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Comprehensive Study of Static Voltage Stability Methods for Proper Placement and Sizing of STATCOM to Enhance Voltage Stability

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Voltage stability assessment and its enhancement have become the important aspects for modern power system operation and control. Static and dynamic are the two most important methods, to analyze the voltage stability. This paper presents a comprehensive study of almost all static voltage stability analysis methods such as PV-QV curve, Modal analysis, Load flow based voltage stability indices and continuation power flow method, for enhancement of voltage stability. Implementation of FACTS device like STATCOM, in the system, which is having fast and very flexible control, to achieve the maximum enhancement of loading margin in the power system is also presented. This enables one to identify the system's critical area and to develop systematic approach for proper placement and sizing of STATCOM in the power system network.

The main contribution of this paper is identification of weak buses of power system using static voltage stability analysis methods and deciding proper location and size of STATCOM for voltage stability enhancement, under a novel load increase scenario i.e. active and reactive loads have been changed simultaneously at all the load buses under consideration. The study has been carried on various standard IEEE test systems using MATLAB programming as well user friendly Power System Analysis Toolbox (PSAT) of MATLAB. The results of standard IEEE14 and IEEE6 bus test systems have been presented in this paper.

Keywords: *Static voltage stability, Loading margin, PV-QV curve method, Modal analysis, VSI, Power flow, CPF, STATCOM.*

1.0 INTRODUCTION

Recently, voltage stability has gained enormous importance in the power system operation and control. Voltage stability problems mainly occur under heavily stressed conditions of power system. In general, voltage stability is defined as the ability of a power system to maintain steady state voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition [1, 22-24]. Voltage instability occurs mainly due to inadequate Installation of suitable compensating devices at proper locations is an important issue concerned with the reactive power support. Flexible AC transmission system (FACTS) devices like Static Synchronous Compensator (STATCOM) are power electronics based systems, which improves the voltage profile of the system [25]. Furthermore, the voltage stability can be studied either on static or dynamic considerations [2]. reactive power support at critical parts of the power systems.

Static methods of voltage stability evaluation, [3-17] are based on the algebraic equations obtained

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from the power flow model and the dynamic methods are modeled as differential equations. Although the voltage stability is essentially dynamic, the static methods are important owing to their high degree of computational efficiency and for the information they give with respect to sensitivity, stability margin and level of instability.

Static voltage stability can be analyzed effectively and efficiently. These methods examine the viability of the equilibrium point represented by a specified operating condition of the power system. Conventional PV and QV curve methods [3-5] are useful for conceptual analysis of voltage stability. Modal analysis, another static method based on eigen values and eigen vectors, [6-8], identifies the voltage stability critical areas and elements at the point of collapse. To predict how close the system is to the voltage collapse point, many voltage stability indices have been developed. These indices are very much helpful in identification of the weakest bus, line and area in the power network. Usually their values changes between 0 (no load) and 1 (voltage collapse). In [9-10], minimum singular values for the power flow Jacobian matrix, has been used as a static voltage stability index. Chebbo et.al [11] studied voltage collapse at load buses of the network using the concept of maximum power transfer between two buses. Power flow based line voltage stability indices have been proposed in reference [12-13]. In [14-15], the L-index technique to calculate voltage stability margins and locate the weak areas of the network has been presented. Singularity of the conventional Jacobian matrix (drawback of Modal method) at the maximum loading point can be avoided by continuation power flow (CPF) method [16-17]. In this CPF method, conventional power flow equations are slightly reformulated and locally parameterized continuation technique may be applied. These reformulated set of equations remains well conditioned during the resulting, so that the error due to singularity of Jacobian is not encountered. Thus static voltage stability methods identify the weakest possible areas in the power system networks. Furthermore, the loadability margin of the power system can be modified by adding shunt capacitors and/or FACTS controllers at the bus where voltage magnitude is low (weak bus). STATCOM is an important member of FACTS family. Owing to its high cost, proper location of it is utmost important. The systematic approach for this has been presented in [18-20] and MATLAB user friendly power system analysis toolbox (PSAT) [21, 26] is extensively used for analysis purpose.

This paper presents the comprehensive study of almost all static methods of voltage stability analysis. The present work is mainly concerned with identification of the critical bus for placing FACTS controller, STATCOM, properly, under a novel load increase pattern. The novelty of load increase, in the context of the present research, is that in the available literature, load increment (active, reactive and, both active and reactive) has been carried out at individual load buses only. Whereas, in the present research work, along with individual load increment, the active and reactive loads have been changed simultaneously at all the load buses under consideration. The main highlights of the proposed work are:-

1] Evaluation of Static methods of voltage stability analysis such as basic analysis tool-PV and QV curve method, Modal analysis, Bus and line voltage stability indices and Continuation power flow method. All these evaluations has been successfully carried out on various standard IEEE bus systems using special written codes in MATLAB programming and the results of standard IEEE14 bus test system have been demonstrated specifically.

2] Weak bus identification.

3] Installation of STATCOM at a weak bus, identified by static method of voltage stability analysis, under novel load increase pattern. This is very useful for getting maximum benefits of reactive compensation methods which depend greatly on the placement of FACTS devices. Continuation power flow feature of PSAT is used for this purpose.

4] Determining the size of STATCOM to be placed.

2.0 METHODS OF EVALUATION OF STATIC VOLTAGE STABILITY

Static voltage stability is defined as the capability of the system to withstand a small disturbance without abandoning a stable operating point [1, 22-24]. There are different methods to analyze static voltage stability problem to examine two important aspects [22] mainly-

- Proximity to voltage instability
- Mechanism of voltage instability

These methods are enlisted as-

2.1 Conventional basic analytical tool- PV-QV curve method

2.2 Method based on singularity of power flow Jacobian matrix at the point of voltage collapse (Modal Analysis)

2.3 Method of voltage stability indices (VSI)

2.4 Continuation power flow method (CPF)

All these methods are important for weak bus identification (buses with low level of voltages) and which gives correct information for installation of reactive power compensation devices.

2.1 PV-QV curve method

These are the basic analytical tools useful to show the voltage collapse point of the buses in the power system network. Typical PV and QV curves are shown in Figures 1 and 2. These curves are generated by writing special code in MATLAB using basic power equations as-

$$P = \frac{EV}{X} * \sin\theta \qquad \ldots(1)$$

$$Q = \frac{EV}{X} * \cos\theta - \frac{V^2}{X} \qquad \ldots(2)$$

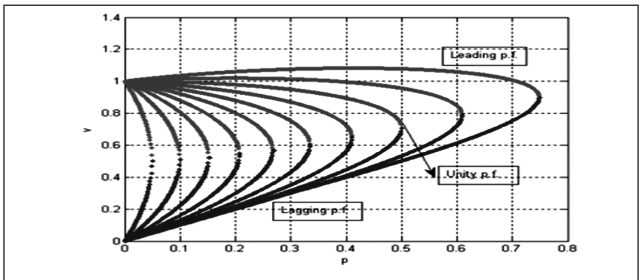

FIG. 1 TYPICAL P-V CURVE

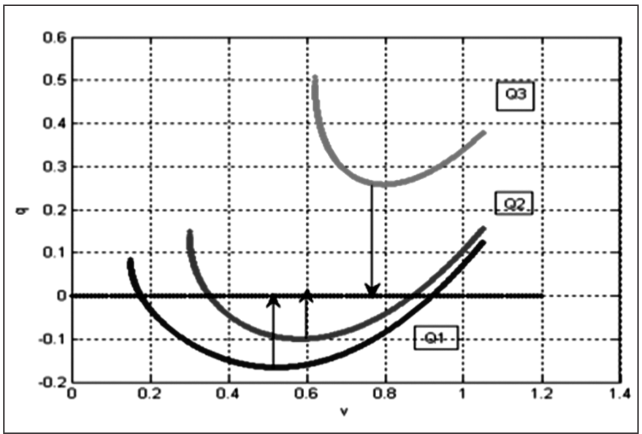

FIG. 2 TYPICAL Q-V CURVE

Certain observations have been made from these curves as-

From P-V curve-

- It represents the variations in voltage at a particular bus as function of total active power supplied to load.
- The upper part of PV curve shows stable region and the lower part of PV curve shows unstable region.
- Tip of "nose curve" is called the maximum loading point or critical point.

From Q-V curve-

- Curve Q1 refers to the system operation far below the maximum power. There is no need for compensation.
- Curve Q2 refers to more loaded situation.
- Curve Q3 corresponds to the situation where the system cannot operate without reactive power injection.

Both methods are widely used as index to find the proximity to voltage collapse, but they have few disadvantages like convergence problem occurring at critical point, lack of information about critical buses etc.

2.2 Method based on singularity of power flow Jacobian matrix at the point of voltage collapse (Modal Analysis)

Modal analysis is widely used to determine the areas which are most vulnerable to voltage stability problem and to select the best location for installing reactive compensation equipment. This method involves the computation of critical eigen value of the reduced Jacobian matrix and associated participation factors. The bus which has the highest bus participation factor is identified as the weakest bus.

This method is mainly dependent on the power flow Jacobian matrix J. The matrix J is reduced to J_R by keeping real power constant.

Let $J_R = \xi\lambda\eta$ …(3)

where,

J_R = is the steady state reduced Jacobian matrix of the system.

ξ = right eigenvector matrix of J_R

η= left eigenvector matrix of J_R

λ= diagonal eigenvalue matrix J_R

Reduced Jacobian matrix can be defined as-

$$J_R^{-1} = \xi\lambda^{-1}\eta \quad \ldots(4)$$

System is defined as voltage stable if all the eigenvalues of J_R are positive. If any of eigenvalues is negative, the system is unstable, and voltage collapse point is reached when at least one of the eigenvalue reaches zero.

Bus, branch and generator participations are calculated based on the right and left eigenvectors which are useful to decide association of elements with the particular mode.

A. ***Bus Participation Factor***

Participation factor relating bus k to mode i is defined as the bus participation factor [6]-

$$P_{ki} = \xi_{ki} * \eta_{ki} \quad \ldots(5)$$

where,

ξ_{ki} = right eigenvector matrix of J_R of bus k to mode i

η_{ki}= left eigenvector matrix of J_R of bus k to mode i

Buses with large participation factors to the critical mode correspond to the most critical system buses.

B. ***Branch and Generator Participation Factor***

The branch participation factor denoting relative participation of branch j in an i^{th} mode is given by –

$$P_{ji} = \frac{\Delta Q_j}{\Delta Q_{max}} \quad \ldots(6)$$

where,

ΔQ_j = incremental change in reactive power loss of branch j

ΔQ_{max} = maximum incremental change in reactive power loss among all branches.

The generator participation factor denoting the relative participation of machine m in an i^{th} mode is given by –

$$P_{mi} = \frac{\Delta Q_m}{\Delta Q_{max}} \quad \ldots(7)$$

where,

ΔQ_m = incremental change in reactive power generation of generator m

ΔQ_{max} = maximum incremental change in reactive power generation of all generators.

2.3 Method of Voltage Stability Indices (VSI)

Voltage stability indices (bus or line) are useful mainly for determining the condition of voltage stability in a power system. These are obtained from basic power flow equations. They provide important information regarding the proximity of a given operating point to voltage collapse. These indices are simple, easy to implement and computationally inexpensive and are based on power transmission concept in a single line connected between as shown in Figure 3.

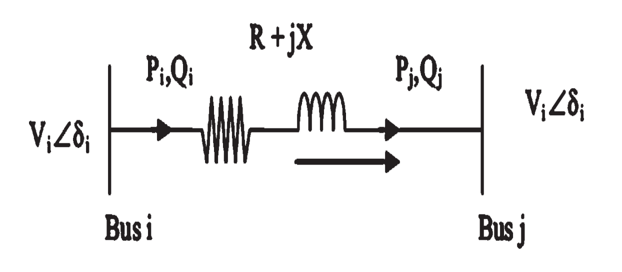

FIG. 3 SINGLE LINE DIAGRAM OF TRANSMISSION LINE

Some of these stability indices are [9-15]:

- *Fast Voltage Stability Index [FVSI]*

The index is given as-

$$FVSI_{ij} = \frac{4 * Z^2 * Qj}{Vi^2 * X} \quad \ldots(8)$$

- *Line Stability Index [Lmn]*

The index is given as-

$$L_{mn} = \frac{4 * X * Qj}{[Vi * \sin(\theta - \delta)]^2} \quad \ldots(9)$$

- *Line Stability Factor [LQP]*

The line stability factor *LQP* is given as-

$$LQP = 4 * \left[\frac{X}{Vi^2}\right] * \left[\frac{X}{Vi^2} * Pi^2 + Qj\right] \quad \ldots(10)$$

where:

θ:line impedance angle.

δ:angle difference between the sending end and the receiving end voltage.

X: line reactance.

Q_j: reactive power flow at the receiving end.

P_j: active power flow at the receiving end.

P_i: active power flow at the sending end.

V_i: sending end voltage.

Z: R + jX, line impedance.

To maintain a secure condition, *Lmn*, *FVSI* and *LQP* should be maintained less than 1.

- *Voltage Collapse Proximity Indices [VCPI]*

The index *VCPI* (power) is defined as follows-

$$VCPI_{(power)} = \frac{P_r}{P_{rmax}} = \frac{Q_r}{Q_{rmax}} \quad \ldots(11)$$

The formula for the index VCPI (loss) is as follows-

$$VCPI_{(loss)} = \frac{P_{loss}}{P_{loss(max)}} = \frac{Q_{loss}}{Q_{loss(max)}} \quad \ldots(12)$$

where the values of P_r, Q_r, P_{loss} and Q_{loss} are obtained from conventional power flow calculations and $P_{r(max)}$ and $Q_{r(max)}$ are the maximum active and reactive power that can be transferred through a line, $P_{loss(max)}$ and $Q_{loss(max)}$ are the real and reactive loss in the line. The VCPI indices vary from 0 (no load condition) to 1 (voltage collapse).

- *L-index* [14]

The indicator L is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. It is defined for each load bus j as-

$$L_j = \left| 1 - \frac{\sum_{i \in \alpha_G} Fji * Vi}{Vj} \right| \quad \ldots(13)$$

The index Lj indicates the proximity of voltage collapse of a power system. A value Lj=1 indicates voltage collapse condition at bus j. Hence for complete system a global indicator L is given-

$$L = \max_{j \in \alpha_L} \{Lj\} \quad \ldots(14)$$

where α_L and α_G are the set of load and generator buses, respectively. V_i and V_j are voltage phasors and the elements of F_{ji} are calculated from the [Y] bus matrix for the network. The L-index varies in a range between 0 (no load) and 1 (voltage collapse).

2.4 Continuation Power Flow Method (CPF)

Continuation power flow method overcomes the problem of singularity of Jacobian matrix at maximum loading point. To apply continuation technique, the power flow equations must be reformulated to include load parameter λ. This method is based on predictor–corrector technique shown in Figure 4. This method provides valuable insight into the voltage stability of system and the areas prone to voltage collapse and can be used for tracing complete PV curve.

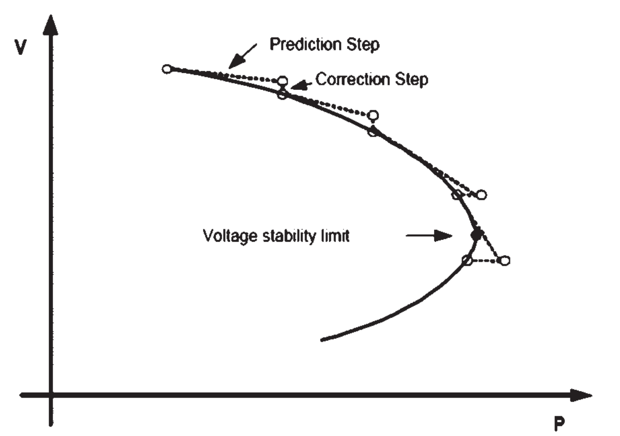

FIG. 4 THE PREDICTOR-CORRECTOR SCHEME OF CONTINUATION POWER FLOW METHOD

It has three basic steps [16-17]:

1] Reformulation of NR-power flow equations to include load parameter λ-

The conventional power flow equations -

$$P_i - V_i \sum_{j=1}^{n} V_j Y_{ij} \cos(\theta_i - \theta_j - \gamma_{ij}) = 0 \qquad \ldots(15)$$

$$Q_i - V_i \sum_{j=1}^{n} V_j Y_{ij} \sin(\theta_i - \theta_j - \gamma_{ij}) = 0 \qquad \ldots(16)$$

are modified by incorporating λ as-

$$P_{Li} = P_{Li0}(1 + \lambda K_{Li})$$
$$Q_{Li} = Q_{Li0}(1 + \lambda K_{Li})$$
$$P_{Gi} = P_{Gi0}(1 + \lambda K_{Gi}) \qquad \ldots(17)$$

Applying continuation power flow algorithm to these equations, the whole set of equations can be written as-

$$F(\theta(v, \lambda) = 0 \qquad \ldots(18)$$

where θ ----- Vector of bus voltage angle

v ---- Vector of bus voltage magnitude

and λ ----- Loading parameter

It starts from a known solution and uses predictor–corrector scheme to find subsequent solutions at different load levels.

2] Predictor step-

A predictor step can be given by equation (19), where First term is conventional load flow Jacobian augmented by one column and second term is tangent vector‘t’.

$$\begin{bmatrix} F_\theta & F_v & F_\lambda \end{bmatrix} \begin{bmatrix} d\theta \\ dv \\ d\lambda \end{bmatrix} = 0 \qquad \ldots(19)$$

3] Corrector step-

It corrects the Predicted solution by using modified NR-power flow with new set of equations as-

$$\begin{bmatrix} F(x) \\ x_k - \eta \end{bmatrix} = \begin{bmatrix} 0 \end{bmatrix} \qquad \ldots(20)$$

3.0 STATIC SYNCHRONOUS COMPENSATOR

Static Synchronous Compensator (STATCOM) is part of the flexible alternating current transmission system (FACTS) device family. It is based on a Voltage Source Converter (VSC), consists of thyristors with turn-off capabilities like GTO or IGBT’S, a dc storage capacitor and a series reactor [18, 25]. It either supplies reactive power to the bus where it is connected or absorbs reactive power from that same bus in order to control the bus’s voltage amplitude. Figure 5 shows the structure and operational characteristics. In this paper, the inherent STATCOM model in MATLAB PSAT toolbox is applied.

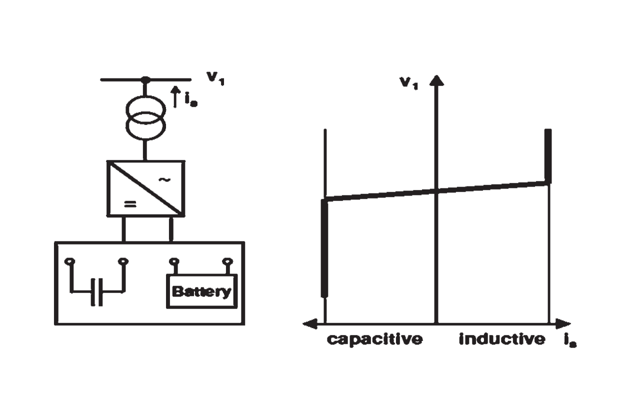

FIG. 5 STATCOM STRUCTURE AND VOLTAGE/ CURRENT CHARACTERISTIC

4.0 DEVELOPMENT OF SYSTEMATIC METHODOLOGY FOR COMPREHENSIVE STUDY

The motivation of this work is to study various methods of static voltage stability analysis for proper installation of FACTS device (STATCOM) to enhance voltage stability. The study is carried out on different standard IEEE bus systems under different conditions of loading as well as contingencies. Such study is found out to be very helpful and promising in determination of placement and sizing of STATCOM to enhance the voltage stability. Following are the steps to be followed for doing such vast study-

A] Identification of the weakest bus using mainly three stability criterion namely, Modal analysis, method of voltage stability indices and continuation power flow method. All these methods are based on Newton Raphson load flow method.

B] Comparative analysis of these methods for critical bus identification and an important conclusion regarding their accuracy can be drawn.

C] Once the critical bus identification has been investigated, installation of STATCOM is focused under novel load increase scenario as well as different contingencies like generator outages and line outages.

The steps described above can be explained through block diagram shown in Figure 6.

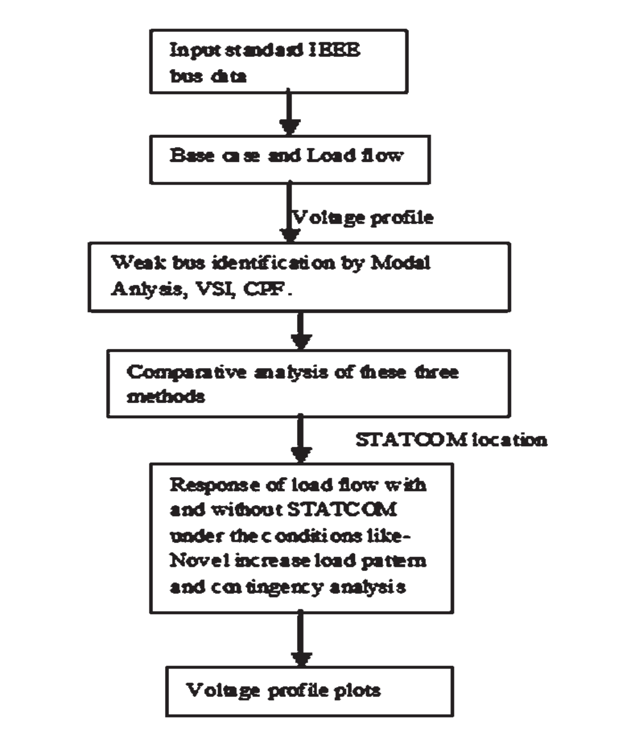

FIG. 6 OUTLINE FOR SYSTEMATIC METHODOLOGY FOR PLACEMENT OF STATCOM

Thereafter proper size of STATCOM can be decided by using CPF feature of PSAT, MATLAB user-friendly toolbox.

5.0 RESULTS AND DISCUSSIONS

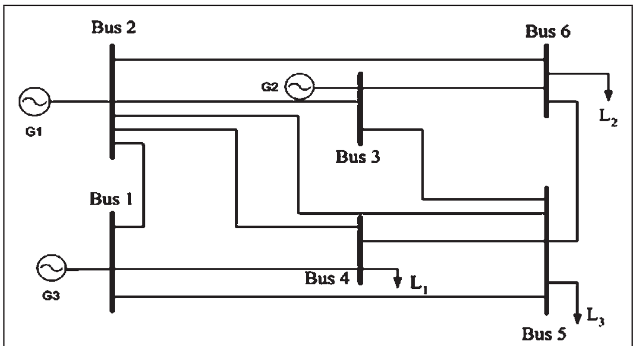

FIG.7 STANDARD IEEE-6 BUS SYSTEM

In order to study voltage stability problem with static methods of evaluation for suitable location of STATCOM, the simulations were run on various standard IEEE bus test systems under novel load increase pattern as well contingencies and the results of standard IEEE-6 and IEEE-14 bus test systems have been shown specifically. Standard IEEE-6 bus test system consisting of two generators, three load buses and eleven interconnected branches and standard IEEE-14 bus test system consisting of five generators, nine load buses, and twenty interconnected branches are shown in Figure 7 and Figure 8.

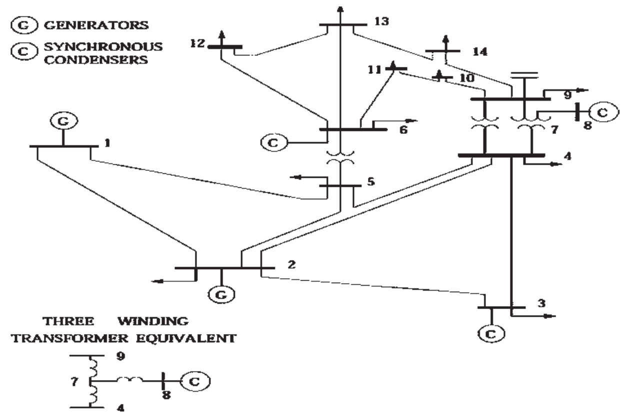

FIG. 8 STANDARD IEEE-14 BUS SYSTEM

The weakest bus is determined using three criterion mentioned earlier as Modal analysis, Method of VSI, CPF. A special code written in MATLAB has been developed for first two methods as well as for novel load increase pattern whereas CPF feature of PSAT is extensively used for demonstrating results of CPF method with and without STATCOM, for determining size of STATCOM and also for screening of contingencies. The computations of all these static methods are based on N-R load flow in MATLAB environment.

5.1 Comparative analysis of static voltage stability methods

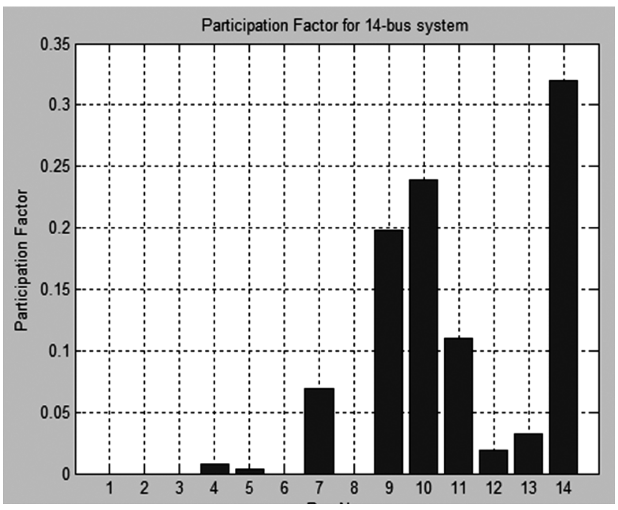

FIG. 9 BUS PARTICIPATION FACTOR ASSOCIATED FROM MINIMUM EIGENVALUE FOR CRITICAL OPERATING CASE.

MODAL ANALYSIS For the standard IEEE-14 bus test system, the eigen values of the reduced Jacobian matrix J_R have been calculated as shown in Table 1 and it can be noticed that the smallest eigenvalue = 2.7089, hence mode 7 is the most critical mode. The bus participating factor for this mode has been calculated and the result is shown in Figure 9.

TABLE 1
THE VALUE OF EIGEN VALUE ASSOCIATED WITH THE REDUCED JACOBIAN MATRIX

Mode	Eigen Value
1	65.3806
2	39.4295
3	21.8093
4	18.8763
5	16.3490
6	11.2569
7	2.7089
8	5.5424
9	7.6209

Here, the largest participation value (0.3198) at bus 14 indicates highest contribution of this bus to voltage collapse. Hence bus 14 is identified as weak bus by this modal analysis technique.

METHOD OF VSI

To analyze the system using this method under stressed conditions, following different sets of loading pattern is adapted here-

Case 1: Active load change at individual load bus.

Case 2: Reactive load change at individual load bus.

Case 3: Active and Reactive load change at individual load bus.

Case 4: Active and Reactive load change simultaneously on all load buses.

A program to calculate the index for each line was developed with novelty method of load increase scenario. Table 2 illustrates the results for different loading pattern. The results shown in Table 2 are only for bus no.14 (to avoid lengthiness).

Variations of various indices can be plotted against the different type of loadings to understand the response of critical lines on concerned load bus. However, in this paper, variation of Line indices such as FVSI, Lmn and LQP with reactive power load only for critical lines of bus 14 (line 16: connected between bus 9 and 14, and line 25: connected between bus 13 and 14) have been shown in Figure 10, Figure 11 and Figure 12 respectively.

For any kind of loading, bus 14 is found out to be weak bus.

TABLE 2

RESULTS FOR VSI OF IEEE 14-BUS TEST SYSTEM

A] Load change at individual load bus

Loading pattern at Bus14	Lines	FVSI	Lmn	LQP	VCPI(P)	VCPI(l)	Max. L-index	VSF
Active load change	5-6	0.9629	1.0504	0.9648	0.9671	-	0.7738	0.717916
	11-6	0.8881	0.8780	0.7234	0.7429	1.2160		
	12-6	1.1202	1.0727	0.9112	0.9354	1.6165		
	Remark: Bus 14 has minimum value of VSF and maximum L-index value with three critical lines mentioned above.							
Reactive load change	9-14	1.0014	0.9737	0.7880	0.01140	0.1033	0.2939	0.7913
	13-14	1.2667	1.2229	1.0101	0.0165	0.1459		
	Remark: Bus 14 has minimum value of VSF and maximum L-index value with two critical lines mentioned above.							
Both Active Reactive load change	5-6	1.0462	1.1232	1.0480	1.04492	-	0.7503	0.6666
	11-6	0.9893	0.9814	0.8058	0.8293	1.4167		
	12-6	1.2442	1.2036	1.0160	1.0452	1.5820		
	Remark: Bus 14 has minimum value of VSF and maximum L-index value with three critical lines mentioned above.							

B] LOAD CHANGE SIMULTANEOUSLY ON ALL LOAD BUSES

Loading pattern	Lines	FVSI	Lmn	LQP	VCPI(P)	VCPI(l)	Max. L-index	VSF
Active load change	4-2	1.4293	1.2893	1.8865	1.3570	-	0.5108	0.8577
	5-6	1.3189	1.5296	1.3483	1.3228	-		0.8661
	11-6	1.1024	1.0560	0.9006	0.9257	2.7707		0.9081
	12-6	1.3630	1.2826	1.1207	1.1424	2.7362		0.9221
	Remark: Bus 14 has maximum L-index value with critical lines mentioned above. Line 4-2 is least secured owing to minimum value of VSF.							
Reactive load change	4-9	1.3153	1.3247	1.0225	0.0749	0.3837	0.1977	0.9731
	14-9	0.9510	0.9357	0.7689	0.0002	0.0001		0.8779
	Remark: Bus 14 has maximum L-index value with critical lines mentioned above. Line 14-9 is least secured owing to minimum value of VSF.							
Both Active Reactive load change	4-9	1.0942	1.1606	1.3878	0.5655	-	0.3670	0.8660
	5-6	1.0106	1.0859	1.0229	1.0148	-		0.9098
	11-6	0.9413	0.9199	0.7680	0.7878	2.3681		0.9038
	12-6	1.1512	1.1057	0.9421	0.9617	1.6082		0.9227
	Remark: Bus 14 has maximum L-index value with critical lines mentioned above. Line 4-9 is least secured owing to minimum value of VSF.							

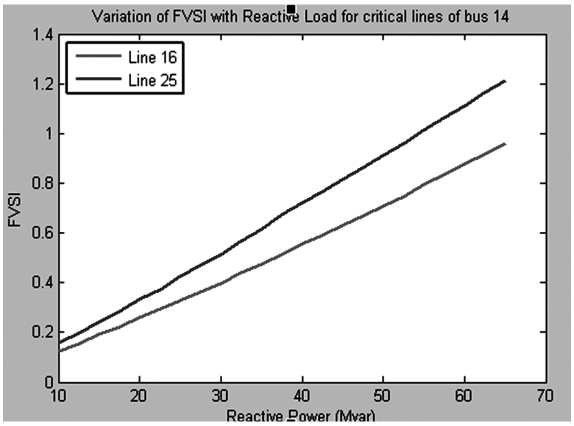

FIG.10 VARIATION OF FVSI WITH REACTIVE LOAD

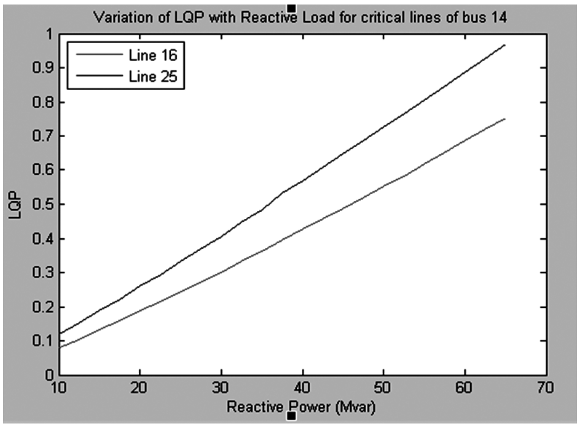

FIG.11 VARIATION OF LQP WITH REACTIVE LOAD

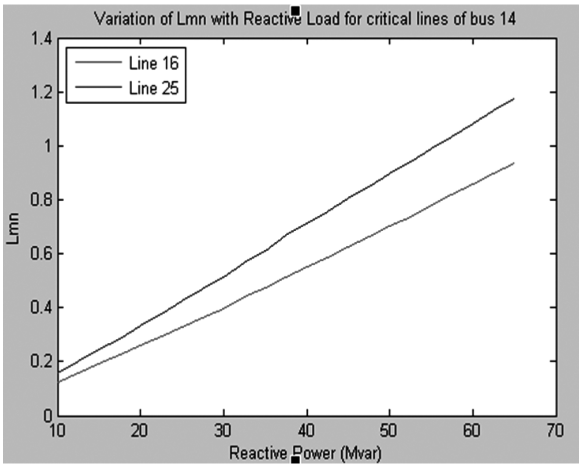

FIG.12 VARIATION OF LMN WITH REACTIVE LOAD

CONTINUATION POWER FLOW METHOD (CPF)

For identification of weak bus by this method, a special code in MATLAB is developed. The results obtained using this programme is compared with those obtained using CPF feature of PSAT. Results of this have been shown in figure 13, which shows that bus no.14 is the weakest bus (minimum voltage level at bus 14, 0.68148 p.u.).

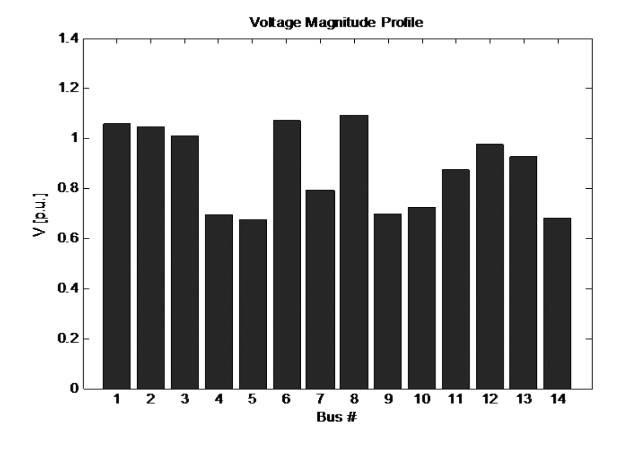

FIG.13 VOLTAGE MAGNITUDE PROFILE

Thus the results obtained by these methods produce an important conclusion as-

Owing to singularity of Jacobian at voltage collapse point in modal analysis technique and the threshold values of all VSI are not fixed rather are changing with operating conditions, critical bus identification is better carried out by CPF method and is the most accurate method for estimating the loading margin.

5.2 Proper placement and sizing of STATCOM to enhance voltage stability

Once the critical bus has been identified, simulation for proper installation of STATCOM is being carried out using CPF feature of user friendly MATLAB toolbox, PSAT. For this following different cases are considered –

Case 1:- Improvement in voltage magnitude profile and the establishment of lodability margin with and without properly placed STATCOM.

Case 2:- Evaluation of the system under stressed conditions with and without STATCOM, connected one by one to the load buses. Stressed conditions are created on the system by considering the same sets of loading pattern which was adapted in the previous method of VSI.

Case 3:- Decision of proper size of STATCOM by establishing lodability margin for different ratings of STATCOM.

Case 4:- Screening of contingencies when generation outages and transmission line tripping are considered. Identification of critical contingency, under the presence of properly placed STATCOM is very much useful in power system planning and operation.

All the four cases mentioned above are successfully tested on a standard IEEE-6 bus and IEEE-14 bus test systems.

Case 1:- Figure 14 shows the improvement of voltage profile to enhance the voltage stability by proper placement of STATCOM at weak bus (bus no.14). Also the loadability margin has been improved as shown in Figures 15 and 16.The results are shown in Table 3.

TABLE 3		
VOLTAGE MAGNITUDE IN P.U. AND WEAK BUS		
Bus No.	**Vm without STATCOM in p.u.**	**Vm with STATCOM in p.u.**
1	1.06	1.06
2	1.045	1.045
3	1.01	0.92173
4	0.69289	0.92569
5	0.68532	1.07
6	1.07	0.98722
7	0.79138	1.09
8	1.09	0.95871
9	0.69736	0.95875
10	0.72065	0.95459
11	0.87511	1.0005
12	0.97628	1.0324
14	0.68148	1.0285
Remark: Max.loadability λ (p.u.) Without STATCOM= 2.8286, With STATCOM= 2.90911		

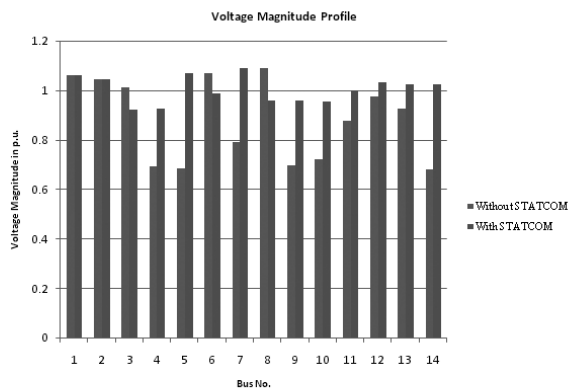

FIG. 14 VOLTAGE MAGNITUDE PROFILE WITH AND WITHOUT STATCOM

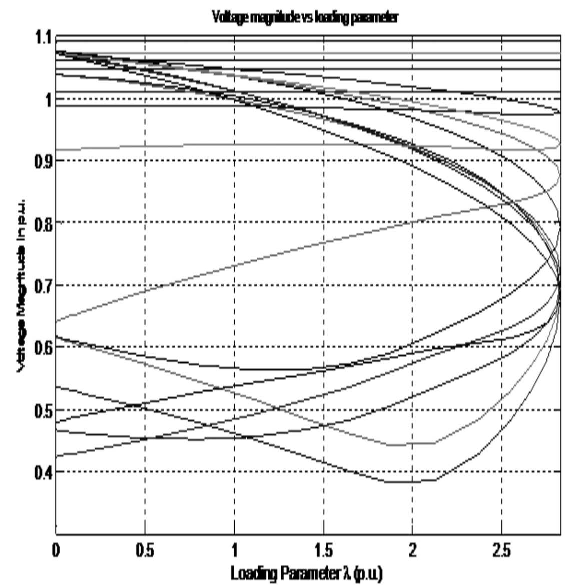

FIG.15 LOADABILITY MARGIN WITHOUT STATCOM

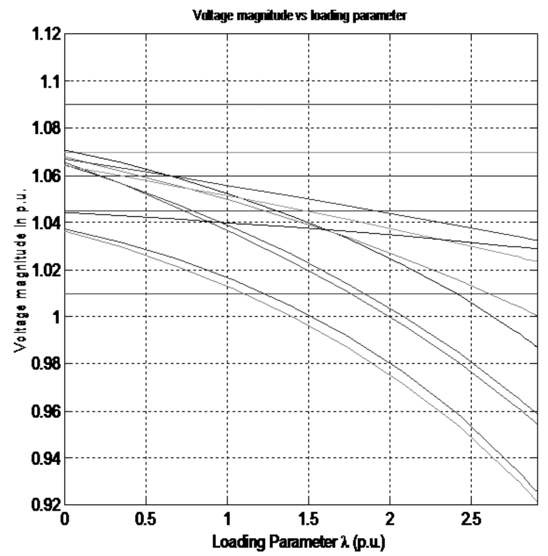

FIG. 16 LOADABILITY MARGIN WITH STATCOM

Thus bus 14 is found out to be weak bus and it is observed that loadability along with voltage magnitude gets improved when STATCOM is placed at bus 14.

Case 2:- For this case standard IEEE-6 bus system is considered and results for the different sets a,b,c,and d are presented in Table 4.

Here bus no.4 is identified as a weak bus. From the results it is clear that, STATCOM not only improves the voltage magnitude profile but also loadability margin when connected to bus 4.

Case 3:- To decide the optimal size of STATCOM, simulations are carried out on a standard IEEE-14 bus system. After running CPF, bus no.14 was found out to be a weak bus. Various capacities of STATCOM in the range of 1p.u. to 4 p.u. have been considered in order to determine the optimal size of STATCOM (1 p.u. corresponds to 100MVA). From Table 5, it is clear that optimal size of STATCOM not only depends on loadability margin but voltage magnitude of the respective buses also. STATCOM of size 3.25 p.u. (i.e. 325 MVA) gives satisfactory load bus voltages with increased loadability from 2.8286 p.u. to 2.9012 p.u. Hence STATCOM of size 3.25 p.u. can be finally recommended for its optimal placement to assess the voltage stability. Whereas though STATCOM of size 4 p.u. gives increased loadability margin from 2.8286 p.u. to 3.2770 p.u., it cannot be taken into consideration since voltage magnitude does not satisfactorily improve as is the case with 3.25 p.u. size of STATCOM. Figure 17 shows voltage magnitude profile with different sizes of STATCOM.

TABLE 4
RESULTS FOR NOVEL LOAD INCREASE PATTERN FOR CASE 2

A] Load change at individual load buses Loading pattern at bus 4 for sets a, b and c and STATCOM connected to bus 4

Sl. No.	**Without STATCOM**		
	Set a	**Set b**	**Set c**
Vm_4	0.5322	0.5292	0.5277
Vm_5	0.7408	0.7421	0.7496
Vm_6	0.8425	0.8441	0.8507
λ_{max}	10.7395	10.6583	10.2445
Remark: All values are in p.u.			
Sl. No.	**With STATCOM**		
	Set a	**Set b**	**Set c**
Vm_4	0.9856	0.9877	0.9895
Vm_5	0.8311	0.8344	0.8419
Vm_6	0.8599	0.8626	0.8698
λ_{max}	11.1066	10.9402	10.4867

B] Simultaneous load change at all load buses STATCOM connected to bus 4

Sl. No.	**Without STATCOM**		
	Set a	**Set b**	**Set c**
Vm_4	0.5246	0.5263	0.5205
Vm_5	0.7238	0.7141	0.7051
Vm_6	0.83055	0.8229	0.8179
λ_{max}	10.6491	10.546	10.0411
Remark: All values are in p.u.			
Sl. No.	**With STATCOM**		
	Set a	**Set b**	**Set c**
Vm_4	0.9852	0.9885	0.9907
Vm_5	0.8194	0.8134	0.8101
Vm_6	0.8500	0.8445	0.8429
λ_{max}	10.9930	10.7455	10.1562

TABLE 5
LOADABILITY MARGIN AND SIZE OF STATCOM FOR CASE 3

Sl.No.	Without STATCOM	With STATCOM rating in p.u.				
		1 p.u.	2 p.u.	3 p.u.	3.25 p.u.	4 p.u.
V_{m4}	0.6929	0.9984	0.9679	0.9318	0.9217	0.8897
V_{m5}	0.6853	1.0031	0.9730	0.9361	0.9257	0.8919
V_{m7}	0.7914	1.0416	1.0194	0.9941	0.9872	0.9656
V_{m9}	0.6973	1.0298	0.9970	0.9668	0.9587	0.9339
V_{m10}	0.7206	1.0217	0.9929	0.9626	0.9546	0.9305
V_{m11}	0.8751	1.0404	1.0231	1.0051	1.0005	0.9866
V_{m12}	0.9763	1.0506	1.0420	1.0343	1.0324	1.0275
V_{m13}	0.9259	1.0530	1.0351	1.0257	1.0234	1.0172
V_{m14}	0.6815	1.0377	1.0336	1.0296	1.0285	1.0257
λ_{max}	2.8286	1.4424	2.1559	2.7639	2.9012	3.2770
Remark- STATCOM of size 3.25 p.u. gives satisfactory load bus voltages with increased loadability from 2.8286 p.u. to 2.9012 p.u.						

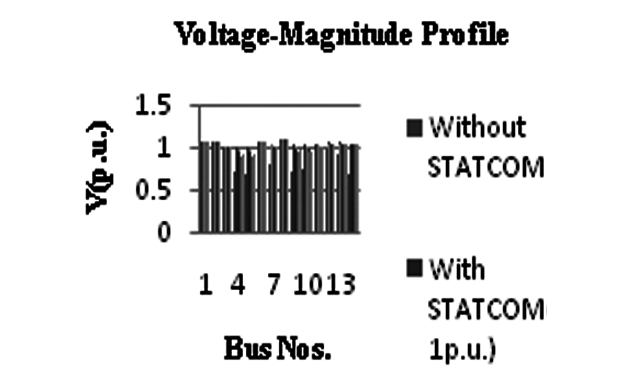

FIG.17 VOLTAGE MAGNITUDE PROFILE WITH DIFFERENT SIZES OF STATCOM

Case 4:- Contingency analysis

Contingency analysis is a very important aspect of the energy management system. Determination of critical element of the system is very useful for taking proper corrective actions to avoid system blackouts. Results for Standard IEEE-6 bus have been shown in Table 6 indicating severe contingency (critical contingency) along with corrective action.

TABLE 6		
CONTINGENCY ANALYSIS FOR CASE 4		
A] Generator Outage		
Sl.No.	**Bus no.**	**Max. loadability λ_{max} (p.u.)**
1.	1	8.6706
	3	8.5652

B] Line outage		
Sl.No.	**Line to and from**	**Max.loadability λ_{max}(p.u.)**
1.	2-3	11.1675
	3-6	7.9131
	4-5	6.6606
	3-5	8.092
	5-6	8.0328
	2-4	2.9159
	1-2	8.1201
	1-4	3.9876
	1-5	8.4585
	2-6	10.9085
	2-5	7.3987
Remark: STATCOM connected to the bus 4 where line 2-4 is connected (critical line with lowest loadability) improves the loadability λ_{max}=11.0861 p.u.		

6.0 CONCLUSIONS

Systematic methodology for proper placement and sizing of STATCOM based on static methods of voltage stability analysis has been presented in this paper. Comprehensive study has been carried out on standard IEEE6 bus and IEEE14 bus test systems under novel load increase scenario and contingencies. The observations can be concluded as-

- Conventional analytical tools PV and QV curve method only determine the feasible voltage stability region and fail to identify weak bus.
- Singularity of Jacobian matrix and varying nature of threshold values as per operating conditions, are the main limitations of remaining methods, Modal analysis and Method of VSI.
- When three methods namely, Modal analysis, method of VSI and CPF method are implemented on standard IEEE14 bus test system respectively, bus number 14 was found out to be weak bus. But from accuracy and speed of calculation point of view, CPF method is found out to be most useful method.
- Loadability margin (λ) has been improved by proper placement and sizing of STATCOM. This assures the enhancement of voltage stability.

This comprehensive study and evaluation of static methods of voltage stability adds an important and significant contribution for the proper placement and sizing of FACTS devices, specifically STATCOM for enhancing the voltage stability of the power system and for mitigating the voltage collapse problems.

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