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Voltage Collapse Prediction and Voltage Stability Enhancement by Using Static Var Compensator

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Abstract
Voltage instability is gaining importance because of unusual growth in power system. Reactive power limit of power system is one of the reasons for voltage instability. Preventing Voltage Collapsesare one of the challenging tasks present worldwide.This paper presents static methods like Modal Analysis, Two Bus Thevenin Equivalent and Continuation Power Flow methods to predict the voltage collapse of the bus in the power system.These methods are applied on WSCC – 9 Bus and IEEE – 14 Bus Systems and test results are presented.
Key Words—Continuation Power Flow, FACTS, QV Modal Analysis, SVC, Two Bus Thevenin Equivalent, Voltage Collapse

I. INTRODUCTION

The important operating tasks of power utilities are to keep voltage within an allowable range for high quality customer services. Increase in the power demand has been observed all over the world in recent years. The existing transmission lines are being more and more pressurized. Such systems are usually subjected to voltage instability; sometimes a voltage collapse. Voltage collapse has become an increasing threat to power system security and reliability. The voltage stability is gaining more importance nowadays with highly developed networks as a result of heavier loadings. Voltage instability may result in power system collapse. Voltage stability is the ability of power system to maintain steady acceptable voltages at all buses in the system under normal conditions [1].

Voltage collapseis the process by which the sequence of events accompanying voltage instability leads to a low unacceptable voltage profile in a significant part of the power system [2]. The main symptoms of voltage collapse are low voltage profiles, heavy reactive power flows, inadequate reactive support, and heavily loaded systems. The consequences of collapse often require long system restoration, while large groups of customers are left without supply for extended periods of time.

There are several counter measures to prevent voltage collapse such as use of reactive power compensating devices, network voltage and generator reactive output control, under voltage load shedding, use of spinning reserve, coordination control of protective devices and monitoring stability margin. But the most ultimate and fast method of prevention is action on load. This can be implemented directly through load shedding for under voltage instability. Shedding a proper amount of load at proper place within a proper time is ultimate way to prevent voltage instability.

Voltage stability problem can be assessed through steady state analysis like load flow simulations. The voltage stability problem is associated with reactive power and can be solved by providing adequatereactive power support to the critical buses. The control of reactive power of a switched capacitor bank is usually discrete in nature. Recenttrend is to replace the switched capacitor banks by SVC to have a smooth control on reactive power. SVC has thecapability of supplying dynamically adjustable reactive power within the upper and lower limits [3]. In the normaloperating region, a SVC adjusts its reactive power output to maintain the desired voltage. For such an operation, the SVCcan be modeled by a variable shunt susceptance. On the other hand, when the operation of the SVC reaches the limit,it cannot adjust the reactive power anymore and thus can be modeled by a fixed shunt susceptance.

There are many methods currently in use to help in the analysis of static voltage stability. Some of them are PV analysis, QV analysis, Fast Voltage Stability Index (FVSI), multiple load flow solutions based indices, voltage instability proximity indicator [4], Line stability index, Line stability Factor, Reduced Jacobian Determinant, Minimum Singular Value of Power Flow Jacobian, and other voltage indices methods. The minimum singular value of the load flow jacobian matrix is used as an index to measure the voltage stability limit is considered by reference [5]. Energy method [6, 7] and bifurcation theory [8] are also used by some researchers to determine the voltage stability limit. However, most of theresearchers used the conventional P- V or Q- V curve as a tool to assess the voltage stability limit of a power system [1].Both P-V and Q-V curves are usually generated from the results of repetitive load flow simulations under modifiedinitial conditions. Once the curves are generated, the voltage stability limit can easily be determined from the "nose" point of the curve. Point of collapse method and continuation method are also used for voltage collapse studies [9].Of these two techniques continuation power flow method is used for voltage analysis. These techniques involve the identification of the system equilibrium points or voltage collapse points where the related power flow Jacobian becomes singular [10, 11].

In this paper the following methods are used

1. Modal Analysis method is used to identify the weak bus by calculating participation factors and sensitivity factors.
2. Two Bus Thevenin Equivalent method is used to determinethe maximum loading capability of a particular load bus in a power system through the Thevenin equivalent circuit and also the loading capability of the bus after the placement of SVC device.
3. Continuation power flow is implemented in Power System Analysis Toolbox (PSAT) used to find the system loadability, optimal location and rating of the SVC device

II. FACTS MODELLING

The following general model is proposed for correct representation of SVC in voltage collapse studies [11].

The model includes a set of differential and algebraic equations of the form:

$$\dot{x_c} = f_c(x_c, V, \theta, u)$$
$$P = g_P(x_c, V, \theta) \quad (1)$$
$$Q = g_P(x_c, V, \theta)$$

Where x_c represents the control system variables and the algebraic variables $V$and θdenote the voltagemagnitudesand phases at the buses to which the FACTS devices areconnected. Finally, the variables $u$represent the input controlparameters, such as reference voltages or reference powerflows.

2.1. Static Var Compensator (SVC)

The SVC uses conventional thyristors to achieve fast control of shunt-connected capacitors and reactors. The configuration of the SVC is shown in Fig.1, which basically consists of a fixed capacitor (C) and a thyristorcontrolled reactor (L). The firing angle control of the thyristor banks determines the equivalent shunt admittancepresented to the power system.A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductivecurrent so as to maintain or control bus voltage of the electrical power system. Variable shunt susceptance model ofSVC [2] is shown in Fig.1.

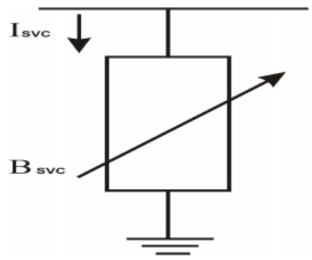

Fig.1. Equivalent circuit of SVC

As far as steady state analysis is concerned, both configurations can modelled along similar lines, The SVC structure shown in Fig. 1 is used to derive a SVC model that considers the Thyristor Controlled Reactor (TCR) firing angle as state variable. This is a new and more advanced SVC representation than those currently available. The SVC is treated as a generator behind an inductive reactance when the SVC is operating within the limits. The reactance represents the SVC voltage regulation characteristic. The reason for including the SVC voltage current slope in power flow studies is compelling. The slope can be represented by connecting the SVC models to an auxiliary bus coupled to the high voltage bus by an inductive reactance consisting of the transformer reactance and the SVC slope, in per unit (p.u) on the SVC base. A simpler representation assumes that the SVC slope, accounting for voltage regulation is zero. This assumption may be acceptable as long as the SVC is operating within the limits, but may lead to gross errors if the SVC is operating close to its reactive limits [12].

The current drawn by the SVC is, $I_{SVC} = jB_{SVC}V_K$

The reactive power drawn by SVC, which is also the reactive power injected at bus k is,

$$Q_{SVC} = Q_K = -{V_K}^2 B_{SVC} \quad (2)$$

Where,

$V_K -$ Voltage at bus k

$B_{SVC} -$ Voltage at bus k

Q_{SVC} $-$ReactivePower drawn or generated by SVC

III. METHODOLOGY

3.1. Modal Analysis Method

Gao, Morison and Kundur [13] proposed this method in 1992. It can predict voltage collapse in complex power system networks. It involves mainly the computing of the smallest eigenvalues and associated eigenvectors of the reduced Jacobian matrix obtained from the load flow solution. The eigenvalues are associated with a mode of voltage and reactive power variation, which can provide a relative measure of proximity to voltage instability. Then, the participation factor can be used effectively to find out the weakest nodes or buses in the system.

Modal analysis, $\Delta V/\Delta Q$, is a powerful technique topredict voltage collapses and determine stability margins in power systems. By using the reduced Jacobian matrix,$\Delta V/\Delta Q$ is able to compute the eigenvalues and eigenvectors to determine stability modes and provide aproximity measure of stability margins. The power systemequations are given by:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = J\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (3)$$

By considering ΔP is equal to zero, the reduced Jacobian matrix is expressed as:

$$J_R = \frac{\Delta Q}{\Delta V} - \left(\frac{\Delta Q}{\Delta\theta}\cdot\left(\frac{\Delta P}{\Delta\theta}\right)^{-1}\cdot\frac{\Delta P}{\Delta V}\right) \quad (4)$$

By taking the right and left eigenvector matrix into account, the J_R matrix can be expressed as:

$$J_R = \xi\Lambda^{-1}\eta \quad (5)$$

Where $\xi$and η are the left and the right eigenvectors and Λ is diagonal eigenvector matrix ofJ_R .

Participation factor for i^{th}mode of bus k is determined as follows

$$P_{ki} = \xi_{ki}\eta_{ik} \quad (6)$$

Sinceξ,η and Λ have dominant diagonal elements, the *V-Q* sensitivity to system parameters is determined as:

$$\frac{\Delta V}{\Delta Q} = diag(\xi\cdot\Lambda^{-1}\cdot\eta) \quad (7)$$

Once the values Δ*V*/Δ*Q* are close to zero or even their signs change from positive to negative, the system reaches voltage instability.

3.2. Two Bus Thevenin Equivalent Method

3.2.1. Without Placement of SVC

A Simple and direct method of determining the steady state voltage stability limit of a power system is presented in reference [14].Consider a simple Two-Bus system as shown in Fig 2. The generator at bus 1 transfers power through a transmission line having an impedance of Z = R +jX to a load center at bus 2. Bus 1 is considered as a swing bus where both the voltage magnitude V_2 and angleδ_2 , are kept constant.

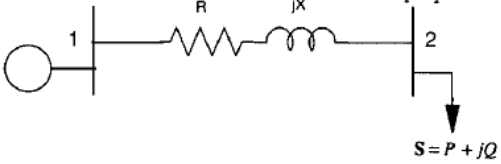

Fig.2. A Simple Two-Bus System

For a given value of V_1 the relationship between the load voltage magnitude $V_2$and the load power S = P +jQ can readily be written as

$$V_1 = V_2 + IZ = V_2 + I\sqrt{R^2+X^2} \quad (8)$$

Critical loading is found as follows

$$S_m = \frac{V_1^{\,2}}{2}\;\frac{Z-(R\cos\theta + X\sin\theta)}{(R\sin\theta + X\cos\theta)^2}$$

Where $Z = \sqrt{R^2+X^2}$

The maximum reactive power loading Q_m (with P = 0) and the corresponding voltage can be obtained from the above equations by setting θ = 0.

$$Q_m = \frac{V_1^{\,2}(Z-X)}{2R^2} \text{and} V_{cr} = \sqrt{\frac{V_1^{\,2}-2Q_mX}{2}}$$

3.2.2. After Placement of SVC

A Simple and direct method of determining the steady state voltage stability limit of a power system after the placement of Static Var Compensator (SVC) is presented in reference [15].A SVC of finite reactive power rating is placed at the load center in two bus equivalent model and it is shown in fig. 3.

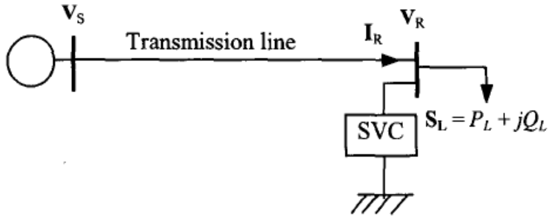

Fig.3. Simple Two bus system with SVC

The receiving end voltage decreases as the load increases and reactive power will be injected by SVC to boost the voltage. Voltage collapse occurs when there is further increase in load after SVC hits its maximum limit. Inorder to prevent voltage collapse, SVC is considered as fixed susceptanceB_c.

Receiving end current from fig.3 is given by

$$I_R = jB_cV_R + \left(\frac{S_L}{V_R}\right)^* \quad (9)$$

Above non-linear expression can be expressed as

$$\int(S,\theta) = 0 \quad (10)$$

For given power factor angleθ, feasible solution of eq. 10 is considered as critical load apparent power at the nose point of SV curve.

3.3. Continuation Power Flow Method

A method of finding a continuum of power solutions is starting at some base load and leading to steady state voltage stability limit (critical point) of the system is proposed in reference [16].

The Continuation Power Flow method implemented in PSAT consists of a predictor step realized by the computation of the tangent vector and a corrector step that can be obtained either by means of a local parameterization. Power System Analysis Toolbox (PSAT) is a Matlab toolbox for electric power system analysis and control [17, 18].

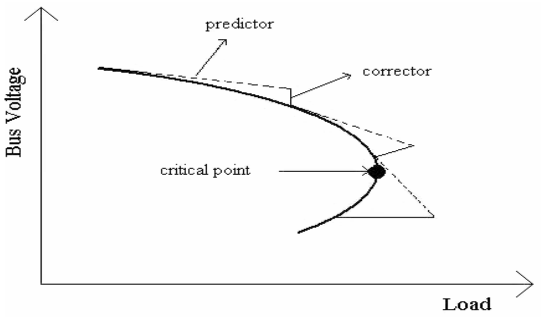

Fig. 4. Illustration of prediction-correction steps

IV. RESULTS AND DISCUSSIONS

The three methods which are discussed in chapter 3 are implemented on WSCC 9 Bus and IEEE 14 Bus Systems.

4.1. WSCC 9 Bus System

4.1.1. Modal Analysis method

Table 1 shows the voltage profile of all buses of the Western System Coordinating Council (WSCC) 3-Machines 9-Bus system as obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level (± 5%); some standards consider (± 10%). The lowest voltage compared to the other buses can be noticed in bus number 5. Since there are nine buses among which there is one swing bus, two PV buses and six PQ buses then the total number of eigenvalues of the reduced Jacobian matrix $J_R$is expected to be six.Participation factors is calculated for min. Eigen value$\lambda_{min} = 5.9589$.

Table 1
Voltage Profile, Participation Factors, VQ Sensitivity Factor and Stability Margin for WSCC 9 Bus System

Bus No.	Voltage Profile	Participation Factors	VQ Sensitivity Factor	Stability Margin
1	1.04	-	-	-
2	1.0253	-	-	-
3	1.0254	-	-	-
4	1.0259	0.1258	0.0431	-
5	0.9958	0.2999	0.0910	**2.44**
6	1.0128	0.2787	0.0907	2.76
7	1.0261	0.0846	0.0142	-
8	1.0162	0.1498	0.0715	3.37
9	1.0327	0.0657	0.0410	-

The result shows that the buses 5, 6 and 8 have the highest participation factors to the critical mode. The largest participation factor value "**0.3**" at bus 5 indicates the highest contribution of this bus to the voltage collapse. From table 1, it can be noticed that buses 5, 6 and 8 highest QV Sensitivity Factors. The largest QVsensitivity factor value **0.0910** at bus 5 indicates the highest contribution to the voltage collapse compared toother buses while the lowest QV Sensitivity factorindicates the most stable bus.The Q-V curves shown in figure 5and table 1 confirm the results obtained previously by the modal analysis method. It can be seen clearly that bus 5 is the most critical bus compared with the other buses, where any more increase in the reactive power demand at that bus will cause a voltage collapse.

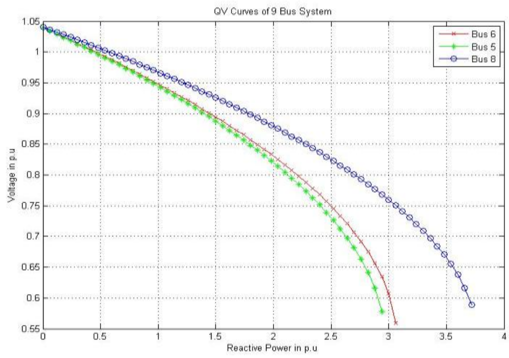

Fig. 5. Q-V curve for load buses of WSCC – 9 Bus System

4.1.2. Two Bus Equivalent Method

The load voltage vs apparent power graph is shown in fig. 6 for all buses of WSCC-9 Bus system at 0.8 power factor lag and it is found that bus 5 is the

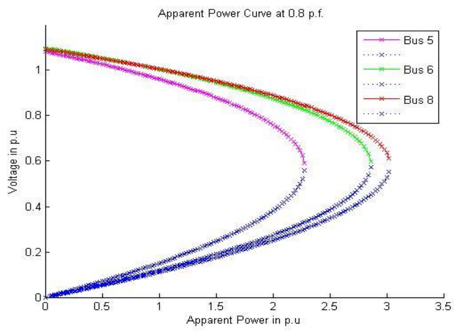

Fig. 6. Voltage vs Apparent Power of WSCC 9 Bus System at 0.8 p.f

leaststable i.e., critical loading (MVA in p.u.) of the bus is less when compared to all other load buses.

The critical load apparent power of bus 5 of WSCC-9 Bus system using NR method is found to be 2.04 p.u. whereas that found by the Two-Bus method is 2.05 p.u. The error occurredis only 0.49%. In fig.7 the variation of critical loading of bus 5 at various pf's with different SVC values are shown.

Table 2
Comparison of Results obtained by Two Bus and Newton Raphson Methods of Bus 5 of WSCC-9 Bus System

SVC Value in p.u.	Power factor	Critical Apparent Power (p.u.)		Error	Critical Voltage V_{Cr}
		NR Method	Two Bus Equivalent Method		
0	1	2.900	2.96508	2.24	0.777
	0.9	2.220	2.22509	0.23	0.656
	0.8	2.040	2.05183	0.58	0.630
	0.7	1.935	1.94813	0.67	0.596
0.4	1	2.985	3.0117	0.89	0.808
	0.9	2.295	2.31246	0.76	0.666
	0.8	2.110	2.13178	1.03	0.651
	0.7	2.000	2.01952	0.98	0.627
0.8	1	3.080	3.08804	0.26	0.818
	0.9	2.370	2.3750	0.21	0.708
	0.8	2.185	2.19178	0.31	0.672
	0.7	2.070	2.09520	1.21	0.657
1.2	1	3.175	3.18485	0.31	0.862
	0.9	2.455	2.46158	0.26	0.729
	0.8	2.265	2.28748	0.99	0.696
	0.7	2.150	2.18964	1.84	0.671
1.6	1	3.280	3.3268	1.42	0.884
	0.9	2.545	2.56724	0.87	0.754
	0.8	2.350	2.35502	0.21	0.726
	0.7	2.235	2.24186	0.31	0.678

Table 2 summarizes the results obtained by the Two-Bus method as well as the repetitive load flow simulations. It can be noticed from Table 2 that the results (apparent power at the voltage collapse point) obtained by the load flow simulations (Newton-Raphson method) are slightly lower than the corresponding values found by the Two- Bus method and maximum error that observed at the bus 5 of WSCC - 9 Bus system is 2.06% at a load power factor of unity and when the system is equipped without SVC. The next maximum error is observed at the bus 5 of WSCC - Bus System is 1.39% at load power factor of 0.7 and when the system is equipped with SVC value of 1.2. The error of critical loading is less than 3 % for two methods which is acceptable. The critical voltage of the bus is also increasing as the susceptance of SVC is increased.

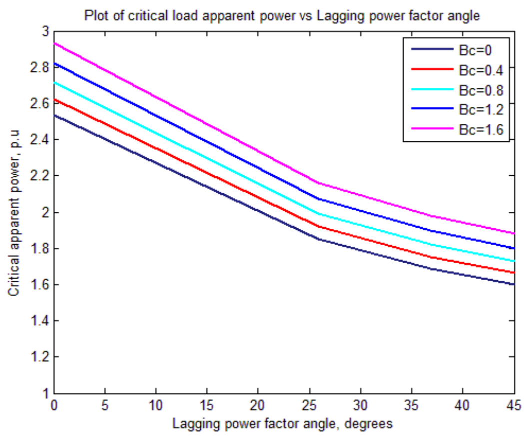

Fig. 7. Variation of Critical Load Apparent Power against Load PF Bus 5 of WSCC-9 Bus System with Various Values of SVC

4.1.3. Continuation Power Flow Method

The voltage profile and critical loading is found by using this method. The weak bus is identified based on the voltage profile. The weak bus is considered as the optimal location of the SVC. The voltage profile and the critical loading are observed after the placement of SVC at the weak bus. The following table gives the voltage profile, critical loading of system for base case without placement of SVC and after placement of SVC.

Table 3
Voltage Profile of WSCC 9 Bus System with and Without Placement of SVC

Bus No.	Base Case Voltage loading $\lambda = 2.641$	Voltages after SVC at bus 5 $\lambda = 3.389$	Voltages after SVC at bus 6 $\lambda = 2.977$	Voltages after SVC at bus 8 $\lambda = 2.945$
1	1.04	1.04	1.04	1.04
2	1.025	1.025	1.025	1.025
3	1.025	1.025	1.025	1.025
4	0.8267	0.96259	0.8974	0.82831
5	0.58925	1.05	0.59272	0.59257
6	0.73574	0.80578	1.05	0.74649
7	0.83834	0.90311	0.82357	0.91929
8	0.79649	0.82115	0.79183	1.05
9	0.91187	0.92781	0.95582	0.9762

From Table 3, we can observe that the voltage of bus 5 is low for base case without svc when compared to other load buses voltage. The optimal placement location for the SVC is bus 5 considering the voltage of the buses. Improvement in the voltages of all buses and the loading capability is increased from 2.641 to 3.386 after the placement of SVC of susceptance 3.0 at bus 5 can be observed compared to bus 6 and 8. Better voltage profile is observed when SVC is placed at bus 5 than other buses i.e., 6 and 8.

4.2. IEEE 14 Bus System

4.2.1. Modal Analysis

Table 4 shows the voltage profile of all buses of the IEEE 14 Bus system as obtained from the load flow. It can be seen that all the bus voltages are within the acceptable level (± 5%).Participation factors is calculated for min. Eigen valueλ_{min} = 2.7705.

Table 4
Voltage Profile, Participation Factors, VQ Sensitivity Factor and Stability Margin for IEEE 14 Bus System

Bus No.	Voltage Profile	Participation Factors	VQ Sensitivity Factor	Stability Margin
1	1.06	-	-	-
2	1.04	-	-	-
3	1.01	-	-	-
4	1.0103	0.0093	0.0437	-
5	1.0158	0.0047	0.0446	-
6	1.07	-	-	-
7	1.0443	0.0695	0.0781	-
8	1.08	-	-	-
9	1.0289	0.1916	0.1029	2.2179
10	1.0285	0.2321	0.1369	1.848
11	1.0454	0.1093	0.1285	-
12	1.0532	0.0223	0.1422	-
13	1.0464	0.0349	0.0869	-
14	1.0182	0.3264	0.2085	1.15

Since there are 14 buses among which there is one swing bus, four PV buses and 9 PQ buses then the total number of eigenvalues of the reduced Jacobian matrix $J_R$is expected to be 9. From table 4 results that the buses 14, 10 and 9 have the highest participation factors for the critical mode. The largest participation factor value (0.3264) at bus 14 indicates the highest contribution of this bus to the voltage collapse. From table 4.7, it can be noticed that buses 14, 12 and 10 highest QV Sensitivity Factors. The largest QV sensitivity factor value **0.2085** at bus 14 indicates the highest contribution to the voltage collapse compared to other buses while the lowest QV Sensitivity factor indicates the most stable bus.

From fig.8, Q-V curves, prove the results obtained previously by modal analysis method. It can be seen clearly that bus 14 is the most critical bus compared the other buses, where any more increase in the reactive power demand in that bus will cause a voltage collapse and also bus 14 has less stability margin compared to other load buses

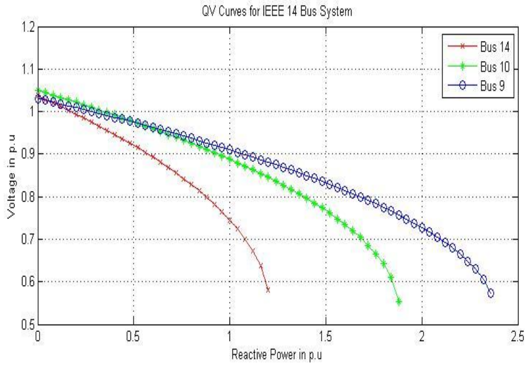

Fig.8. Q-V curve for load buses of IEEE-14 Bus System

4.2.2. Two Bus Equivalent Method

The load voltage vs apparent power graph is drawn for all buses in IEEE-14 Bus system at Zero power factor and it is found that bus 14 is least stable when compared to all other buses.

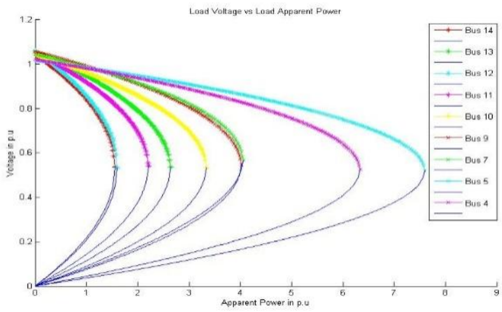

Fig.9. Load Voltage vs Apparent Power of IEEE-14 Bus System at Zero Power Factor

So the bus 14 is considered as weak bus and the critical loading of bus is increased by connecting a shunt connected shunt compensator called Static Var Compensator (SVC) of different values.The following table gives the critical loading and critical voltages with different pf's and various susceptance values of SVC.

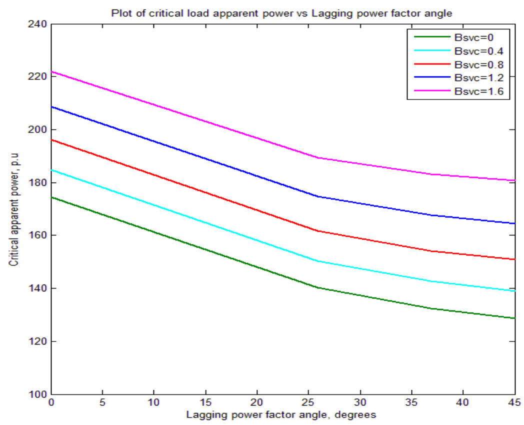

Fig. 10.Variation of Critical Load Apparent Power against Load PF at Bus 14 of IEEE-14 Bus System with Various Values of SVC

Table 5
Comparison of Results obtained by Two-Bus and Newton Raphson Methods of Bus14 of IEEE-14 Bus System

SVC value in p.u.	Power Factor	Critical Loading in p.u.		Error (%)	Critical Voltage V_{Cr}
		NR Method	Two Bus Equivalent Method		
0	1	1.70	1.7458	2.69	0.663
	0.9	1.36	1.4022	3.14	0.605
	0.8	1.29	1.3248	2.70	0.582
	0.7	1.24	1.2842	3.56	0.551
0.4	1	1.81	1.8491	2.16	0.703
	0.9	1.47	1.5033	2.26	0.629
	0.8	1.39	1.4259	2.58	0.625
	0.7	1.35	1.3867	2.72	0.616
0.8	1	1.93	1.9625	1.68	0.743
	0.9	1.59	1.6173	1.71	0.669
	0.8	1.51	1.5420	2.12	0.683
	0.7	1.47	1.5054	2.41	0.683
1.2	1	2.05	2.0863	1.77	0.849
	0.9	1.72	1.7468	1.56	0.772
	0.8	1.65	1.6757	1.55	0.749
	0.7	1.62	1.6436	1.45	0.718
1.6	1	2.19	2.2202	1.37	0.923
	0.9	1.88	1.8942	0.75	0.828
	0.8	1.81	1.8332	1.12	0.841
	0.7	1.79	1.8054	0.85	0.804

Table5summarizes the results obtained by the Two-Bus method as well as the repetitive load flow simulations. It can be noticed from Table 2 that the results (apparent power at the voltage collapse point) obtained by the load flow simulations (Newton-Raphson method) are slightly lower than the corresponding values found by the Two- Bus method and maximum error that observed at the bus 5 of WSCC - 9 Bus system is 3.56% at a load power factor of 0.7&next maximum error is observed at the bus 5 of WSCC - Bus System is 3.14% at load power factor of 0.9 when the system is equipped without SVC. 2.72% error is obtained when the system is equipped with SVC value of 0.4 at 0.7 load p.f. The error of critical loading is less than 4 % for two methods which is acceptable. The critical voltage of the bus is also increasing as the susceptance values of SVC are increased.

In fig. 10 the critical loading of bus 14 vs power factors at various values of SVC is plotted. The critical loading is increased as the susceptance value of SVC is increasing.

4.2.3. Continuation Power Flow Method

The voltage profile and critical loading is found by using this method. The weak bus is identified based on the voltage profile. The weak bus is considered as the optimal location of the SVC. After placement of SVC, the voltage profile and the critical loading of the bus is observed. The following table gives the voltage profile, critical loading of system for base case without placement of SVC and after placement of SVC.

Table 6
Voltage profile of IEEE 14 Bus System with and without placement of SVC

Bus No.	Voltages for base case without SVC (λ=1.6818)	Voltages after placement of SVC at bus 14 (λ=2.01) Bsvc=1.8685	Voltages after placement of SVC at bus 10 (λ=2.02) Bsvc=2.13	Voltages after placement of SVC at bus 13 (λ=2.05) Bsvc=1.6178
1	1.06	1.06	1.06	1.06
2	1.045	1.045	1.045	1.045
3	1.01	1.01	1.01	1.01
4	0.75366	0.73977	0.74902	0.72113
5	0.78254	0.77056	0.77521	0.75988
6	1.07	1.07	1.07	1.07
7	0.70134	0.79682	0.83378	0.75045
8	1.09	1.09	1.09	1.09
9	0.6465	0.80371	0.85671	0.73985
10	0.6349	0.78949	1.05	0.75042
11	0.65644	0.80358	0.88168	0.82453
12	0.65446	0.82573	0.75942	0.94646
13	0.63932	0.83612	0.74024	1.05
14	0.58826	1.05	0.65851	0.79688

From Table 6, we can observe that the voltage of bus 14 is low for base case without svc when compared to other load buses voltage. The optimal placement location for the SVC is bus 14 considering the voltage of the buses. Improvement in the voltages of all buses and the loading capability is increased from 1.6818 to 2.01 after the placement of SVC of susceptance value 1.8685 at bus 14 can be observed when compared to bus 10 and 13. Better voltage profile is observed when SVC is placed at bus 14 than other buses (i.e., 9 & 13).

V. CONCLUSIONS

In this paper, Modal Analysis Method, Two Bus Equivalent Method, and Continuation Power Flow Method are used in voltage stability analysis of power systems are presented. The voltage collapse problem is studied by using above three methods. Bus 5 & 6 are more susceptible to voltage collapse in WSCC - 9 bus system while Bus 14 is more susceptible to voltage collapse in IEEE 14 bus systemby all the three methods. The Q-V curves are used successfully to confirm the result obtained by Modal analysis technique, where the same buses are found to be the weakest and contributing to voltage collapse. The stability margin or the distance to voltage collapse is identified based on voltage and reactive power variation. Furthermore, the result can be used to evaluate the reactive power compensation and better operation & planning. The critical loading of the weak bus is determined by using Two Bus Equivalent method in a single shot rather than repetitive load flow solution of NR method and its critical loading is enhanced by placing the shunt compensation device called Static Var Compensator of different susceptance values. Continuation Power Flow method is used for determining the critical loading as well as the voltage profile of the test system with and without placement of SVC is observed. The reactive power support to the weak bus is provided by using shunt connected FACTS device Static Var Compensator (SVC) which is modelled as variable suscpetance mode. The voltage stability of the weak bus is enhanced after the placement of SVC.

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