Planning Reconfigurable Reactive Control for Voltage Stability Limited Power Systems

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***Abstract*—This paper proposes an optimization-based method of planning reactive power control for electric transmission systems to endow them with the capability of being reconfigured to a secure configuration under a list of contingencies. The overall objective function is to minimize the installation cost of new controls such as mechanically switched capacitors, while satisfying the requirements of voltage stability margin and voltage magnitude under a contingency list. The backward/forward search algorithm with linear complexity is used to select candidate locations for switched capacitors. Optimal locations and amounts of new switch controls are obtained by solving a sequence of mixed integer programming problems. The modified New England 39-bus system and a North American power system with 6358 buses are adopted to illustrate the effectiveness of the proposed method.**

***Index Terms*—Mixed integer programming, reactive power planning, reconfiguration, voltage stability.**

I. Introduction

APPROPRIATE long-term planning to strengthen transmission capability is necessary to increase future reliability levels of the electric transmission system. There are three basic options for strengthening transmission systems: 1) build new transmission lines, 2) build new generation at strategic locations, and 3) introduce additional control capability. However, options 1) and 2) have become less and less viable because of the difficulty in obtaining right-of-way and expensive investment of the transmission or generation facilities. As a result, there is a significantly increased potential for application of additional power system control to expand transmission in the face of growing transmission usage. In this paper, we focus on planning reconfigurable reactive power control to increase the voltage stability limit and thus enhance transmission capability in voltage stability limited systems.

There are three basic problems to be addressed for planning reconfigurable reactive power control:

1) when is system enhancement needed;
2) where to implement the enhancement; and
3) how much is the reactive power control needed.

We address the first question using the techniques of continuation power flow (CPF) [1]–[3] and fast contingency screening [4], [5]. The last two questions could be answered under an optimization framework. The problem addressed in this paper is similar to the reactive power planning problem [6]–[11]. Generally, the reactive power planning problem can be formulated as a mixed integer nonlinear programming problem to minimize the installation cost of reactive power devices subject to a set of equality and inequality constraints. In the work described in this paper, however, we explicitly target the planning of reactive power *controls*, i.e., reactive power devices intended to serve as control response for contingency conditions. Instead of considering only the most severe contingency or considering several contingencies sequentially [12], the proposed planning method considers multiple contingencies simultaneously.

Vaahedi *et al.* in [13] presented a dynamic security constrained OPF tool which simultaneously considered voltage magnitude constraints and voltage stability margin constraints under normal and contingency conditions. The tool was based on a three level hierarchical decomposition scheme where each subproblem was solved by the interior point method. The CPF program was used to validate the voltage stability margin. The objective function did not include fixed cost.

Yorino *et al.* in [14] proposed a mixed integer nonlinear programming formulation for reactive power control planning which takes into account the expected cost for voltage collapse and corrective controls. The Benders decomposition technique was applied to obtain the solution.

Feng *et al.* in [15] identified reactive power controls using linear optimization with the objective of minimizing the control cost. The voltage stability margin sensitivity [16]–[18] was used in the formulation. This formulation is suitable to the operational decision making problem. However, fixed installation costs of new controls should be included in the long-term planning problem.

In this paper, a comprehensive methodology is proposed for the long-term reactive power control planning to improve voltage stability and against contingencies. Mechanically switched capacitors are used as the reactive power control means. Such devices have been used for post-contingency control [19]–[26]. Fast contingency screening and continuation power flow techniques are utilized to determine investment years for the necessary network enhancements. A backward/forward search algorithm with linear complexity is used to select

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candidate control locations. A sequence of mixed integer programming (MIP) using voltage stability margin sensitivities and voltage magnitude sensitivities is proposed to obtain optimal reactive control locations and amounts. The objective function of the MIP is to minimize the total installation cost including fixed cost and variable cost of new controls while satisfying the requirements of voltage stability margin and voltage magnitude under normal and contingency conditions. The CPF program is utilized to check the true voltage stability margin and voltage magnitude after each MIP iteration. This iterative process is required to account for system nonlinearities and to improve the optimality of the solution. The branch-and-bound method is used to solve the MIP problem [27]. 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.

- No new lines or transformers are installed or considered in the planning expansion, and generation expansion occurs only at existing generation facilities. These assumptions represent the extreme form of a reliance on control to strengthen/expand transmission capability without building new transmission lines or strategically siting new generation.
- There exists an equilibrium point after a contingency. If this assumption is not satisfied, we first restore the equilibrium point by using minimum amount of reactive power controls [28]–[30].

The paper is organized as follows. Some fundamental concepts of voltage stability margin and margin sensitivity are introduced in Section II. Section III describes the proposed method of the long-term reactive power control planning. Numerical results are discussed in Section IV. Section V concludes.

II. Voltage Stability Margin and Margin Sensitivity

The goal of the paper is to determine locations and amounts for switched capacitors so as to enable improve voltage stability margin. In this section, we formally define the notion of voltage stability margin and its sensitivity to parameters, for we use such sensitivities in determining the desired locations and amounts of reactive power control devices. Voltage stability margin is defined as the distance between the voltage collapse point of the system power-voltage (PV) curve and the forecasted total system real power load as shown in Fig. 1. The potential for contingencies such as unexpected component (generator, transformer, transmission line) outages in an electric power system often reduces the voltage stability margin [31]–[33]. We are interested in finding effective and economically justified reactive power controls to steer operating points far away from voltage collapse points by having a prespecified margin and a satisfactory voltage profile under a set of prescribed contingencies.

Switched capacitors are adopted to improve the voltage stability margin. We think of each such capacitor as a controllable discrete switch that may be switched in or out as needed. Fig. 1 shows the voltage stability margin under different operating conditions and switches (controls).

One question of the reactive power control planning is how much of the control is needed for the requirement of a given

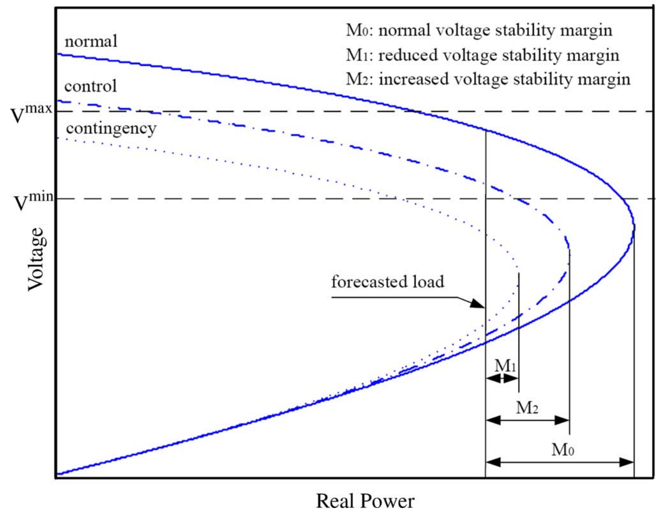

Fig. 1. Voltage stability margin for different operating conditions.

amount of margin increase. One way to answer the question is to use the idea of the (voltage stability) margin sensitivity, which is the change in voltage stability margin with respect to a (small) change in power system parameter or control variable. In the following, the analytical expression of the margin sensitivity is given. Detailed development of margin sensitivity is found in [16]–[18], [34], and [35].

Suppose that the steady state of the power system satisfies a set of equilibrium equations expressed in the vector form

$$F(x, p, \lambda) = 0 \tag{1}$$

where x is the vector of state variables, p is any parameter in the power system steady state equations such as the susceptance of shunt capacitors or the reactance of series capacitors, and λ is the bifurcation parameter which is a scalar. At the voltage collapse point of the system PV curve, the value of the bifurcation parameter is equal to λ^*.

A specified system scenario can be parameterized by λ as

$$P_{li} = (1 + K_{lpi}\lambda)P_{li0} \tag{2}$$

$$Q_{li} = (1 + K_{lqi}\lambda)Q_{li0} \tag{3}$$

$$P_{gj} = (1 + K_{gj}\lambda)P_{gj0} \tag{4}$$

where P_{li0} and Q_{li0} are the initial loading conditions at bus i at the base case, K_{lpi} and K_{lqi} are factors characterizing the load increase pattern, P_{gj0} is the real power generation at bus j at the base case, and K_{gj} represents the generator load pick-up factor.

The voltage stability margin can be expressed as

$$M = \sum_{i=1}^{n} P_{li}^* - \sum_{i=1}^{n} P_{li0} = \lambda^* \sum_{i=1}^{n} K_{lpi} P_{li0}. \tag{5}$$

The sensitivity of the voltage stability margin with respect to the control variable at location i, S_i, is

$$S_i = \frac{\partial M}{\partial p_i} = \frac{\partial \lambda^*}{\partial p_i} \sum_{i=1}^{n} K_{lpi} P_{li0}. \tag{6}$$

If the voltage collapse is due to a saddle-node bifurcation, the bifurcation point sensitivity with respect to the control variable p_i evaluated at the saddle-node bifurcation point is

$$\frac{\partial \lambda^*}{\partial p_i} = -\frac{w^* F^*_{p_i}}{w^* F^*_\lambda} \tag{7}$$

where w^* is the left eigenvector corresponding to the zero eigenvalue of the system Jacobian F_x, F_λ is the derivative of F with respect to the bifurcation parameter λ, and F_{pi} is the derivative of F with respect to the control variable p_i.

If the voltage collapse is due to a limit-induced bifurcation [36], the bifurcation point sensitivity with respect to the control variable p_i evaluated at the critical limit point (as opposed to at the saddle-node bifurcation point) is

$$\frac{\partial \lambda^*}{\partial p_i} = -\frac{w^* \begin{pmatrix} F^*_{p_i} \\ E^*_{p_i} \end{pmatrix}}{w^* \begin{pmatrix} F^*_\lambda \\ E^*_\lambda \end{pmatrix}} \tag{8}$$

where $E(x, \lambda, p) = 0$ is the limit equation representing the binding control limit (i.e. $Q_i - Q_i^{\max} = 0$ representing generator i reaches its reactive power limit), E_λ is the derivative of E with respect to the bifurcation parameter λ, and E_{pi} is the derivative of E with respect to the control variable p_i, w^* is the nonzero row vector orthogonal to the range of the Jacobian J of the equilibrium and limit equations where

$$J = \begin{pmatrix} F^*_x \\ E^*_x \end{pmatrix}.$$

The voltage stability margin sensitivities are updated at each backward/forward search step in Section III-D, and at each optimization iteration in Sections III-E and III-F to account for system nonlinearities.

III. Algorithm of Reactive Power Control Planning

The proposed reactive power control planning approach requires five basic steps: 1) development of generation/load growth future, 2) voltage stability assessment by fast contingency screening and CPF, 3) determination of expansion year, 4) selection of candidate control locations, and 5) development of reactive power control plan by solving the initial and successive MIP problems. The first three steps are described briefly, with more emphasis placed on the fourth and fifth steps.

A. Development of Generation and Load Growth Future

In this step, the generation/load growth future is identified, where the future is characterized by a load growth percentage for each load bus and a generation allocation for each generation bus. The identified generation/load growth future can be easily implemented in the CPF program [1] by parameterization as shown in (2)–(4).

B. Voltage Stability Assessment by Fast Contingency Screening and CPF

We can use the CPF program to calculate the voltage stability margin of the system under each contingency. However, the CPF algorithm is time-consuming. If many contingencies must be assessed, the calculation time is long. The margin sensitivity can be used to speed up the contingency analysis procedure. First, the CPF program is used to calculate the voltage stability margin at the base case, the margin sensitivity with respect to line admittances S_l, and the margin sensitivity with respect to bus power injections S_{pq}. For circuit outages, the resulting voltage stability margin is estimated as

$$M^{(k)} = M^{(0)} + S_l \Delta l \tag{9}$$

where $M^{(k)}$ is the voltage stability margin under contingency k, $M^{(0)}$ is the voltage stability margin at the base case, and Δl is the negative of the admittance vector for the outaged circuits.

For generator outages, the resulting voltage stability margin is estimated as

$$M^{(k)} = M^{(0)} + S_{pq} \Delta pq \tag{10}$$

where Δpq is the negative of the output power of the outaged generators.

Then the contingencies are ranked from most severe to least severe according to the value of the estimated voltage stability margin. After the ordered contingency list is obtained, each contingency is evaluated starting from the most severe one using the CPF program. Evaluation terminates after encountering a certain number of sequential contingencies having voltage stability margin greater than or equal to the required value, where the number depends on the size of the contingency list. A similar idea has been used in online risk-based security assessment [5]. Note that the voltage stability margin sensitivities are used for contingency ranking purpose in this step. The true voltage stability margin under each contingency is calculated using the CPF program.

C. Determination of Expansion Year

Assuming positive load growth but without transmission system enhancement, the voltage stability margin under normal and contingency conditions decreases with time. The year when the voltage stability margin becomes less than the required value is the time to enhance the transmission system by adding reactive power controls.

D. Stage 1: Selection of Candidate Control Locations

An important step in the reactive power control planning problem is the selection of the candidate locations for reactive power control devices. Candidate control locations may be chosen based on experience and/or the relative value of linear sensitivities of new control devices. In this case, however, there is no guarantee that the selected candidate control locations are sufficient to provide needed voltage stability margin for all predefined contingencies. On the other hand, the computational burden to solve the MIP problem presented in Sections III-E and III-F may be high if all buses in a large power system are selected as candidates. To identify a sufficient but not excessive number of locations, the backward/forward search algorithm with linear complexity proposed in [37] can be used to find candidate locations for switched capacitors. It is assumed that the capacity of the switched capacitor at each location is fixed at the maximum allowable value in this stage. The main steps to select appropriate candidate reactive power control locations are as follows.

1) Choose an initial set of control locations using the bisection approach for each identified contingency possessing unsatisfactory voltage stability margin according to the following 3 steps.
   a) Rank the feasible control locations according to the numerical value of margin sensitivity in descending order with location 1 having the largest margin sensitivity and location n having the smallest margin sensitivity.
   b) Estimate the voltage stability margin with top half of the controls switched in as

$$M_{est}^{(k)} = \sum_{i=1}^{\lfloor n/2 \rfloor} B_i^{\max} S_i^{(k)} + M^{(k)} \tag{11}$$

   where $M_{est}^{(k)}$ is the estimated voltage stability margin and $\lfloor n/2 \rfloor$ is the largest integer less than or equal to $n/2$. If the estimated voltage stability margin is greater than the required value, then reduce the number of control locations by one half, otherwise increase the number of control locations by adding one half of the remaining.
   c) Continue in this manner until we identify the minimum set of control locations that satisfies the voltage stability margin requirement.
2) Refine candidate control locations for each identified contingency possessing unsatisfactory voltage stability margin using a backward/forward search algorithm with complexity linear in the number of feasible reactive power controls.
   The backward/forward search algorithm begins at the initial control configuration and searches from that configuration in a prescribed direction, either backward or forward. We give only the backward search algorithm here since the forward search algorithm is similar.
   Consider the graph where each node represents a configuration of discrete controls, and two nodes are connected if and only if they are different in one control. The graph has 2^n nodes where n is the number of feasible controls. We pictorially conceive of this graph as consisting of layered groups of nodes, where each successive layer (moving from left to right) has one more control "on" (or "closed") than the layer before it, and the tth layer (where $t = 0, \ldots, n$) consists of a number of nodes equal to $n!/t!(n-t)!$. Fig. 2 illustrates the graph for the case of four controls. The backward search algorithm has four steps.
   2.1) Select the node corresponding to all controls in the initial set that are closed.
   2.2) For the selected node, use the CPF program to check if the voltage stability margin requirement is satisfied for the concerned contingency on the list. If not, then stop, the solution corresponds to the previous node (if there is a previous node, otherwise no solution exists).

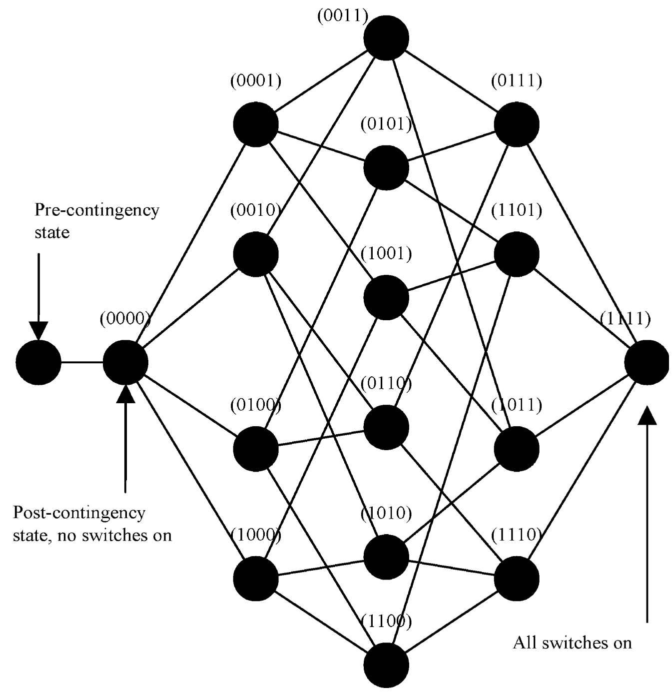

Fig. 2. Graph for four-switch problem.

   2.3) For the selected node, update margin sensitivities and eliminate (open) the control that has the smallest margin sensitivity. We denote this as control i^*

$$i^* = \arg\left\{\min_{i\in\Omega_c} S_i^{(k)}\right\} \tag{12}$$

   where
   $\Omega_c = \{\text{set of closed controls for the selected node}\}$,
   $S_i^{(k)}$ is the margin sensitivity with respect to the size of the switched capacitor at location i under contingency k.
   2.4) Choose the neighboring node corresponding to the control i^* being off. If there is more than one control identified in step 3, i.e., $|i^*| > 1$, then choose any one of the controls in i^* to eliminate (open). Return to step 2.
   If step 2 of the above procedure results in no solution in the first iteration, then no previous node exists. In this case, we extend the graph in the forward direction.
3) Obtain the final candidate control locations as the union of nodes for which voltage stability margin is satisfied, as found in step 2) for every identified contingency.

E. Stage 2: Formulation of Initial MIP

In stage 1, we find the candidate locations for switched capacitors. We use the initial MIP to estimate the locations and amounts of switched capacitors from stage 1 candidates. The MIP minimizes control installation cost while satisfying the requirements of voltage stability margin and voltage magnitude. The multiple contingencies identified in Section III-B are treated simultaneously in the optimization formulation as follows:

$$\text{minimize}$$
$$F = \sum_{i\in\Omega} C_{vi} B_i + C_{fi} q_i \tag{13}$$
$$\text{subject to}$$
$$\sum_{i\in\Omega} S_i^{(k)} B_i^{(k)} + M^{(k)} \geq M_r,\ \forall k \tag{14}$$
$$V_j^{\min} \leq \sum_{i\in\Omega} S_{V,j,i}^{(k)} B_i^{(k)} + V_j^{(k)} \leq V_j^{\max},\ \forall j,k \tag{15}$$
$$0 \leq B_i^{(k)} \leq B_i,\ \forall k \tag{16}$$
$$B_i^{\min} q_i \leq B_i \leq B_i^{\max} q_i \tag{17}$$
$$q_i = 0, 1. \tag{18}$$

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

Variable definition follows.

- C_f is fixed installation cost and C_v is variable cost of switched capacitors.
- B_i: size of the switched capacitor at location i.
- $q_i = 1$ if location i is selected for reactive power control expansion, otherwise, $q_i = 0$.
- Ω: set of candidate locations to install switched capacitors.
- Superscript k represents the contingency causing insufficient voltage stability margin and/or voltage violation problems.
- $B_i^{(k)}$: size of the switched capacitor to be switched in at location i under contingency k.
- $S_i^{(k)}$: sensitivity of the voltage stability margin with respect to the size of the switched capacitor at location i under contingency k.
- $M^{(k)}$: voltage stability margin under contingency k and without controls.
- M_r: required voltage stability margin.
- Subscript j represents the bus with unsatisfactory voltage magnitude.
- $S_{V,j,i}^{(k)}$: sensitivity of the voltage magnitude at bus j with respect to the size of the switched capacitor at location i under contingency k [38].
- $V_j^{(k)}$: voltage magnitude at bus j under contingency k and without controls.
- $V_j^{\min}$: minimum allowable voltage at bus j.
- $V_j^{\max}$: maximum allowable voltage at bus j.
- B_i^{min}: minimum size of the switched capacitor at location i.
- B_i^{max}: maximum size of the switched capacitor at location i.

The inequalities in (14) and (15) are the constraints of voltage stability margin and voltage magnitude, respectively. For the problem having k voltage stability margin violation and m voltage magnitude violation and n selected candidate control locations, there are $n(k+2)$ decision variables and $k + 2m + 3n + 2kn$ constraints. The backward/forward search algorithm provides effective ways to limit the number of candidate control locations and thus to reduce the computational burden for solving the above MIP formulation. The branch-and-bound method is used to solve the MIP problem.

The output of the MIP 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 and the voltage magnitude are recalculated using the CPF program to check if sufficient margin is achieved and voltage magnitude is within the limits for each concerned contingency. This step is necessary because the voltage stability margin and the voltage magnitude nonlinearly depend on control variables, and our MIP algorithm uses linear sensitivities to estimate the effect of variations of control variables on the voltage stability margin and the voltage magnitude. As a result, there may be contingencies that violate the requirements of voltage stability margin and/or voltage magnitude after updating the network configuration according to results of the initial MIP problem. Also, the obtained solution may not be optimal after solving the initial MIP problem. The reactive control amount and location can be further refined by recomputing voltage magnitude, voltage magnitude sensitivities, voltage stability margin and margin sensitivities (with updated network configuration) under each concerned contingency, and solving successive MIP problems with updated information, as described in the next subsection.

F. Stage 3: Formulation of Successive MIP

The successive MIP is formulated to minimize the total installation cost of switched capacitors subject to the constraints of the requirements of voltage stability margin and voltage magnitude, as follows:

$$\text{minimize}$$
$$F = \sum_{i\in\Omega} C_{vi} \overline{B}_i + C_{fi} \overline{q}_i \tag{19}$$
$$\text{subject to}$$
$$\sum_{i\in\Omega} \overline{S}_i^{(k)} \left(\overline{B}_i^{(k)} - B_i^{(k)}\right) + \overline{M}^{(k)} \geq M_r,\ \forall k \tag{20}$$
$$V_j^{\min} \leq \sum_{i\in\Omega} \overline{S}_{V,j,i}^{(k)} \left(\overline{B}_i^{(k)} - B_i^{(k)}\right) + \overline{V}_j^{(k)} \leq V_j^{\max},\ \forall j,k \tag{21}$$
$$0 \leq \overline{B}_i^{(k)} \leq \overline{B}_i,\ \forall k \tag{22}$$
$$B_i^{\min} \overline{q}_i \leq \overline{B}_i \leq B_i^{\max} \overline{q}_i \tag{23}$$
$$\overline{q}_i = 0, 1. \tag{24}$$

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

Variable definition follows.

- $\overline{B}_i$: new size of the switched capacitor at location i.
- $\overline{q}_i$: new binary location variable for switched capacitor at location i.
- $\overline{S}_i^{(k)}$: updated sensitivity of the voltage stability margin with respect to the size of the switched capacitor at location i under contingency k.
- $\overline{B}_i^{(k)}$: new size of the switched capacitor at location i under contingency k.
- $\overline{M}^{(k)}$: updated voltage stability margin under contingency k.

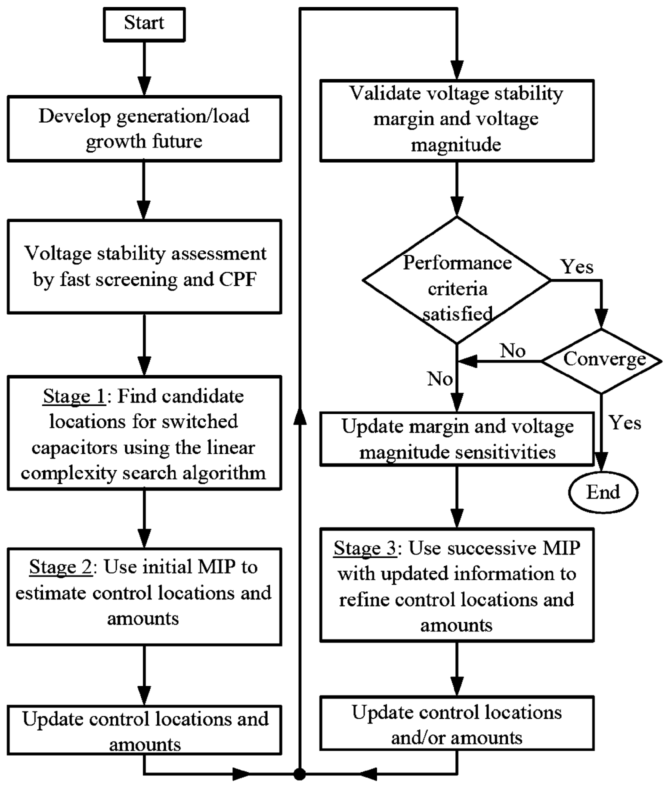

Fig. 3. Flowchart for the reactive power control planning.

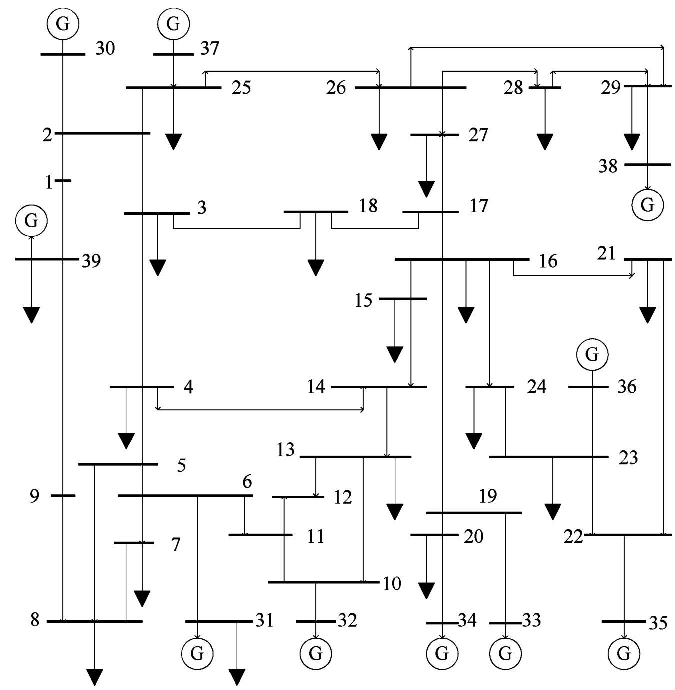

Fig. 4. Modified New England 39-bus test system.

TABLE I
PARAMETER VALUES ADOPTED IN OPTIMIZATION PROBLEM

	Shunt capacitor (500 kV)	Shunt capacitor (230 kV)
Variable cost ($ million/100 Mvar)	0.41	0.41
Fixed cost ($ million)	1.3	0.28
Maximum size (p.u.)	1.5	1.5
Minimum size (p.u.)	$B_{imin}=10^{-3}$	$B_{imin}=10^{-3}$

- $\overline{S}^{(k)}_{V,j,i}$: updated sensitivity of the voltage magnitude at bus j with respect to the size of the switched capacitor at location i under contingency k.
- $\overline{V}^{(k)}_{j}$: updated voltage magnitude at bus j under contingency k.

The above MIP will be re-executed until all concerned contingencies have satisfactory voltage stability margin and voltage magnitude and there is no significant movement of the decision variables. The sensitivities, voltage stability margin and voltage magnitude are updated at each MIP iteration to account for system nonlinearities. There may be situations where this refinement process may not converge. If this is the case, the algorithm will terminate after a prespecified number of iterations. Among the executed iterations, the minimum cost solution satisfying the requirements of voltage stability margin and voltage magnitude might be useful if such a solution exists.

The overall procedure for the reactive power control planning is shown in Fig. 3 which integrates the above-mentioned steps.

IV. NUMERICAL RESULTS

A. Results of a Small System

The proposed method has been applied to the modified New England 39-bus system shown in Fig. 4. The original real and reactive power loads in [39] are multiplied 1.38 times with associated increases in real and reactive power capacities of generating units proportional to their original value in order to stress the system.

In the simulations, the following conditions are implemented unless stated otherwise.

- Loads are modeled as constant power.
- Reactive power output limits of generators are modeled.
- In computing voltage stability margin, the power factor of the load 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% of system load.
- $V_i^{\min} = 0.9$ p.u. and $V_i^{\max} = 1.1$ p.u.
- Switched shunt capacitors are adopted to improve the voltage stability margin and voltage profile.
- The parameter values adopted in the optimization problem are given in Table I. The compensation equipment costs are from [32].

Considering all N-1 contingencies (excluding radial transmission line outages), using the algorithm presented in Section III-B, three generator contingencies (G31, G32, and G35) cause the post-contingency voltage stability margin less than 10% as shown in Table II. The outages of the largest two generators G38 and G39 create unsolvable cases which was addressed in [30]. The voltage stability margins under all nonradial transmission line outages are greater than 10%. Table II also shows the rank of the generator contingencies. We

TABLE II
VOLTAGE STABILITY MARGIN UNDER CONTINGENCIES

Contingency	Voltage stability margin (%) (rank)
(1). Outage of the generator at bus 31	2.69 (3)
(2). Outage of the generator at bus 32	2.46 (2)
(3). Outage of the generator at bus 35	2.42 (1)
(4). Outage of the generator at bus 30	28.14 (8)
(5). Outage of the generator at bus 33	10.20 (4)
(6). Outage of the generator at bus 34	17.08 (7)
(7). Outage of the generator at bus 36	16.23 (6)
(8). Outage of the generator at bus 37	16.06 (5)

TABLE III
MARGIN SENSITIVITIES TO SHUNT CAPACITORS

Candidate buses	Margin sens. under cont. (1) (p.u.)	Margin sens. under cont. (2) (p.u.)	Margin sens. under cont. (3) (p.u.)
Bus 12	0.995	0.963	0.922
Bus 11	0.991	0.969	0.912
Bus 6	0.954	1.014	0.881
Bus 10	0.979	0.943	0.926
Bus 5	0.934	0.988	0.865
Bus 13	0.961	0.915	0.899
Bus 7	0.928	0.985	0.853
Bus 8	0.907	0.960	0.831
Bus 14	0.869	0.826	0.806
Bus 4	0.837	0.841	0.777
Bus 15	0.582	0.555	0.564
Bus 3	0.518	0.512	0.486
Bus 16	0.418	0.401	0.425
Bus 24	0.394	0.378	0.409
Bus 21	0.320	0.307	0.382
Bus 22	0.184	0.175	0.328
Bus 23	0.193	0.184	0.285
Bus 19	0.181	0.173	0.186
Bus 20	0.102	0.098	0.105

will use the proposed method to plan switched shunt capacitors to increase the voltage stability margin for the first three contingencies in Table II. Margin sensitivities to shunt capacitors under the three contingencies are shown in Table III.

The candidate control locations are determined based on the linear search algorithm presented in Section III-D. The best seven candidate buses to install switched shunt capacitors are buses 5, 6, 7, 10, 11, 12, and 13. Note that the candidate locations identified by the backward/forward search algorithm to install switched shunt capacitors to increase the loadability in the system level are buses 10, 11, 12, and 13 instead of those near bus 35 under the outage of the generator at bus 35 because buses 10, 11, 12, and 13 have relatively large margin sensitivities as shown in Table III. This result can be supported by the fact that the bottom left area in the New England 39-bus system is a weak area with load more than generation. On the other hand, the bottom right area in the system is relatively strong. It can maintain load and generation balance even under the outage of the generator at bus 35. The superiority of the identified reactive control locations over others is also verified by comparing

TABLE IV
VERIFIED VOLTAGE MAGNITUDE AND VOLTAGE STABILITY MARGIN

Contingency	Without shunt compensation		With shunt compensation		Iteration number for MIP
	Voltage stability margin (%)	Max/Min voltage (pu)	Voltage stability margin (%)	Max/Min voltage (pu)	
(1). Outage of the generator at bus 31	2.69	1.02/0.77	10.22	1.03/0.90	3
(2). Outage of the generator at bus 32	2.46	1.02/0.76	10.00	1.03/0.90	
(3). Outage of the generator at bus 35	2.42	1.03/0.83	10.00	1.04/0.94	

TABLE V
REACTIVE CONTROL ALLOCATIONS WITH SHUNT CAPACITORS

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	1.500	1.500	1.500	1.500
Bus 6	1.500	1.500	1.500	1.500	1.500
Bus 7	1.500	0.537	0.537	0.537	0.537
Bus 11	1.500	1.186	1.186	1.186	1.186
Bus 12	1.500	1.500	1.500	1.383	1.500

the increase in voltage stability margin for a same amount of reactive control at different locations using the CPF program. For these candidate locations, the optimization-based reactive power control planning algorithm presented in Sections III-E and III-F was carried out.

After three MIP iterations, the overall iterative procedure converges and the requirements of voltage stability margin and voltage magnitude are satisfied under the planned reactive controls. Table IV gives the verified results of the reactive power control planning with the CPF program. Table V shows the results where the optimal allocations for switched shunt capacitors are 1.500, 1.500, 0.537, 1.186, and 1.500 p.u. at buses 5, 6, 7, 11, and 12, respectively. The total installation cost is \$9.05 million for the reactive control allocations. Note that the total cost is \$9.42 million and the system has satisfactory voltage stability margin and voltage magnitude after solving the initial MIP. The proposed iterative reactive control planning procedure reduces the total cost while satisfying the requirements of voltage stability margin and voltage magnitude.

The proposed reactive control planning method considers multiple contingencies simultaneously. Table VI lists the result of independent control allocation for each contingency and the union of the control allocations. Comparing Table V with Table VI, it is clear that the overall cost of control allocation when considering multiple contingencies simultaneously is less than that when considering each contingency independently.

The computation in the proposed reactive control planning method is done only to 1) calculate voltage magnitude, voltage magnitude sensitivities, voltage stability margin and margin sensitivities and 2) solve the optimization. It is only in calculating voltage magnitude, voltage magnitude sensitivities, voltage stability margin and margin sensitivities that we must deal with the full size of the power system. The CPU time for the reactive control planning of the modified New England 39-bus system is 0.53 s on a standard 2.2-GHz machine.

TABLE VI
REACTIVE CONTROL ALLOCATIONS FOR EACH CONTINGENCY

Locations for shunt cap.	Maximum size limit (p.u.)	Union of control allocations (p.u.)	Control allocation for cont. (1) (p.u.)	Control allocation for cont. (2) (p.u.)	Control allocation for cont. (3) (p.u.)
Bus 5	1.500	1.500	1.500	1.500	0
Bus 6	1.500	1.500	1.500	1.500	0
Bus 7	1.500	1.500	1.500	1.500	0
Bus 10	1.500	1.500	0	0	1.500
Bus 11	1.500	1.500	0.163	0.084	1.500
Bus 12	1.500	1.500	1.500	1.500	1.500
Bus 13	1.500	1.449	0	0	1.449

TABLE VII
VERIFIED VOLTAGE MAGNITUDE AND VOLTAGE STABILITY MARGIN UNDER THE HIGHER LOADING LEVEL

Contingency	Without shunt compensation		With shunt compensation		Iteration number for MIP
	Voltage stability margin (%)	Max/Min voltage (pu)	Voltage stability margin (%)	Max/Min voltage (pu)	
(1). Outage of the generator at bus 31	1.70	1.02/0.75	10.13	1.03/0.90	3
(2). Outage of the generator at bus 32	1.47	1.02/0.74	10.00	1.03/0.91	
(3). Outage of the generator at bus 35	1.42	1.02/0.82	10.01	1.05/0.94	

TABLE VIII
REACTIVE CONTROL ALLOCATIONS UNDER THE HIGHER LOADING LEVEL

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	1.331	1.331	1.331	1.331
Bus 6	1.500	1.500	1.500	1.500	1.500
Bus 10	1.500	1.113	1.113	1.113	1.113
Bus 11	1.500	1.500	1.500	1.485	1.500
Bus 12	1.500	1.500	1.500	1.500	1.500

The computational performance of the proposed reactive control planning method is examined against a higher system loading level and a lower system loading level. For the higher system loading level, the system real and reactive power loads are multiplied 1.01 times. The post-contingency voltage stability margin and voltage magnitude decrease when the load increases as shown in Table VII. The overall iterative procedure converges at the third iteration. The requirements of voltage stability margin and voltage magnitude are satisfied under the planned controls as shown in Table VII. Table VIII shows the optimal allocations for switched shunt capacitors under the higher loading level.

For the lower system loading level, the system real and reactive power loads are multiplied 0.96 times. The post-contingency voltage stability margin and voltage magnitude increase when the load decreases as shown in Table IX. After three MIP iterations, the overall iterative procedure converges and the requirements of voltage stability margin and voltage magnitude are satisfied under the planned controls as shown in Table IX. Table X shows the optimal allocations for switched shunt capacitors under the lower loading level.

TABLE IX
VERIFIED VOLTAGE MAGNITUDE AND VOLTAGE STABILITY MARGIN UNDER THE LOWER LOADING LEVEL

Contingency	Without shunt compensation		With shunt compensation		Iteration number for MIP
	Voltage stability margin (%)	Max/Min voltage (pu)	Voltage stability margin (%)	Max/Min voltage (pu)	
(1). Outage of the generator at bus 31	6.83	1.02/0.81	12.34	1.03/0.90	3
(2). Outage of the generator at bus 32	6.61	1.03/0.80	12.34	1.03/0.90	
(3). Outage of the generator at bus 35	6.58	1.03/0.88	10.00	1.03/0.92	

TABLE X
REACTIVE CONTROL ALLOCATIONS UNDER THE LOWER LOADING LEVEL

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	1.500	1.500	1.500	0.692
Bus 6	1.500	1.444	1.444	1.444	0.704
Bus 7	1.500	0.817	0.817	0.817	0.685
Bus 12	1.500	0.747	0.747	0.747	0.747

TABLE XI
VOLTAGE STABILITY MARGIN UNDER CONTINGENCIES FOR THE LARGE SIZE POWER SYSTEM

Contingency number	Voltage stability margin (MW)
(1). 2040	917
(2). 2067	928
(3). 2072	945
(4). 2071	1258
(5). 2058	1259
(6). 2070	1343
(7). 2081	1416
(8). 2076	1512
(9). 2075	1537
(10). 2078	1545

B. Results of a Large Size System

In this section, the application of the proposed method to a North American power system with 6358 buses, 7724 branches, and 1821 generators is presented. The total generation of the system is 96 262 MW and the total load is 93 240 MW. In the simulations, the following conditions are implemented.

- In computing voltage stability margin, generation is increased in area 40 and load is increased in areas 14, 22, 24, 26, and 30.
- $V_i^{\min} = 0.9$ p.u. and $V_i^{\max} = 1.1$ p.u.
- Required voltage stability margin is assumed to be 1200 MW.

Among the 74 considered contingencies, there are three contingencies causing the voltage stability margin less than 1200 MW as shown in Table XI. Ten candidate locations are selected to install switched shunt capacitors. Margin sensitivities to shunt capacitors under the three contingencies are shown in Table XII.

Table XIII shows the results of the optimal allocations for switched shunt capacitors. Table XIV gives the verified results of the reactive power control planning with the CPF program.

TABLE XII
MARGIN SENSITIVITIES TO SHUNT CAPACITORS FOR THE LARGE SIZE POWER SYSTEM

Candidate buses	Margin sens. under cont. (2040) (p.u.)	Margin sens. under cont. (2067) (p.u.)	Margin sens. under cont. (2072) (p.u.)
Bus 30005	0.625	0.660	0.630
Bus 30015	0.592	0.633	0.606
Bus 30020	0.592	0.784	0.739
Bus 30035	0.458	0.463	0.538
Bus 40489	0.469	0.489	0.471
Bus 40687	0.583	0.633	0.605
Bus 45029	0.517	0.549	0.527
Bus 45035	0.578	0.636	0.609
Bus 45095	0.457	0.468	0.454
Bus 45197	0.516	0.540	0.522

TABLE XIII
REACTIVE CONTROL ALLOCATIONS FOR THE LARGE SIZE POWER SYSTEM

Locations for shunt cap.	Max size limit (p.u.)	Overall optimal control allocation (p.u.)	Solution to cont. (2040) (p.u.)	Solution to cont. (2067) (p.u.)	Solution to cont. (2072) (p.u.)
Bus 30005	1.500	1.500	1.500	1.278	1.328
Bus 30015	1.500	0.261	0.261	0.261	0.261
Bus 40687	1.500	1.500	1.500	1.239	1.287
Bus 45035	1.500	1.500	1.500	1.500	1.298

TABLE XIV
VERIFIED VOLTAGE MAGNITUDE AND VOLTAGE STABILITY MARGIN FOR THE LARGE SIZE POWER SYSTEM

Contingency Number	Without shunt compensation		With shunt compensation		Iteration number for MIP
	Voltage stability margin (MW)	Max/Min voltage (pu)	Voltage stability margin (MW)	Max/Min voltage (pu)	
(1). 2040	917	1.07/0.97	1200	1.09/0.99	4
(2). 2067	928	1.07/0.97	1200	1.09/0.99	
(3). 2072	945	1.07/0.98	1200	1.10/0.99	

After four MIP iterations, the overall iterative procedure converges and the requirements of voltage stability margin and voltage magnitude are satisfied under the planned controls. The CPU time for the reactive control planning of the large system is 45.04 s on a standard 2.2-GHz machine.

V. CONCLUSION

This paper presents an optimization-based method of planning reactive power controls in electric power transmission systems to satisfy the requirements of voltage stability margin and voltage magnitude under normal and contingency conditions. The planned reactive power controls are capable to serve as control response for contingencies. The backward/forward search algorithm with linear complexity is used to select candidate locations for reactive power controls. Optimal locations and amounts of new reactive power controls are obtained by solving a sequence of MIP problems. The proposed algorithm can handle a large-scale power system because it significantly reduces the computational burden by utilizing the sensitivities of voltage stability margin and voltage magnitude. The effectiveness of the method is illustrated using the modified New England 39-bus system and a North American power system with 6358 buses. The results show that the method works satisfactorily to plan reactive power controls. We envision that the method to be used in generating less costly transmission reinforcement solutions in comparison to solutions which include new transmission, helping to identify more options during the planning process.

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