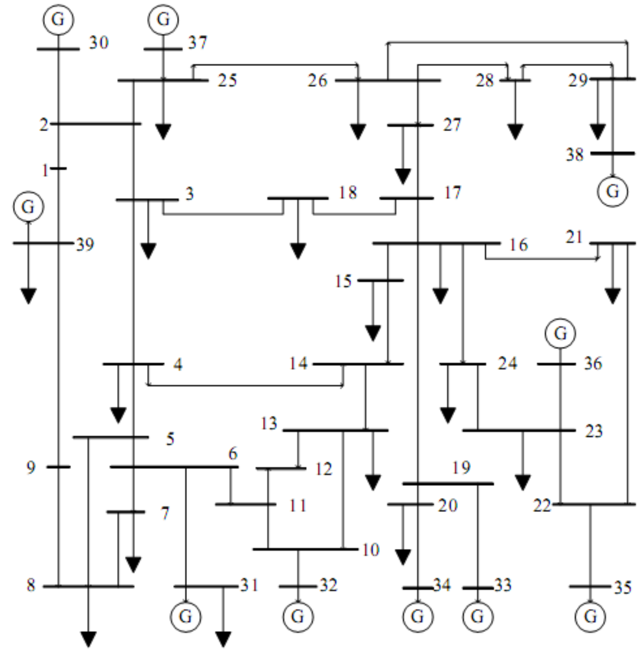

Figure 2. New England 39-bus test system

TABLE I. Parameter Values in the Optimization Formulation

	Shunt capacitor	Series capacitor
Maximum size (p.u.)	1.5	70% compensation
Minimum size (p.u.)	$B_{i\min} = 10^{-3}$	$X_{j\min} = 10^{-3}$

Considering all N-1 contingencies, using the fast contingency screening and CPF methods, there exist 3 contingencies that result in a post-contingency voltage stability margin less than 10% as shown in Table Ⅱ.

TABLE II. Voltage Stability Margin under Three Moderate Contingencies

Contingency	Voltage Stability Margin (%)
(1).Outage of the generator at bus 31	2.69
(2).Outage of the generator at bus 32	2.46
(3).Outage of the generator at bus 35	2.42

The candidate control locations are determined based on the linear search algorithm. The best seven candidate buses to install switched shunt capacitors are buses 5, 6, 7, 10, 11, 12, and 13. The best eight candidate lines to install switched series capacitors are lines 2-3, 3-4, 4-5, 6-7, 8-9, 13-14, 15-16, and 16-19. For these candidate locations, the optimization based reactive power control planning algorithm was carried out.

In order to demonstrate the efficacy of the proposed method, two cases are considered as follows. In case 1, only switched shunt capacitors are chosen as candidate controls while both switched shunt and switched series capacitors are chosen as candidate controls in case 2. Table Ⅲ shows the results for case 1 where the optimal allocations for switched shunt capacitors are 0.747 p.u., 1.500 p.u., 0.866 p.u., 1.500 p.u. and 1.500 p.u. at buses 5, 6, 10, 11, and 12 respectively. The total cost is $ 9.006 million for the control allocations in case 1. On the other hand, the optimal control allocations for case 2 are shown in Table Ⅳ indicating a switched series capacitor of 0.011 p.u. on line 2-3, a switched series capacitor of 0.025 p.u. on line 8-9 and a switched shunt capacitor of 0.973 p.u. at bus 12. For case 2, the total cost for control allocations is $ 7.326 million which is 18.7% less than that of case 1. This result shows that benefit can be obtained by coordinated planning of different types of discrete reactive power controls. Table Ⅴ gives the verified results of the reactive power control planning with the continuation power flow program. Clearly, the voltage stability margins of the concerned contingencies are all increased to be greater than the required value of 10% under the planned controls. The iteration number in the second column represents the number of times of performing the MIP to get the optimal solution.

TABLE III. CONTROL ALLOCATIONS FOR SHUNT CAPACITORS TO INCREASE VOLTAGE STABILITY MARGIN

Locations for shunt cap.	Maximum size limit (p.u.)	Overall optimal control allocation (p.u.)	Solution to cont. (1) (p.u.)	Solution to cont. (2) (p.u.)	Solution to cont. (3) (p.u.)
Bus 5	1.500	0.747	0.747	0.747	0.747
Bus 6	1.500	1.500	1.384	1.500	1.500
Bus 10	1.500	0.866	0.866	0.866	0.866
Bus 11	1.500	1.500	1.500	1.500	1.500
Bus 12	1.500	1.500	1.500	1.500	1.500

TABLE IV. CONTROL ALLOCATIONS FOR SHUNT AND SERIES CAPACITORS TO INCREASE VOLTAGE STABILITY MARGIN

Locations for shunt and series cap.	Maximum size limit (p.u.)	Overall optimal control allocation (p.u.)	Solution to cont. (1) (p.u.)	Solution to cont. (2) (p.u.)	Solution to cont. (3) (p.u.)
Bus 12	1.500	0.973	0.258	0.361	0.973
Line 2-3	0.011	0.011	0.011	0.011	0.011
Line 8-9	0.025	0.025	0.025	0.025	0.025

TABLE V. VOLTAGE STABILITY MARGIN UNDER PLANNED CONTROLS

Candidate controls	Iteration number for MIP	Voltage stability margin for cont. (1)	Voltage stability margin for cont. (2)	Voltage stability margin for cont. (3)
Shunt capacitors	6	10.01%	10.01%	10.01%
Shunt and series capacitors	3	10.01%	10.01%	10.02%

IV. CONCLUSION

This paper presents an optimization based method of planning reactive power controls in electric transmission systems to satisfy the voltage stability margin requirement under a set of contingencies. The backward/forward search algorithm with linear complexity is used to select candidate locations for switched shunt and series capacitors. Optimal locations and amounts of new switch controls are obtained by solving a sequence of mixed integer programming problems. The effectiveness of the method is illustrated using the New England 39 bus system. The results show that the method works satisfactorily to plan reactive power controls.

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