Voltage Stability Enhancement in Contingency Conditions Using Shunt FACTS Devices

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Abstract— **this paper investigates the application of FACTS devices to extend voltage stability margin in electric power systems. Most of methods proposed for allocation of FACTS devices consider only the normal state of network. Nevertheless, voltage collapses usually initiated by a single contingency. Therefore, in this paper a strategy for location of FACTS devices based on contingency studies is proposed. Using modal analysis, a probabilistic index is defined which can be used to rank of system buses based on their effect on system voltage stability enhancement under all possible contingencies. It is shown that this method leads to a uniform reactive power supply in the system. Consequently, it will be effective in more contingency conditions. The IEEE 14-bus test system is used to demonstrate the proposed approach of placing shunt FACTS devices. The obtained results show that allocation of FACTS devices using the proposed approach improves the system voltage stability under contingency conditions with smaller size of FACTS to be installed compared to other methods.**

Keywords— **FACTS, Voltage Stability, Contingency, Modal analysis**

I. INTRODUCTION

Voltage stability is increasingly becoming a limiting factor in the planning and operation of many power systems [1, 2]. With increasing system loading and open transmission access, power systems are more vulnerable to voltage instability. Together with ever-present disturbances, this may result in a serious consequence of a voltage collapse as shown by a number of major incidents throughout the world [1, 2].

Voltage collapse tends to occur from lack of reactive-power support in heavily stressed conditions, which are usually triggered by system faults. Therefore, this phenomenon is closely related to a reactive-power planning problem including contingency analyses, where suitable conditions of reactive-power reserves are analyzed for secure operations of power systems under normal states as well as contingency conditions [3]. Conventional reactive power control can be used to provide steady state voltage control and enhance power system voltage stability. These devices, however, are based on electro-mechanical mechanisms thus preventing high speed and flexible control. Moreover, extensive use of these devices may cause some of the voltage control problems found today as pointed out by several investigations [4, 5].

Flexible ac transmission system (FACTS) controllers, on the other hand, are being increasingly used to provide voltage and power flow control in many utilities. Their application to improve voltage stability margin in highly developed networks is demonstrated [6, 7]. Application of FACTS devices is a very effective solution to prevent voltage instability and voltage collapse due to their fast and very flexible control. Nevertheless, the damping effect of FACTS devices is known to be strongly influenced by their location [8]. Therefore, optimal location of FACTS is a very important issue and several methods [9-11] are proposed for it.

One of the shortcomings of those methods is that they only consider the normal state of system. However, voltage collapses are mostly initiated by a disturbance (e.g. the outage of a line or a generation unit). So, to locate FACTS devices, consideration of contingency conditions is more important than consideration of normal state of system and some approaches are proposed to locate of FACTS devices with consideration of contingencies, too [3, 12, 13].

Ref. [12] determines the location of FACTS devices based on the most dangerous contingency. The severity of a contingency is defined as the amount of overloading of lines. In [13], the security index defined for ranking of contingencies is based on the number of low voltage buses and overloaded lines as well as their severity. Nevertheless, these methods do not consider the likelihood of the contingencies occurring. It seems that consideration of high probability contingencies with more importance is more reasonable.

Ref. [4] proposes a comprehensive formulation for reactive power planning problem including the allocation of FACTS devices, which directly takes into account the expected cost for voltage collapse and corrective controls such as load shedding in contingencies together with the control effects by the devices to be installed. The inclusion of load shedding and voltage collapse costs into the formulation guarantees the feasibility of the problem but represents a computational burden to the optimization problem which is very complicated and time consuming for a real system with a large number of buses.

This paper investigates the application of shunts FACTS controllers to improve the voltage stability of power system in contingency conditions. To determine the most effective location of FACTS devices a new formulation is proposed based on modal analysis and determination of bus participation factors. The objective in this approach is to find the buses that have the most effect on voltage instability. A probabilistic index is defined which considers the participation of each bus to voltage instability as well as the vicinity of system to instability and the probability of the occurrence of each contingency. Buses are then ranked by their corresponding index values. This ranking represents the best location for one shunt FACTS controller.

In this paper, section II discusses the contingency impact on voltage instability. Section III describes the modal analysis which is the mathematical tool needed to identify critical buses prone to voltage instability. In section IV, the proposed approach is presented and in section V, an example system is used to demonstrate the proposed approach. Finally, section VI presents the main conclusion of the paper.

II. Voltage instability

Voltage collapse is a process in which, the appearance of sequential events together with the voltage instability in a large area of system can lead to the case of unacceptable low voltage condition in the network, if no preventive action is committed. Occurrence of a disturbance or load increasing can leads to excessive demand of reactive power. Therefore, system will show voltage instability. If additional resources provide sufficient reactive power support, the system will be established in a stable voltage level. However, sometimes there are not sufficient reactive power resources and the excessive demand of reactive power can leads to voltage collapse [4].

Voltage collapse can be initiated due to small changes of system condition (e.g. Load increasing) as well as large disturbances (e.g. line outage or generation unit outage). Under these conditions, shunt FACTS devices such as SVC and STATCOM can improve the system security with fast and controlled injection of reactive power to the system. However, when the voltage collapse is due to excessive load increasing, FACTS devices cannot prevent the voltage collapse and only postpone it until they reach to their maximum limits [14]. Under these situations, the only way to preventing the voltage collapse is load curtailment or load shedding. So, reactive power control using FACTS devices is more effective in large disturbances, and contingencies should be considered in voltage stability analysis. Therefore, in this paper we focus on contingencies. Nevertheless, the defined index to ranking buses could be utilized with consideration of normal state of system and load increasing.

III. Modal Analysis

Voltage collapse is a dynamic phenomenon with rather slow dynamics and a time domain ranging from a few seconds to some minutes, or more. Owing to its quasi-static character, it has mostly been static methods that were proposed for its analysis [13]. Modal analysis is the most effective static method. It involves the computation of critical eigenvalue of the reduced power system steady state Jacobian matrix and the associated participation factors, which show how close the current operating point of power system is to the voltage collapse point.

Using the reduced Jacobian matrix, the voltage magnitude and the incremental change in bus reactive injection can be examined. Due to high dependency of voltage magnitudes and reactive power injections, at each operating point, we can keep the real power (P) constant and voltage stability can be evaluated by considering the incremental relationship between reactive power (Q) and voltage magnitude (V). The effect of changes in system conditions is taken into account by studying the incremental relationship between (Q) and (V) in different operating conditions.

As the power flow method is implemented for voltage stability analysis, the Jacobian matrix of solved load flow equations, by Newton-Raphson method, can be used. The linearized steady-state system voltage equations are expressed as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{1}$$

where ΔP, ΔQ, $\Delta\theta$ and ΔV are incremental changes in bus real power, reactive power, voltage angle and voltage magnitude respectively.

To express the relation between ΔQ and ΔV for a small change in real power, ΔP =0 can be assumed. This yield:

$$\Delta Q = (J_{QV} - J_{Q\theta} \cdot J_{P\theta}^{-1} \cdot J_{PV}) \cdot \Delta V \tag{2}$$

Rearrange (2), then

$$\Delta V = J_R{}^{-1} \Delta Q \tag{3}$$

where,

$$J_R = (J_{QV} - J_{Q\theta} \cdot J_{P\theta}^{-1} \cdot J_{PV}) \tag{4}$$

J_R is called the reduced Jacobian matrix of the system. It relates the bus voltage magnitude and reactive power injection. Let

$$J_R = \xi \Lambda \eta \tag{5}$$

where ξ, η and Λ are right eigenvector, left eigenvector and diagonal eigenvalue matrix of J_R respectively.
From (3) and (5)

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \tag{6}$$

and

$$v = \Lambda^{-1} q \tag{7}$$

where $V = \eta \Delta V$ is the vector of modal voltage variations and $q = \eta \Delta Q$ is the vector of modal reactive power variations, and

$$\xi^{-1} = \eta \quad (8)$$

Equation (7) represents uncoupled first order equations. Thus for the ith mode:

$$v_i = \frac{1}{\sigma_i} q_i \quad (9)$$

The eigenvalues of the reduced Jacobian matrix identify different modes through which the voltage of system could become unstable. The magnitude of the eigenvalues provides a relative measure of the proximity to instability. If $\sigma_i > 0$, the ith modal voltage and the ith modal reactive power variation are along with the same direction, indicating that the system is voltage stable. If $\sigma_i < 0$, the ith modal voltage and the ith modal reactive power variation are along with the opposite directions, indicating that the system is voltage unstable. In this sense, the magnitude of σ_i determines the degree of stability of the ith modal voltage. The smaller the magnitude of positive σ_i, the closer ith modal voltage is to being unstable [4].

Using modal analysis, we can determine the effect or participation of system buses in voltage instability and critical modes near the point of collapse. Relative participation of kth bus to ith mode is expressed by bus participation factor as follow:

$$P_{ki} = \xi_{ki}\eta_{ik} \quad (10)$$

where ξ_{ki} and η_{ik} are kth element of the right and left eigenvectors corresponding to ith eigenvalue of J_R respectively.

Bus participation factors represent the area corresponding to each mode. The larger the magnitude of P_{ki}, the kth bus is more effective in stabilization of ith mode. Therefore, it is possible to determine buses that provide the most effective corrective controls to improve voltage stability. Note that a large disturbance such as the loss of transmission or generation equipment can be modeled by a discrete change in the system equations or parameters. For example, the loss of a transmission line can be modeled by removing the line from the system load flow equations.

IV. Proposed Method for Locating FACTS Devices

As mentioned previously, voltage collapse is usually initiated by disturbances in a system vulnerable to voltage instability. Voltage instability could be recognized by modal analysis of power system steady state Jacobian matrix under contingency condition. If the smallest eigenvalues of reduced Jacobian matrix are negative or very close to zero, then voltage instability is possible. Under these conditions, it is necessary to increase the magnitude of critical modes until the system security is ensured and voltage stability is achieved. This can be done via corrective operations such as providing reactive power support with FACTS devices.

Voltage instability is due to critical modes of reduced Jacobian matrix. Therefore, in our proposed method the objective is to determine system buses that have the most effect on the critical modes. Critical modes are determined based on modal analysis of system reduced Jacobian matrix under contingency conditions and the effectiveness of buses on these critical modes is recognized by their participation factors.

In the proposed method, for each contingency we define a probabilistic index using (11) which evaluates the relative participation of each bus in voltage instability caused by all of the critical eigenvalues corresponding to that contingency:

$$PCM_i = \sum_{j=1}^{m} P_{outage}(k) \times \left(\frac{P_{ij}}{\sigma_j} \right) \quad (11)$$

PCM_i : contribution of bus i to voltage instability caused by critical modes under kth contingency state;

$P_{outage}(k)$:likelihood of kth contingency occurring corresponding to outage of line k;

m : number of critical eigenvalues in kth contingency;

P_{ij} : participation factor of bus i to critical eigenvalue j;

σ_j : critical eigenvalue j;

We make the convention that the term critical mode is used to identify all eigenvalues whose magnitudes are smaller than a prescribed critical value ($\sigma_{critical}$). The critical value is determined based on the bus voltage magnitudes profile in the system.

The probabilistic index defined by (11) represents the relative contribution of each bus to critical modes of kth contingency condition. Then, we calculate the total participation in all critical modes (TPCM) for each bus considering all possible contingencies by following equation:

$$TPCM_i = \sum_{k=1}^{L} \sum_{j=1}^{m} P_{outage}(k) \times \left(\frac{P_{ij}}{\sigma_j} \right) \quad (12)$$

where TPCM$_i$ is the total participation of bus i in all critical modes under all possible contingencies and L is the number of possible contingencies.

For calculation of TPCM the outage of all lines is considered. If system has critical modes in normal state (i.e. without any outage) due to special operating conditions, then this condition could be included in (12) with consideration of corresponding probability.

TPCM demonstrates the relative contribution of each bus to system voltage instability under all possible system states. According to (12), the larger the magnitude of bus participation factor in critical modes, that bus is more effective in voltage instability. On the other hand, the smaller the magnitude of positive σ_j, that mode is more critical. In addition, bus contributions to voltage instability under contingencies are weighted by the likelihood of contingencies occurring. Consequently, contingencies with higher probability will be more important in locating FACTS devices.

TPCM values are calculated for every bus using (12). Buses are then ranked by their corresponding TPCM values. In general, the larger value a bus has the more effective it will be. The bus with the largest TPCM is considered as the best location for one shunt FACTS device, Because according to definition of TPCM, that bus is more effective in more probable contingencies (i.e. larger $P_{outage}(k)$) or is more effective in more critical modes (i.e. smaller σ_j).

For a large-scale power system, more than one FACTS device may have to be installed in order to achieve the desired performance. However, budgetary constraints force the utilities to limit the number of FACTS devices to be placed in a given system. Given such a limit on the total number of FACTS devices to be installed in a power system, the location of the next controllers can be determined according to the ranking of buses in an iterative approach. At each step, one FACTS device is installed at the bus with the largest TPCM value. Note that installation of a controller in the determined location mitigates the critical modes caused by that bus and other buses close to it. Therefore, the ranking of buses after the next iteration does not necessarily match the previous one. The flowchart of Fig. 1 demonstrates the proposed strategy of FACTS devices locating.

V. CASE STUDY

In this section, the IEEE 14 bus test system shown in Fig. 2 is used to demonstrate the proposed approach of placing FACTS in a power system. The load and generation of the system is scaled by the factor of 0.95.

Performing load flow for the normal state of the system, the smallest eigenvalue of the reduced Jacobian matrix is determined as $\sigma_{\min} = 2.71$. With the assumption of $\sigma_{critical} = 1$, the calculated eigenvalue is not critical. Then, contingency analyses corresponding to line outages are performed. In this simulation, the failure probability of all lines is assumed equal to 0.02. In each contingency state, the eigenvalues of reduced Jacobian matrix are calculated. The three smallest eigenvalues of each state are shown in table 1 where the critical eigenvalues are specified by colored cells. One can see that critical eigenvalues exist only in two contingencies corresponding to the outage of lines 1 and 10. Bus participation factors associated with the critical eigenvalues are calculated using modal analysis. The result is shown in table 6 in the appendix. The TPCM value of buses is shown in table 2 which is calculated using (12). According to table 2, bus 12 has the largest TPCM. Therefore, it is chosen as the best location to place first FACTS device.

Installation of a shunt FACTS controller (e.g. a STATCOM) at bus 12, changes it to a PV bus. The voltage of this bus is constant until the shunt FACTS device reaches its reactive power limit. We set the voltage of this bus at 1.05 pu. The sufficient capacity to keep the voltage of bus 12 constant under all contingencies is 8 MVAr. After installing STATCOM at bus 12, we performed the contingency analysis again. Tables 3 and 4 present the results. According to table 3, one can see that the smallest eigenvalue in each contingency condition is increased considerably. However, the outage of line 1 still causes an eigenvalue smaller than the critical value, because we install the FACTS controller at a bus that is far from this line. When this line is out of circuit, injection of reactive power to bus 12 can not influence considerably the reactive losses caused by the overload of line 2.

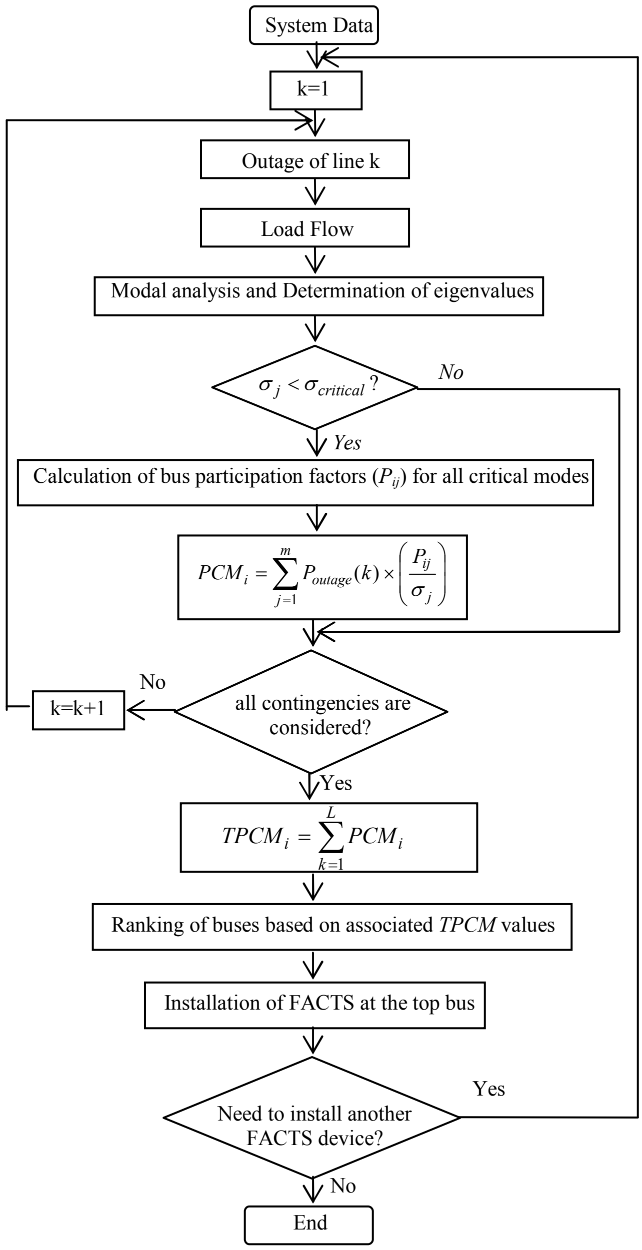

Fig. 1 flowchart of the proposed method

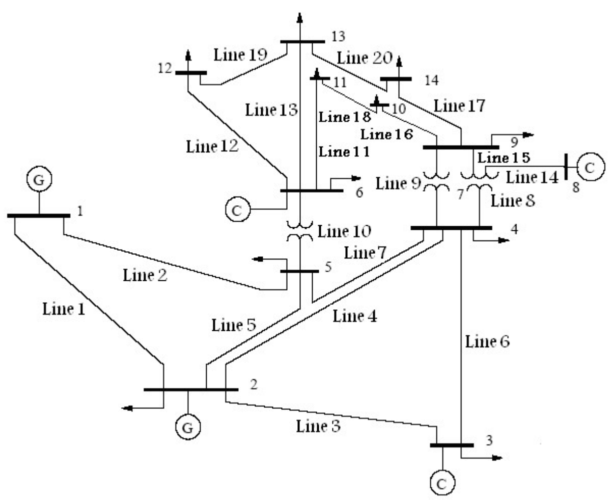

Fig. 2 IEEE 14-bus power system

TABLE 1
THE THREE SMALLEST EIGENVALUES FOR DIFFERENT CONTINGENCIES

contingency	$\sigma_{\min 1}$	$\sigma_{\min 2}$	$\sigma_{\min 3}$
1 line (1-2)	0.1202	2.5076	3.350
2 line (1-5)	2.6334	5.5253	7.6623
3 line (2-3)	2.5139	4.1422	5.5968
4 line (2-4)	2.6389	5.5318	7.6599
5 line (2-5)	2.6766	5.5468	7.6689
6 line (3-4)	2.6501	5.5453	7.6784
7 line (4-5)	2.6193	5.5263	7.6513
8 line (4-7)	2.4671	5.5083	7.6689
9 line (4-9)	2.4350	5.5267	7.6689
10 line (5-6)	0.4627	4.000	6.2199
11 line (6-11)	1.3764	4.5484	7.0003
12 line (6-12)	2.2747	3.4231	6.8293
13 line (6-13)	1.6374	3.7727	7.3455
14 line (7-8)	2.0172	6.5611	14.3417
15 line (7-9)	1.7331	5.4479	7.6090
16 line (9-10)	1.9465	3.0652	9.3284
17 line (9-14)	1.9693	3.0471	6.8017
18 line (10-11)	2.1765	5.3288	5.5991
19 line (12-13)	2.6711	4.1235	5.9822
20 line (13-14)	1.7820	5.4382	5.6578

TABLE 2
TPCM VALUES OF BUSES

Bus No.	TPCM	Bus No.	TPCM
1	0	8	0.0119
2	0.0090	9	0.0166
3	0.0096	10	0.0183
4	0.0101	11	0.0207
5	0.0092	12	0.0242
6	0.0216	13	0.0235
7	0.0134	14	0.0212

TABLE 3
THE SMALLEST EIGENVALUE ASSOCIATED WITH CONTINGENCIES AFTER INSTALLATION OF STATCOM AT BUS 12

contingency	$\lambda_{\min}$	contingency	$\lambda_{\min}$
Normal State	2.7971		
1 line (1 - 2)	0.5987	11 line (6 - 11)	1.3906
2 line (1 - 5)	2.7109	12 line (6 - 12)	2.8101
3 line (2 - 3)	2.5755	13 line (6 - 13)	2.4062
4 line (2 - 4)	2.7171	14 line (7 - 8)	2.0626
5 line (2 - 5)	2.7576	15 line (7 - 9)	1.7806
6 line (3 - 4)	2.7290	16 line (9 - 10)	1.9465
7 line (4 - 5)	2.6970	17 line (9 - 14)	2.1623
8 line (4 - 7)	2.5354	18 line(10 - 11)	2.2324
9 line (4 - 9)	2.5044	19 line (12 - 13)	2.6712
10 line (5 - 6)	1.8798	20 line (13 - 14)	1.7820

TABLE 4
TPCM VALUES OF BUSES

Bus No.	TPCM	Bus No.	TPCM
1	0	8	0.0043
2	0.0026	9	0.0039
3	0.0029	10	0.0037
4	0.0027	11	0.0025
5	0.0022	12	0
6	0.0010	13	0.0008
7	0.0040	14	0.0028

Depending upon the available budget, the placement of FACTS device can proceed by following the new ranked list of table 4, where bus 8 as a PV bus will be the second choice. This means that we need to increase the capacity of reactive power generation at this bus. however, we can keep the reactive power capacity of this bus constant and install the FACTS device in the next top bus, which is bus 7. To keep the voltage of buses 7 and 12 constant under all contingencies, we need to install FACTS devices with the capacity of 20MVAr and 11MVAr at these buses , respectively. After installing the second FACTS device, all eigenvalues are increased and the critical eigenvalues are disappeared. Table 5 presents the smallest eigenvalue in each system state. Now, there is no critical eigenvalue and therefore, TPCM value for all buses is zero.

Comparison of the result obtained here with those of [3], shows the same improvement of system voltage stability in contingency conditions as well as normal state. Nevertheless, it needs a smaller size of FACTS devices to be installed. In addition, the proposed method has less time consuming calculations. In [3], the optimal SVC allocations are 0.19, 0.25, and 0.25 pu at buses 10, 13, and 14, respectively and these reactive power are fully used for the outage of line 1. On the other hand, the optimal FACTS devices allocations obtained by the proposed method are 0.2, and 0.11 pu at buses 7, and 12, respectively. Therefore, the number of STATCOMs to be installed is decreased as well as their reactive power capacity. The reason is that the allocated FACTS devices proposed by [3] are applied only in one area of the network (i.e. at three close buses). This causes a non-uniform reactive power supply in the network. However, the method proposed in this paper, allocates FACTS devices in two separated areas of the network that leads to a more uniform reactive power supply in the system. Consequently, it will be effective in more contingency conditions correspond to the outage of lines.

TABLE 5
THE SMALLEST EIGENVALUE ASSOCIATED WITH CONTINGENCIES AFTER INSTALLATION OF STATCOM AT BUS 7

contingency	$\lambda_{\min}$	contingency	$\lambda_{\min}$
Normal State	3.8519		
1 line (1 - 2)	2.0977	11 line (6 - 11)	1.9540
2 line (1 - 5)	2.7668	12 line (6 - 12)	3.8724
3 line (2 - 3)	3.7513	13 line (6 - 13)	3.1345
4 line (2 - 4)	3.8393	14 line (7 - 8)	3.8520
5 line (2 - 5)	3.8466	15 line (7 - 9)	1.7835
6 line (3 - 4)	3.8452	16 line (9 - 10)	1.9465
7 line (4 - 5)	3.8348	17 line (9 - 14)	2.1620
8 line (4 - 7)	3.8352	18 line (10 - 11)	3.5056
9 line (4 - 9)	3.5957	19 line (12 - 13)	3.6140
10 line (5 - 6)	2.5203	20 line (13 - 14)	2.4246

VI. CONCLUSION

Application of FACTS devices can improve considerably the system voltage stability and prevent voltage collapse. Nevertheless, location of FACTS devices strongly influences their damping effect. Therefore, optimal location of FACTS is a very important issue. In this paper, we investigated the application of FACTS devices to extend voltage stability margin in contingency conditions. A probabilistic index based on modal analysis and calculation of bus participation factors was defined which can be used to rank of system buses based on their effect on system voltage stability enhancement under all possible contingencies. The proposed method selects the most effective bus to voltage instability as the best place for installing FACTS. Results obtained from simulations show that the proposed method could allocate FACTS devices with a simple and straightforward approach in order to improve system voltage stability with consideration of contingency conditions.

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APPENDIX

TABLE 6
BUS PARTICIPATION FACTORS IN CRITICAL CONTINGENCY CONDITIONS

Contingency / Bus	1 line(1-2)	10 line(5-6)
2	0.0544	0
3	0.0577	0
4	0.0603	0.0017
5	0.0550	0.0008
6	0.0816	0.1867
7	0.0773	0.0133
8	0.0716	0
9	0.0874	0.0486
10	0.0905	0.0757
11	0.0890	0.1373
12	0.0893	0.2172
13	0.0900	0.1971
14	0.0961	0.1217