Paper

A New Approach for Preventive/Corrective Control Strategy to Avoid Voltage Collapse Based on FACTS Devices Investment

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This paper proposes a new method of optimal FACTS devices allocation to be used in the preventive/corrective control (PCC) against voltage collapse. The new formulation takes into consideration the transition states that the power system may expose such as normal state and contingency states. For the severe contingencies that drive the system to voltage collapse, the corrective control is initiated by means of fast response of FACTS and load shedding to restore the system with small positive load margin, then the preventive control is carried out using all the fast and slow devices ensuring security margin and voltage feasibility. For this control strategy, FACTS allocation are determined based on the minimum cost for the installations and the operations.. The problem is formulated as a mixed integer nonlinear programming problem, which is solved using hybrid genetic algorithm/successive liner programming (GA/SLP) approach. The IEEE 57 bus system is tested to demonstrate the effectiveness of the proposed method.

Keywords: VAR planning, voltage stability, FACTS devices, preventive/corrective control, genetic algorithms

1. Introduction

As power systems become more complex and heavily loaded the electric utilities attempt to maximally utilize their transmission system capacities, where the economical and environment pressures limit their scope to expand transmission facilities. As a result, in such environment, more attention is paid to the voltage collapse problem that considered being responsible for some recent major blackouts. Several research studies have been published for this subject, where large portion of them is concentrated on control strategy itself against this phenomenon based on the available control devices including load shedding [(10)(11)]. It is known that a large amount of load shedding is required to save the system if the VAR allocations are improper. This implies that the VAR allocations should be well planed taking into account the control strategy to be used. Traditionally, VAR planning problem is concerned with voltage feasibility solely [(1)~(3)]. Recently, a few references have been found which address the VAR planning considering voltage stability [(4)(5)]. However, it is observed that the obtained solutions are unnecessarily expensive in order to satisfy all the specified feasibility and stability constraints.

Therefore, the authors have introduced a new formulation for VAR planning problem [(13)]. Different from the previous formulations, the method takes into account possible transition states after contingency, where the installation and the operation costs are considered including load shedding cost to minimize the total cost. The problem is formulated as a mixed integer nonlinear programming (MINP) problem and the generalized Benders decomposition (GBD) technique is used as a solution method. Although the validity of the formulation has been confirmed, the authors have experienced a bad convergence in some situations, which is discussed in [(13)]. This difficulty is solved in [(14)] using a hybrid GA/SLP method.

This paper is an extension of the authors work [(13)(14)], where the formulation is modified to include the concept of the preventive/corrective control. This treatment enables us to accommodate real power system circumstances, where the fast devices including FACTS to be installed can be used for the corrective control to restore the system against the sever contingencies that drive the system to unstable region. Then, all the available control devices "slow and fast" are used for the preventive control to keep the system security. Such a formulation for FACTS allocation considerably reduce the amount of load shedding, saving the total cost, which is the new proposal of this paper.

The objective function is to minimize the sum of the installation costs and expected operating costs, which is evaluated probabilistically taking into account the possible power system transition states. The operating costs include the expected costs for the contingencies, such as the costs of load shedding, expected voltage collapse cost and the cost of other emergency control. The problem is formulated as a MINP problem, where a new solution method is proposed to solve the difficulties experienced in [(13)]. That is, a two-level hybrid algorithm using GA and SLP is proposed in this paper.

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2. Preliminaries

The possible power system transition states that we have considered in this paper may be simplified as shown in Fig. 1. We assume that the power system is operating at the base case A and a contingency k occurs with probability (α), where the proceeding state is assumed to be state B, which will result in either voltage collapse case with probability (β) or stable case with probability ($1-\beta$). The probability (β) is formulated as a function of the load power margin just after the contingencies. This treatment comes from a fact that a load power margin corresponds to the voltage collapse condition in the static sense but actually various dynamic and human factors affect the cause of voltage collapse. The basic concept of this treatment has been proposed in [13], where more detailed explanation is given. In this paper, the control reactions are considered, which are classified into slow and fast time scales to define preventive/corrective control (PCC) states. The installation of fast devices of FACTS can first contribute to the corrective control (CC) to remedy the system, where only fast devices such as load shedding, AVR of generators react with the FACTS. Then, after a while, the other slow devices, as well as the fast devices, can act as the preventive control (PC) to keep the system security. The former state is defined as corrective state (C) and the latter as preventive state (D) in Fig. 1, where the control mode is assumed to be triggered according to the load margin value as follows.

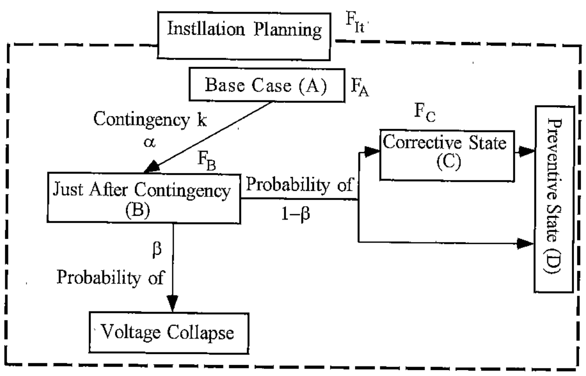


Fig. 1. System transition states

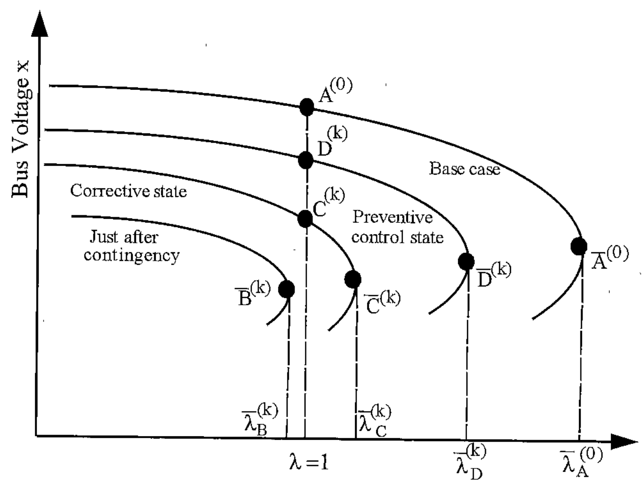


Fig. 2. Corrective/Preventive control

Fig. 2 illustrates the concept of PCC by PV diagrams. If the contingency results in unsolvable case, implying that voltage collapse with negative load margin, then the fast devices for CC quickly react to restore system solvability with small positive margin (state C). After the system is stabilized the PC is further performed based on all the slow and fast devices to ensure the specified security margin and allowable voltages level (State D).

In general, the PCC can be achieved by using all the available devices, where load shedding is used as a last resort since shedding large amount of load will result in too expensive PCC cost. Therefore, a well planned VAR allocation will result in a low total control cost.

3. Problem Formulation

3.1 Objective Function According to the power system operation states in Fig. 1, the VAR planning problem is reformulated so as to take into account the cost reduction effect by the investments of new FACTS devices, which can reduce the amount of load shedding in PCC and consequently the total control cost. In other words, the objective of this paper is to install new FACTS devices with the minimum total cost that can achieve the balance between the security and economic concerns. The objective function is the sum of the expected operation costs for the individual states in Fig. 1 and the installation cost of FACTS devices as follows.

$$\mathrm{F} = \mathrm{F_{It}} + \mathrm{F_A} + \mathrm{F_B} + \mathrm{F_{PC}} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

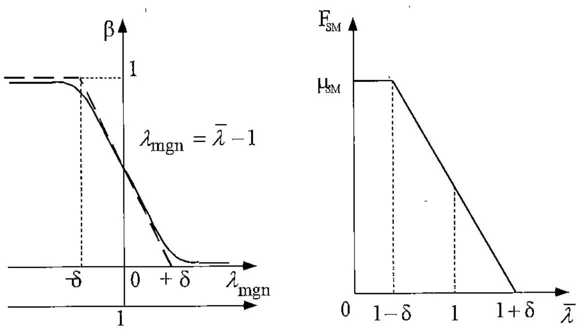
where

$$\mathrm{F_B} = \sum_{k=1}^{m} \alpha^{(k)} \beta^{(k)} \mathrm{F_{BD}}$$

$$\mathrm{F_{PC}} = \left\{ \sum_{k=1}^{n} \alpha^{(k)} \left(1-\beta^{(k)}\right) \left(\mathrm{F_C^{(k)}} + \mathrm{F_D^{(k)}}\right) + \sum_{k=1+n}^{m} \alpha^{(k)} \left(1-\beta^{(k)}\right) \left(\mathrm{F_D^{(k)}}\right) \right\}$$

where $\mathrm{F_{It}}$ is the investment cost; $\mathrm{F_A}$ is the base case operating cost; $\mathrm{F_B}$ and $\mathrm{F_{PC}}$ are the expected costs for just after contingencies and for the preventive/corrective control, respectively; $\mathrm{F_{BD}}$ is the breakdown cost; $\mathrm{F_C^{(k)}}$ is CC cost; $\mathrm{F_D^{(k)}}$ is PC cost, where superscript k implies contingency k; n is the number of contingencies leading to negative load margin; m is the total number of contingencies under investigation. It is noted that the operation costs $\mathrm{F_A}$, $\mathrm{F_B^{(k)}}$ and $\mathrm{F_{PC}^{(k)}}$, are the expected costs with probabilities α, and β [13].

It is worthwhile to mention that in reference [13], in order to simplify the too complex problem, it is assumed that the breakdown probability β is regarded as a function of loading margin ($\lambda_{mgn} = \overline{\lambda} - 1$), as shown in Fig. 3(a). This assumption implies that voltage collapse will occur at the nose point with probability 0.5; the larger is the margin, the smaller is the probability and vice versa. Thus, probability β is treated as the function of $\overline{\lambda}_B$. According to the probability curve, the expected



(a) Probabilty of voltage collapse (b) Load margin cost

Fig. 3. Treatment of expected voltage collapse cost

voltage collapse cost from state B (F_B) is represented in the same way as described in Fig. 3(b). This cost called load margin cost and is defined mathematically for each contingency as follows.

$$F_{SM}=\beta(\bar{\lambda}_B)F_{BD} \cdots\cdots\cdots\cdots (2)$$

This treatment enables us to include the expected voltage collapse cost into our formulation, where the investment of the new FACTS installation will be decided according to all transition states including voltage collapse state.

In this paper, assuming proper reactions of the fast devices including the load shedding and FACTS, the transitions of power system states of Fig. 1 are simplified. Namely, as soon as a contingency occurs, the system state directly changes from A to C very quickly, where the emergency controls respond fast enough to avoid voltage collapse. In other words, it is assumed that the control coordination is perfect which contribute to prevent the occurrence of the voltage collapse, i.e., the probability of the contingency that proceeds the system directly to the voltage collapse is assumed to be zero. This case can be treated by setting $\beta=0$ in Eq. (1) only, which eliminates F_B as well as state B, simplifying the objective function to the following form:

$$F=F_{It}+F_A+\left\{\sum_{k=1}^{n}\alpha^{(k)}\left(F_C^{(k)}+F_D^{(k)}\right)\right.$$
$$\left.+\sum_{k=1+n}^{m}\alpha^{(k)}\left(F_D^{(k)}\right)\right\} \cdots\cdots\cdots\cdots (3)$$

A detailed description for every term and its associated constraints are presented in the following.

3.2 Investment Cost The total investment cost is expressed as

$$F_{It}(c_{It})=\sum_{i\varepsilon\Omega}(\mu_{fi}+\mu_{vi}c_{It_i})d_i, \quad 0\le c_{It_i}\le c_{It_{i_{max}}} \cdots\cdots\cdots\cdots (4)$$

where μ_{fi} and μ_{vi} are coefficients for the installation cost for candidate FACTS devices i . $d_i=1$ if the site i is selected for FACTS device expansion, otherwise $d_i=0$. Ω is a set of all candidate sites and c_{It_i} is the additional VAR of the FACTS device i. The upper limit, $c_{It_{i_{max}}}$, may be omitted in usual cases but may exist for some situation.

3.3 Constraints for Operating States Each state in Fig. 1 has a set of operating constraints, which will be explained in this section. Two operating points are defined for states A, C and D at the nominal load operating point with ($\lambda=1$) and at point of collapse with ($\lambda=\bar{\lambda}$) as shown in Fig. 2, where the superscript k refers to contingency k and notation "$\bar{*}$" represents voltage collapse point for each state. The following two sets of constraints are used corresponding to the two operating points for each state. They will be commonly used for each sub-problem hereafter in this paper.

(1) Operating constraints for nominal load Equality constraints are the power flow equations for the nominal load, while the inequality constraints are the bounds for the variables as follows.

$$y_b-s-f(p,x,c,q)=0 \cdots\cdots\cdots\cdots (5)$$

$$\left.\begin{array}{l} x_{min}\le x\le x_{max},\ p_{min}\le p\le p_{max} \\ 0\le s\le s_{max},\ 0\le c\le c_{It} \\ q_{min}\le q\le q_{max} \end{array}\right\} \cdots\cdots (6)$$

where

x: state variable vector (voltage)

y_b: nominal load (base case)

s: load shedding vector

c: control vector of FACTS devices

q: generators reactive power vector

p: control parameter vector of the slow devices

f: power flow equations at the nominal load point

(2) Voltage collapse point constraints The conditions for voltage collapse point [6] are used as equality constraints Eq. (7) with the bounds of variables Eq. (8).

$$\left.\begin{array}{l} y_b+(\bar{\lambda}-1)y_d-\bar{s}-f(\bar{p},\bar{x},\bar{c},\bar{q})=0 \\ w(\bar{p},\bar{s},\bar{c},\bar{\lambda},\bar{x},\bar{q})\bar{f}_{\bar{x}}(\bar{p},\bar{s},\bar{c},\bar{\lambda},\bar{x},\bar{q})=0,\ \|w\|\ne 0 \end{array}\right\} \cdots\cdots (7)$$

$$\left.\begin{array}{l} p_{min}\le\bar{p}\le p_{max},\ 0\le\bar{s}\le s_{max} \\ 0\le\bar{c}\le c_{It},\ q_{min}\le\bar{q}\le q_{max},\ \lambda\le\bar{\lambda}_{min} \end{array}\right\} \cdots (8)$$

where

$\bar{\lambda}$: load parameter value

y_d: load direction vector

$\bar{f}_{\bar{x}}$: pwer flow Jacobian (singular at the nose point)

w: left eigenvector (a row vector)

3.4 Base Case Operation Sub-Problem The objective function is to minimize the production cost or power loss cost while satisfying network performance constraints defined at the nominal load operating point $A^{(0)}$ and nose point $\bar{A}^{(0)}$. This problem is formulated as

$$\left.\begin{array}{l} \text{minimize}\quad F_A=F_{EC}(x_A,p_A,c_A,q_A) \\ \text{subject to} \\ \qquad G_A(x_A,p_A,s_A,c_A,q_A)\le 0 \\ \qquad \bar{G}_A(\bar{x}_A,\bar{\lambda}_A,\bar{p}_A,\bar{s}_A,\bar{c}_A,\bar{q}_A)\le 0 \end{array}\right\} \cdots\cdots (9)$$

where G_A represents the set of constraints described by Eqs. (5) and (6), while $\bar{G}_A$, the collapse point constraint set as defined by Eqs. (7) and (8); F_{EC} is the production or power loss cost. Note that the subscript A refers to base case sub-problem.

3.5 Corrective Control Sub-Problem If a severe contingency occurs that result in an unsolvable case with a negative load margin value, a quick response must be taken to restore system solvability. The corrective control is assumed based on merely the fast control devices, which include load shedding and the new installed FACTS devices to rapidly save the system from the collapse. We also take into account automatic voltage regulations which keep constant generator bus voltages within their reactive power limits. However, the cost associated with the automatic voltage regulations is neglcted in this paper. Accordingly, the objective function in this case is to minimize the cost of the total amount of the fast controls while satisfying the operating constraints defined at the nominal load operating point ($C^{(k)}$) and nose point ($\bar{C}^{(k)}$). This problem is formulated as:

minimize

$$F_C\left(s_C^{(k)}, c_A, c_C^{(k)}\right) = \left\{\sum_l \mu_{sl}\left|s_{Cl}^{(k)}\right| + \sum_j \mu_{cj}\left|c_{Cj}^{(k)} - c_{Aj}\right|\right\} \cdots\cdots (10)$$

subjecte to

$$G_C^{(k)}\left(x_C^{(k)}, p_A^{(k)}, s_C^{(k)}, c_C^{(k)}, q_C^{(k)}\right) \le 0$$
$$\bar{G}_C^{(k)}\left(\bar{x}_C^{(k)}, \bar{\lambda}_C^{(k)}, \bar{p}_A^{(k)}, \bar{s}_C^{(k)}, \bar{c}_C^{(k)}, \bar{q}_C^{(k)}\right) \le 0$$

where $G_C^{(k)}$ and $\bar{G}_C^{(k)}$ are similar to the constraints $\bar{G}_A$ and in Eq. (9) respectively except that the subscript C refers to the corrective state. μ_{sl} is a cost for unit load curtailment at l-th load bus, μ_{cj} is a control cost coefficients for FACTS device j. It is worthwhile to mention that the upper and lower bounds of the voltage magnitudes are not taken into consideration in this subproblem since state (C) is an intermediate state.

As soon as the corrective control is performed to restore system solvability with an arbitrary chosen small positive load margin specified by ($\bar{\lambda}_C \ge \bar{\lambda}_{C\,min}$), the problem is switched to preventive control mode to ensure system security with a desired load margin specified by ($\bar{\lambda}_D \ge \bar{\lambda}_{D\,min}$). This problem is explained as follows.

3.6 Preventive Control Sub-Problem The PC is triggered after the system is stabilized by CC or when the system is stable without CC but the stability margin is too small. This situation allows to use all the available devices including the fast and slow controls to readjust their values to meet the system security. In this work, the VAR control devices such as LTC transformer taps and shunt capacitor/reactor reactances are selected as the slow control variables, p. The objective function is to minimize the cost of the total amount of the fast and slow controls while satisfying the operating constraints defined at the nominal load operating point ($D^{(k)}$) and nose point ($\bar{D}^{(k)}$). The formulation of this problem can be stated as follows.

minimize

$$F_D\left(p_A, p_D^{(k)}, s_D^{(k)}, c_A, c_D^{(k)}\right) = \left\{\sum_l \mu_{sl}\left|s_{Dl}^{(k)}\right| + \sum_i \mu_{pi}\left|p_{Di}^{(k)} - p_{Ai}\right| + \sum_j \mu_{cj}\left|c_{Dj}^{(k)} - c_{Aj}\right|\right\} \cdots\cdots (11)$$

subject to

$$G_D^{(k)}\left(x_D^{(k)}, p_D^{(k)}, s_D^{(k)}, c_D^{(k)}, q_D^{(k)}\right) \le 0$$
$$\bar{G}_D^{(k)}\left(\bar{x}_D^{(k)}, \bar{\lambda}_D^{(k)}, \bar{p}_D^{(k)}, \bar{s}_D^{(k)}, \bar{c}_D^{(k)}, \bar{q}_D^{(k)}\right) \le 0$$

where $G_D^{(k)}$ and $\bar{G}_D^{(k)}$ are similar to the constraints $G_C^{(k)}$ and $\bar{G}_C^{(k)}$ in Eq. (10) respectively except that the subscript D refers to preventive state and the slow control parameter p is included in Eq. (11). μ_{pi} is a control cost coefficient of the slow control device i. Note that the inclusion of the load shedding in each sub-problem described above will guarantee the feasibility of the problem during the computation process. However, since the control costs of load shedding are much higher than the other controls, they will be the final option among the controls. Namely, if there are sufficient FACTS devices are installed in the system, the load shedding will not be carried out.

3.7 Overall Problem Formulation The overall problem may be stated as follows.

minimize

$$F = F_{It} + F_A + \left\{\sum_{k=1}^{n} \alpha^{(k)}\left(F_C^{(k)} + F_D^{(k)}\right) + \sum_{k=1+n}^{m} \alpha^{(k)}\left(F_D^{(k)}\right)\right\}$$

subject to

Invetment constraints $\{0 \le c_{It_i} \le c_{It_{max}}$ for each $i\varepsilon\Omega$

Base case constraints $\{H_A \le 0$

Corrective state constraints $\{H_C \le 0$

Preventive state constraints $\{H_D \le 0$ $\cdots\cdots (12)$

where

$$H_A = \left[G_A; \bar{G}_A\right]$$
$$H_C = \left[G_C^{(k)}; \bar{G}_C^{(k)}\right],\ k = 1, 2, \cdots, n$$
$$H_D = \left[G_D^{(k)}; \bar{G}_D^{(k)}\right],\ k = 1.2, \cdots, m$$

4. Proposed Solution Algorithm

4.1 Preliminary Computation Since the optimization problem described by Eq. (12) is a large scale mixed integer nonlinear programming problem, a hybrid GA/SLP algorithm is presented in this section to solve this problem. In this algorithm, a pre-selection of the set of candidate FACTS sites Ω is carried out first to limit the search space and to reduce computation time. This process is not always necessary but a common practice in solving large-scale VAR planning problem since the set of the candidate sites Ω generally can be kept small even for large-scale systems. In this paper, the concept of participation factors [7] is used to determine the best set of candidate buses for SVCs as follows. The participation factor of bus k in mode i is given by

$$P_{ik} = \xi_{ki}\eta_{ik} \quad \cdots\cdots (13)$$

where ξ_{ki} and η_{ik} are the i^{th} column right eigenvector and row left eigenvector of the power flow Jacobian respectively. Then, the candidate buses, k, for installing SVCs are determined according to highest participation factors for the voltage collapse mode selected as mode i, corresponding to the minimum eigenvalue of the power flow Jacobian.

Another issue is that the size of the candidate buses where it plays an important role for determining the final solution in a reasonable computation time. As far as the authors know, this size is problem dependent and there is no specific method has been used till now to decide this size. The planner experience is usually the final judgment in this size since many factors such as environment limits and economic considerations could affect final decision. Therefore, in this paper, the size of the svc's candidate buses is decided based on the experience of authors, where several examinations are carried out first to decide the most suitable number of buses for the test systems used.

4.2 Overall Algorithm A two level hybrid genetic algorithm/SLP method is proposed to solve the multi-transition problem Eq. (12) as shown in Fig. 4. In the first level, the GA is employed to select the sites and VAR amount of the FACTS devices to be installed in the system, where each individual in the population of the current generation represents a candidate solution. Then, this candidate is evaluated for all transition states under investigation in the second level, where the base case sub-problem Eq. (9), n contingency sates sub-problems Eq. (10) and (m-n) contingency sates sub-problems Eq. (11) are solved individually using SLP, which is known as a fast and robust optimization method for nonlinear problems. Note that for the first n contingencies the corrective control is carried out first and then the preventive control is performed to ensure the system security. Based on the optimization, the fitness of each individual on the population of the current generation is evaluated in terms of the operating costs associated with the individual states and investment cost, where the fitness value of each individual is computed using the inverse of the total objective function F of Eq. (12). Then, the results are passed to the first level, where the genetic algorithm operators, which include reproduction, crossover and mutation operators are applied producing the next generation. These procedures are repeated till the termination criterion is satisfied. A general flowchart of the proposed hybrid GA/SLP is depicted in Fig. 5, in which the abbreviation POC stands for the point of collapse method and POP stands for the current population.

A simple genetic algorithm (SGA) is implemented to show the feasibility of the proposed method. An important step in the implementation is the string representation. The binary bit string representation is used, where

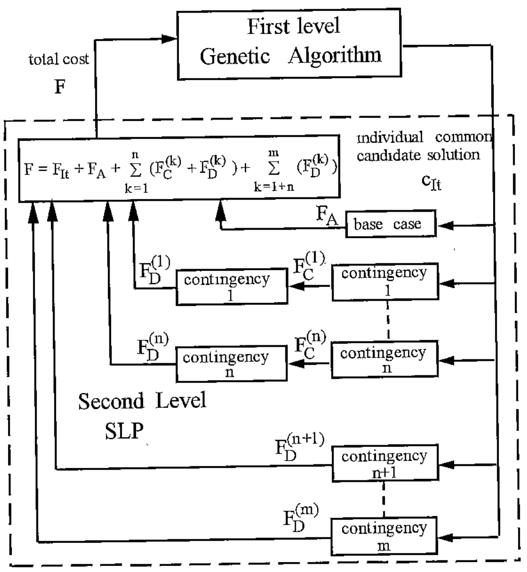


Fig. 4. Two level hybrid GA/SLP itreative procedure

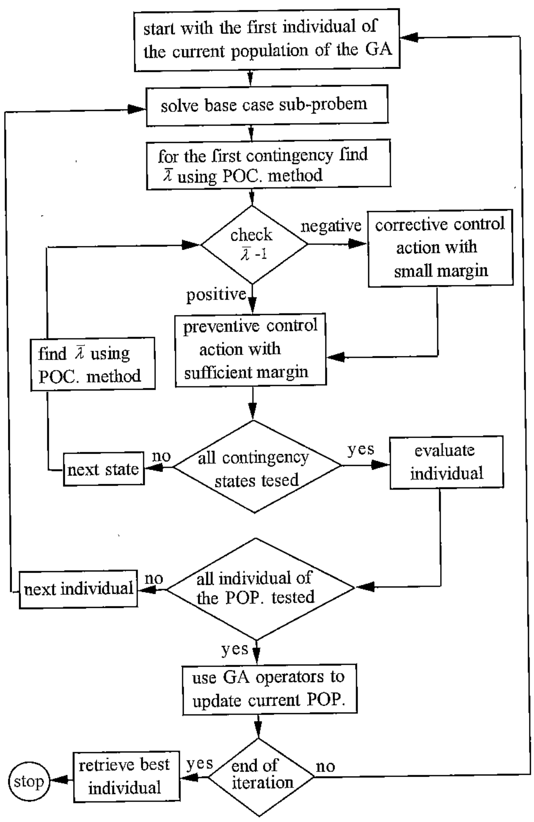


Fig. 5. General flowchart for VAR expansion using GA

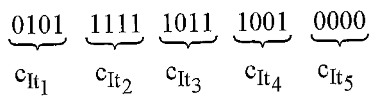


Fig. 6. Chromosome encoding in SGA

each chromosome contains a number of sub-strings equal to the number of the candidate sites of the FACTS devices. Each sub-string is in the form of binary corresponding to the amount of the VAR to be installed. For example, the chromosome shown in Fig. 6 represents a candidate solution for 5 candidate buses for installing FACTS devices, where each sub-string is represented by 4 digits corresponding to the VAR amount to be installed on its own site. Typical genetic algorithm operators (evaluation function, reproduction, crossover and mutation) are used in the proposed algorithm as described in Ref. (8).

4.3 Solution Algorithm for Operation Sub-Problems The operation sub-problems Eqs. (9), (10) and (11) are represented as nonlinear optimization problems. The successive linear programming is used to solve these problems, where each problem is linearized around the power flow solution successively until the convergence is obtained. The linearized formulation for the preventive control sub-problem is given by

minimize

$$\Delta F_D = \frac{\partial F_{SH}}{\partial s}\Delta s + \left[\frac{\partial F_{CL}}{\partial p}\ \frac{\partial F_{CL}}{\partial c}\right]\begin{bmatrix}\Delta p\\ \Delta c\end{bmatrix} \cdots\cdots (14)$$

$$F_{SH} = \sum_l \mu_{sl}\left|s_{Dl}^{(k)}\right|$$

$$F_{CL} = \sum_i \mu_{pi}\left|p_{Di} - p_{Ai}\right| + \sum_j \mu_{cj}\left|c_{Dj} - c_{Aj}\right|$$

subject to

$$\left.\begin{array}{l} A_1 \cdot [\Delta x, \Delta p, \Delta s, \Delta c] \le b_1 \\ A_2 \cdot [\Delta\bar{x}, \Delta\lambda, \Delta p, \Delta s, \Delta\bar{c}] \le b_2 \end{array}\right\} \cdots\cdots\cdots\cdots (15)$$

where A_1 and A_2 are the sensitivity matrices associated with constraints $G_D^{(k)}$ and $\bar{G}_D^{(k)}$ in Eq. (11) respectively; F_{SH} is the load shedding cost; F_{CL} is the control cost. It is noted that in the actual computation $\Delta\bar{\lambda}$ is eliminated in Eqs. (14), (15) by using the sensitivity relation (9) among loading margin $\Delta\bar{\lambda}$ and control variables, Δs, Δp and Δc.

The procedure is in common with each subproblem for every contingency. This is summarized as for the preventive control subproblem as an example as follows:

(1) Solve the post-fault power flow at nominal load operating point, equality constraints associated $G_D^{(k)}$ with constraints with the available control variables (p, c, and s). Then, compute A_1.

(2) Compute the maximum loading point for the post-fault condition and obtain A_2.

(3) Solve optimization problem Eqs. (14), (15) using LP method. If converged, stop. Otherwise update all the control variables and then go step (1).

Although the procedures are the same for all the operation sub-problems, a great care is necessary for the corrective control sub-problem, where the starting values of c and s must be chosen to guarantee the load flow solvability in step (1).

5. Numerical Example

The proposed method has been applied to the IEEE 57 bus system (12), where the original loads as well as generations have been increased uniformly by 70% to define the base case operating point for examinations. The parameters used for the system and SGA are given in the appendix.

Table 1. Load margin and minimum bus voltage values just after contingency states

Contingency	Load margin	Minimum voltage	System state
1 line (26-27)	-0.056	0.50	Collapse
2 line (25-30)	-0.053	0.51	Collapse
3 line (47-46)	-0.057	0.51	Collapse

Table 2. Corrective control results without VAR expansion

Contingency	Load margin	Minimum voltage	Sum of the load shedding
1 line (26-27)	0.05	0.73	0.184
2 line (25-30)	0.05	0.73	0.181
3 line (46-47)	0.05	0.75	0.202

The contingency analysis was carried out first. Namely, the load power margins were computed for all possible N-1 contingencies to select a few contingencies for the examination. According to these results, the most severe three contingencies were the outages of lines (26-27), (25-30) and (46-47). The load margins and the bus voltage magnitudes just after the contingencies are shown in Table 1, in which voltage values are evaluated at the nose point. Note that all the selected contingencies drive the system to unstable zones since the load margins are all negative. This implies that for all these contingencies the corrective control has to be carried out first and then the preventive control should be initiated to maintain system security.

To demonstrate the cost effect of the corrective and preventive controls, two cases are set as follows. Case 1 stands for the situation without VAR expansion, assuming that the corrective and preventive control will be carried out based on the already available installed VAR source and load shedding. Case 2 is a VAR expansion case where new FACTS devices are supposed to be used.

The results of the corrective control for case 1 are shown in Table 2. It is observed that all the unsolvable contingencies are restored to be stable with small positive margins (0.05 for each of them). However the load shedding value for each contingency is relatively high, resulting in high corrective control cost. In order to achieve a secure condition for the load margins and bus voltages, the preventive control is performed. The final states for case 1 are shown in Table 3 after the corrective/preventive control to keep system security for all contingencies. The results show that the system security is maintained on the account of load shedding and consequently the total contingency cost. Note that the load shedding costs and control costs are computed according to the cost functions F_{SH} and F_{CL} in (14) respectively.

In case 2, the modal analysis described in section 4 was applied first in order to select the best candidate buses to install the new SVCs. As mentioned in section 4, the candidate set is decided based on the experience of the authors, where several examinations were carried out first to decide the most suitable number of buses for the test system used, which were [31, 30, 33, 32, 34, 24, 35, 26, 36, 40]. This number of candidate buses represents about 20% of the total number of load buses. Table 4 lists the optimal SVC allocations obtained by the proposed method. The results indicate that the SVC allocations are 0.24, 0.26, 0.18 and 0.30 pu at buses 30, 34, 35 and 36 respectively. Note that only four SVCs are required at buses of the ten candidate buses to maintain system security. Table 4 also lists the reactive power used for the control for each contingency. For example, when outage of line 26-27 occurs, the var amount used at bus 36 for the control is 0.227 of the installed value of 0.3.

The results of the corrective control for the case 2 are shown in Table 5. It is appeared that all the unsolvable contingencies are restored to be stable with small positive margin of 0.05. Note that since there are enough installed FACTS devices, the load shedding is not carried out in this case resulting in zero load shedding cost and consequently small corrective control cost. In order to enhance the load margin and the bus voltages, the preventive control is performed and the results are shown in Table 6. The results show that the new installed FACTS devices are sufficient to maintain system security in all cases resulting in a relatively small contingency cost compared to case 1. In this table the expansion cost is computed as F_{It} of (4), and the total contingency cost is the sum of the operation costs (F_{SH} and F_{CL}) and the common expansion cost F_{It}.

Although we have chosen three most severe contingencies in this examination, it has been confirmed that the FACTS installation obtained successfully keep the security of the system for the other contingencies without load shedding. This implies that the contingency selection based on the load power margin is effective.

Table 3. Results after corrective and preventive control without VAR expansion

Cont. line	Load margin	Minimum voltage	Load shedding cost	Control cost	Total cont. cost
26-27	0.156	0.90	307.30	0.231	307.531
25-30	0.151	0.90	290.04	0.245	290.285
46-47	0.150	0.90	323.20	0.268	323.468

Table 4. Optimal SVC allocations and preventive control sub-problems test results

SVC Optimal Allocations		SVC Max Limits	Preventive control sub-problems optimal solution c_D		
bus #	Optimal solution c_{It}	$c_{It_{max}}$	Cont. line 26-27	Cont. line 25-30	Cont. line 46-47
30	0.24	0.30	0.240	0.240	0.240
34	0.26	0.30	0.260	0.260	0.260
35	0.18	0.30	0.180	0.180	0.180
36	0.30	0.30	0.227	0.223	0.297

In our implementation, in order to keep track of the best individual in the evolution process of the GA, the highest fitness value and associated string are stored in a separate location called a solution set. At the end of the iterations, the best individual for the whole process is retrieved from the solution set as a final solution. The computational characteristic is given in Fig. 7.

The required CPU time to obtain the final solution is 10 hours 24 minutes, where the problem is implemented on a Pentium-133 microcomputer using MATAB. The CPU time is the main drawback of the proposed method since the inclusion of various issues into the formulation increases the size and complexity of the problem. However, the numerical feature of the proposed method is robust enough. In fact, no numerical difficulties have been found in various examinations for different systems.

Finally, it is important to mention that the above results are obtained based on the assumption of the perfect control coordination that prevents the voltage colapse occurrence directly after contingency. Of course this assumption simplified our formulation since F_B is eliminated. However, if the preivous assumption is not the case, i.e., the control coordination is not perfect, the obtained results will be changed, where F_B must be included in the total objective function F and consequently

Table 5. Corrective control results with VAR expansion

Cont. line	Load margin	Minimum voltage	Sum of the load shedding	Cc Bus number 30	34	35	36
26-27	0.05	0.83	0.00	0.24	0.23	0.00	0.00
25-30	0.05	0.83	0.00	0.24	0.23	0.00	0.00
46-47	0.05	0.83	0.00	0.24	0.26	0.03	0.00

Table 6. Results after corrective and preventive control with VAR expansion

Cont. line	Load margin	Minimum voltage	Load shedding cost	Control cost	Expan. cost	Total cont. cost
(26-27)	0.150	0.92	0.00	0.132	41.960	42.092
(25-30)	0.150	0.92	0.00	0.132		42.092
(46-47)	0.150	0.92	0.00	0.139		42.099

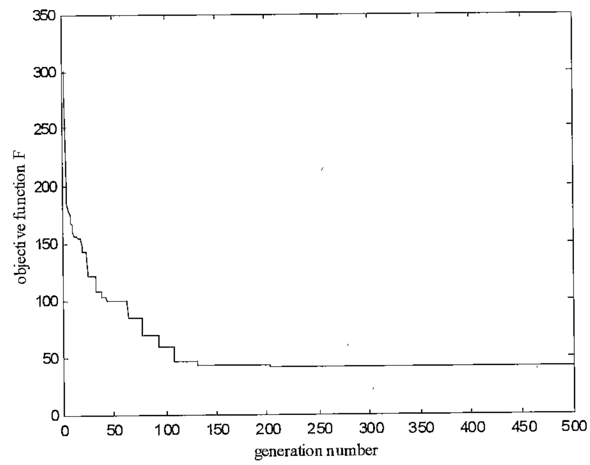


Fig. 7. Evolution of the best objective function value

the decision making will be changed.

6. Conclusion

A new formulation of FACTS devices allocation problem to mitigate voltage collapse is presented in this paper. These FACTS devices are expected to be used in the real time control reactions, which are classified into slow and fast time scales to include the concept of preventive/corrective control and consequently accommodate real power system circumstances. This classification enables us to remedy the system in all credible contingencies including severe contingencies that drive the system to unstable zone, where the corrective control based on merely fast devices is carried out quickly to stabilize the system for the set of the contingencies that leads the system to unstable region. Then, after a while, the other slow devices, as well as the fast devices, can act as the preventive control (PC) to keep the system security. The proposed method has been applied successfully to IEEE 57 bus system. The numerical result indicated that the above control strategy based on the new installation of the FACTS devices is significantly save the total control cost, where the amount of the load shedding, which is usually carried out in such severe contingencies, is considerably decreased and as a result reduce the total cost. This implies that the additional cost of the new investment of FACTS devices is counted as a security cost, which achieves the balance between the security and economic concerns.

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Appendix

V min = 0.9 pu, V max = 1.1 pu, security margin (after corrective control) = 0.05, security margin (after preventive control) = 0.15, $c_{It_{max}} = 0.3$, $\mu_v = 2$, $\mu_f = 10$, $\mu_p = 1$, $\mu_c = 1$, $\mu_s = 1000$ per 100 MW. Population size = 50, crossover probability = 0.1, mutation probability = 0.01, parameter resolution = 4 bits/site and number of iterations = 500.

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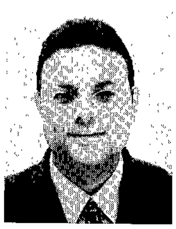

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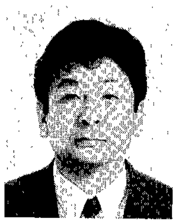

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