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Steady State Voltage Stability Improvement by Determination of Best Location of SVC with Minimum Losses

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Abstract

Voltage stability is essential for a secure power system operation. A lot of works have been developed for this analysis method to improve voltage stability. This study demonstrates the use of latest power system analysis toolbox (PSAT) package for network analysis of alternative means of improving existing transmission system voltage stability. This paper presents the investigation on steady state voltage stability improvement by determination of best location of FACTS controllers such as static Var Compensator (SVC) device with minimum losses. The proposed method explains how voltage stability can be improved with the continuation power flow methods in case of increasing load. Continuation load flow analysis which is currently used for evaluation of location of weak buses/areas of the power system sensitive to load increase. Voltage stability assessment on a 6-bus system has been simulated to test the effectiveness with increasing load. A comparative study between the base case and SVC are presented to demonstrate the effectiveness of SVC .The propose methodology found advantages because it is simple, faster and very convenient to apply for voltage stability analysis.

Keywords- Steady State Stability, Continuation Power Flow, SVC.

“1.Introduction”

Voltage instability problems increasing day by day because of demand increase. It is very important to analyze the power system with respect to voltage stability. power systems operation becomes more important as the load demand increases all over the world. This rapid increasing of load demand forces power systems to operate near critical limits due to economical and environmental constraints. The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. In this paper, voltage stability is studies by using continuation power flow method.

Steady state stability refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes. Steady-state stability is defined as the capability of the network to withstand a small disturbance (fault, small change of parameters, topology modification) in the system without leaving a stable equilibrium point.

On the contrary, voltage instability can be described as the system state, when the voltage slowly decreases (due to insufficient reactive reserves) until significant voltage drop appears (voltage collapse). Such a situation may occur in a relatively large time frame - from tens of seconds to several minutes. Voltage collapse may arise as a result to a combination of different negative factors, such as load increase, long electrical distances between reactive power sources and the loads, too low source voltages, crucial changes in network topology and no reactive compensations available.[1]

Many analysis methods of voltage stability determination have been developed on static analysis techniques based on the power flow model since they are simple, fast and convenient to use. It is known that voltage collapse leads to the reason for several blackouts that have occur throughout many areas. The major reasons for voltage collapse are based on increasing loading, large disturbance and line outage. There are many papers investigate voltage stability on dynamic analysis, static analysis and sensitivity characteristics. The dynamic analysis emphasizes on large disturbance or transient stability occurrence. However, static analysis is considered as a small signal phenomenon, load increasing and line outage. Thus, lot of work is carried out to determine voltage stability on static analysis instead. Generally, when online dynamic voltage stability is not available, static techniques may involve a conventional power flow study. The problem of conventional power flow analysis is the Jacobian of a Newton-Raphson power becomes singular at the steady state voltage stability limit.[2]

One of the main causes of voltage instability in a system is the occurrence of reactive power imbalance in the system. Reactive power imbalance occurs when there is a sudden increase or decrease in reactive power demand in the system. The only way to prevent the occurrence of voltage collapse is either to reduce the reactive power load or to provide the system with additional supply of reactive power before the system reaches the point of voltage collapse. This can be done by connecting sources of reactive power, i.e., shunt capacitors and/or flexible AC transmission system (FACTS) controllers at appropriate locations in the system.

Flexible AC Transmission systems (FACTS) technology helps utilities in reducing transmission congestion and in utilizing more efficiently the existing transmission system without compromising the reliability and security of the system. Their fast response offers high potential for power system stability enhancement apart from steady state flow control. The benefits of employing FACTS are aplenty:(a) They help to increase the power transfer capability of existing transmission systems,(b) They can directly control real and reactive power flow,(c) Provide fast dynamic reactive power support and voltage control,(d)Improve system stability and damp power system oscillations,(e) Reduce financial costs and environmental impact by possible deferral of new transmission lines.[3]

2. Principal Causes Of Voltage Stability Problems

Some of the causes for occurrence of voltage instability are

- Different in Transmission of Reactive Power under Heavy Loads.
- High Reactive Power Consumption at Heavy Loads.
- Occurrence of Contingencies.
- Voltage sources are too far from load canters.
- Due to unsuitable locations of FACTS controllers.
- Poor coordination between multiple FACTS controllers.
- Presence of Constant Power Loads.
- Reverse Operation of ON Load Tap-Changer (OLTC).

3. Prevention of Voltage Instability

Some of the prevention of voltage instability by following:

- Placement of series and shunt capacitors.
- Installation of synchronous condensers.
- Placement of facts controllers.
- Coordination of multiple facts controllers.
- Under-voltage load shedding.
- Blocking of tap-changer under reverse operation.
- Generation rescheduling.

4. Tools for voltage stability analysis-

The most common methods used in voltage stability analysis are continuation power flow, point of collapse, minimum singular value and optimization methods. In this study, continuation power flow method, widely used in voltage stability analysis, is utilized in order to analyze voltage stability of power systems. Voltage stability can be analyzed by using bifurcation theory[4].

4.1 Bifurcation Theory:

Bifurcation theory is used to describe changes in the qualitative structures of the phase portrait when certain system parameters change. Local bifurcations can be studied by analyzing the vector differential equations near the bifurcation equilibrium points. Voltage collapse in power systems can be predicted by identifying parameter values that lead to saddle-node bifurcations. In order to present the characteristic of bifurcation, Equation 1 is considered.

$$F(x, \lambda) = \dot{x} = \lambda - x^2 \qquad \text{------------------------------ (1)}$$

In differential Equation 1, x is the state variable and λ is a parameter. There is a point called equilibrium point where $f(x_0, \lambda_0) = 0$.For this value of λ the linearization of f(x, λ) is singular.

Figure 1 is obtained for f(x, λ), as λ changes. When λ=0 there is a saddle node point. For λ<0, there is no equilibrium whereas for λ>0 there are two equilibrium points as stable and unstable points.

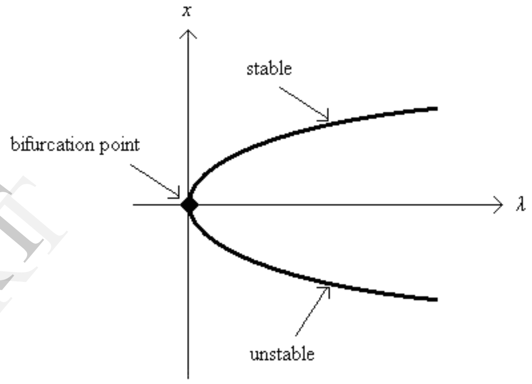

Figure1: Bifurcation diagram for f(x, λ)

The shape of the diagram shown in Figure 1 is quite similar to the bus voltage versus load parameter curves.

4.2 Continuation Load Flow Analysis:

Several static approaches consequential from the traditional load flow programs are being used for the evaluation of the network stability – from the optimal active and reactive power flow (OPF) and Eigen value analysis through the sensitivity based and path-following methods (such as the continuation load flow) up to modal analysis for transient voltage stability. The Jacobian matrix of power flow equations becomes singular at the voltage stability limit. Continuation load flow analysis suitably modifies conventional load flow equations to become stable also in the singular point of the V-P curve and therefore to be capable to calculate both upper and lower part of the V-P curve. Continuation power flow finds successive load flow solutions according to a load scenario. For this, it uses the two-step predictor/corrector algorithms along with single new unknown state variable (so-called continuation parameter). The predictor estimates approximate state variable values in the new step (close to the V-P curve) while the corrector makes the corrections of new state variable values to suit the load flow equations. Moreover, The corrector step then determines the exact solution using Newton-Raphson technique employed by a conventional power flow. After that a new prediction is made for a specified increase in load based upon the new tangent vector. Then corrector step is applied. This process goes until critical point is reached. The critical point is the point where the tangent vector is zero. Based on the differential changes of state variables in each predictor step it is possible to locate weak buses and even areas of the system with largest voltage changes with respect to the load increase. Furthermore, the continuation load flow algorithm can be simply formulated for load increase (both active and reactive) in a single bus, in particular network area with more buses or even in the entire network.

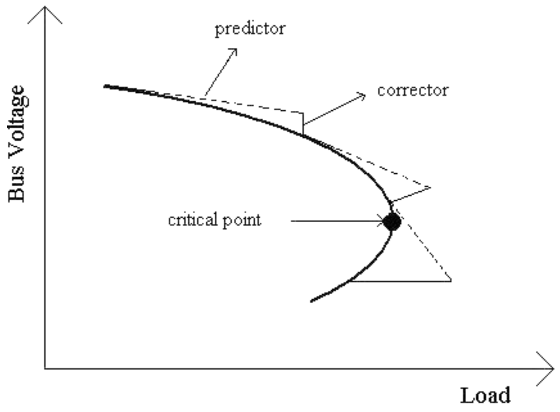

Figure 2: Illustration of prediction-correction steps.

In continuation load flow, first power flow equations are reformulated by inserting a load parameter into these equations [5].

4.3 Mathematical Reformulation

Injected powers can be written for the ith bus of an n-bus system as follows [6]:

$$P_i = \sum_{K=1}^{N} |V_i|\,|V_k|\,(g_{ik}\cos\theta_{ik} + b_{ik}\sin\theta_{ik}) \text{ -------------------- } (2)$$

$$Q_i = \sum_{K=1}^{N} |V_i|\,|V_k|\,(g_{ik}\sin\theta_{ik} - b_{ik}\cos\theta_{ik}) \text{ -------------------- } (3)$$

$$P_i = P_{GI} - P_{DI}, \qquad Q_i = Q_{GI} - Q_{DI}, \text{ -------------------- } (4)$$

Where the subscripts G and D denote generation and load demand respectively on the related bus.

In order to simulate a load change, a load parameter λ is inserted into demand powers p_{di} and q_{di}.

$$P_{di} = p_{dio} + \lambda\,(P_{\Delta base})$$

$$Q_{di} = q_{dio} + \lambda\,(Q_{\Delta base}) \text{ ---------------------- } (5)$$

P_{di} and q_{di} are original load demands on i^{th} bus where $P_{\Delta base}$ and $Q_{\Delta base}$ are given quantities of powers chosen to scale λ appropriately. After substituting new demand powers in Equation (5) to Equation (4), new set of equations can be represented as:

$$F(\theta, V, \lambda) = 0 \text{ --------------------- } (6)$$

Where θ denotes the vector of bus voltage angles and V denotes the vector of bus voltage magnitudes. The base solution for λ=0 is found via a power flow. Then, the continuation and parameterization processes are applied.

4.3.1 Prediction Step:

In this step, a linear approximation is used by taking an appropriately sized step in a direction tangent to the solution path. Therefore, the derivative of both sides of equation (6) is taken

$$F_\Theta d\Theta + F_V dV + F_\lambda\, d\lambda = 0$$

$$\begin{bmatrix} F_\Theta & F_V & F_\lambda \end{bmatrix} \begin{bmatrix} d\Theta \\ dv \\ d\lambda \end{bmatrix} = 0 \text{ ------------------ } (7)$$

In order to solve Equation (7), one more equation is needed since an unknown variable λ is added to load flow equations. This can be satisfied by setting one of the tangent vector components to +1 or -1 which is also called continuation parameter. Setting one of the tangent vector components +1 or -1 imposes a non-zero value on the tangent vector and makes Jacobian non-singular at the critical point. As a result Equation (7) becomes:

$$\begin{bmatrix} F_\theta & F_V & F_\lambda \\ & ek & \end{bmatrix} \begin{bmatrix} D_\theta \\ D_V \\ D_\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \text{ ----------------- } (8)$$

Where e_k is the appropriate row vector with all elements equal to zero except element equals 1. At first step λ is chosen as the continuation parameter. As the process continues, the state variable with the greatest rate of change is selected as continuation parameter due to nature of parameterization. By solving Equation (8), the tangent vector can be found. Then, the prediction can be made as follows:

$$\begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^{P+1} = \begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^{P} + \sigma \begin{bmatrix} d\theta \\ dv \\ d\lambda \end{bmatrix} \text{ -------------------------- } (9)$$

Where the subscript "p+1" denotes the next predicted solution. The step size s is chosen so that the predicted solution is within the radius of convergence of the corrector. If it is not satisfied, a smaller step size is chosen [7].

4.3.2 Correction Step:

In correction step, the predicted solution is corrected by using local parameterization. The original set of equation is increased by one equation that specifies the value of state variable chosen and it results in:

$$\begin{bmatrix} f(\theta, v, \lambda) \\ x_k \end{bmatrix} = [0] \text{ ------------------------------ } (10)$$

Where x_k state variable chosen as continuation parameter and η is the predicted value of this state variable. Equation (10) can be solved by using a slightly modified Newton-Raphson power flow method. If it is decreasing -1 is used in the tangent vector in Equation (7).The continuation power flow is stopped when critical point is reached as it is seen in the flow chart. Critical point is the point where the loading has maximum value. After this point it starts to decrease. The tangent component of λ is zero at the critical point and negative beyond this point. Therefore, the sign of dλ shows whether the critical point is reached or not. It gives satisfactory results.

5. Effect of Facts Devices on Voltage Stability:

The role of FACTS devices in power system performance enhancement becomes more important, since the main responsibility of generation units is to produce active, rather than reactive, power compensation. Flexible AC Transmission Systems (FACTS) obtained a well known reputation for higher controllability in power systems by means of power electronic devices. The first application of FACTS devices is a fast power flow control, which can help to improve the stability and security margin. The influence of these devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. FACTS devices work as fast current, voltage or impedance controllers. The power electronic allows a very short reaction time, down to far below one second [8].

5.1 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 Figure 3.which basically consists of a fixed capacitor (c) and a thyristor controlled reactor (L).The firing angle control of the thyristor banks determines the equivalent shunt admittance presented to the power system. A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control bus voltage of the electrical power system. Variable shunt susceptance model of SVC [8] is shown in Figure 3.

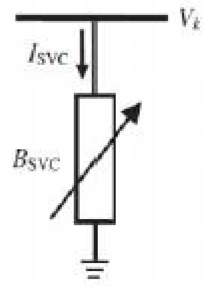

Figure 3.Variable shunt susceptance model

As far as steady state analysis is concerned, both configurations can modeled along similar lines, The SVC structure shown in figure 3 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 [9].

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,

$$Q_{SVC} = Q_K = -V_K^2 B_{SVC}$$

Where, V_K – Voltage at bus K

B_{SVC} - Susceptance

Q_{SVC} - Reactive power drawn by SVC

5.2 Optimal location of (SVC)

To improve the voltage profile and voltage stability of a power system an alternative solution is to locate an appropriate Flexible AC transmission system (FACTS) Device [8]. FACTS devices are the solid state converters having capability of improving power transmission capacity, improving voltage profile, enhancing power system stability, minimizing transmission losses etc.In order to optimize and to obtain the maximum benefits from their use, the main issues to be considered are the type of FACTS devices, the setting of FACTS devices and optimal location of FACTS devices.

6. Test System and Analytical Tools

A Single line diagram of the Six bus test system[10] is depicted in Fig 4. It consists of the three generators. There are six buses with three loads.Base values are 100MW and 400KV. All the results presented in the paper are produced with the help of the Power System Analysis Toolbox, PSAT [11]. PSAT is Power system analysis software, which has many features including power flow and continuation power flow. Using continuation power flow feature of PSAT, voltage stability of the test system is investigated. The behavior of the test system with and without FACTS devices under different loading conditions is studied.

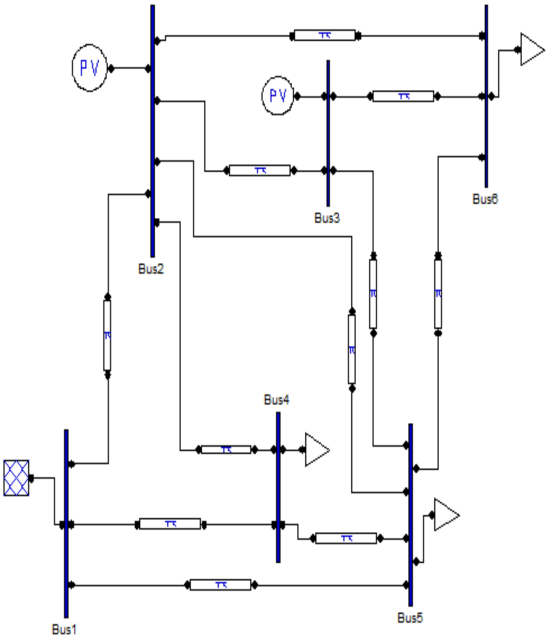

Figure 4.Six bus system

7. Case Study And Simulation Result

A Six bus test system is used to assess the effectiveness of SVC models developed in this paper. The test network was tested without SVC and with SVC. The Continuation Power Flow results and power flow results are given in Table 1.Table 1 shows the Voltage magnitude obtain after power flow and continuation power flow without SVC and with SVC connected at bus 4,5and 6.

From table1 continuation power flow result gives minimum voltage at bus 4, 5, and 6,Hence these buses are called critical buses which experienced maximum change in voltage with the variation in load.

Table1 also shows that as SVC is connected at bus 4, 5, and 6 voltage of these buses become 1 p.u. Loading parameter obtain after SVC connection is given in table2.

Table1.Voltage Magnitude after Power flow and continuation power flow with and without svc:

Bus No.	Power Flow without SVC	Continuation Power Flow without SVC	Power Flow with SVC at bus 4	Power Flow with SVC at bus 5	Power Flow with SVC at bus 6
1	1.05	1.05	1.05	1.05	1.05
2	1.05	1.05	1.05	1.05	1.05
3	1.07	1.07	1.07	1.07	1.07
4	0.98937	0.67811	1	0.99152	0.98923
5	0.98544	0.51104	0.98724	1	0.98445
6	0.98436	0.7372	1.0048	1.0072	1

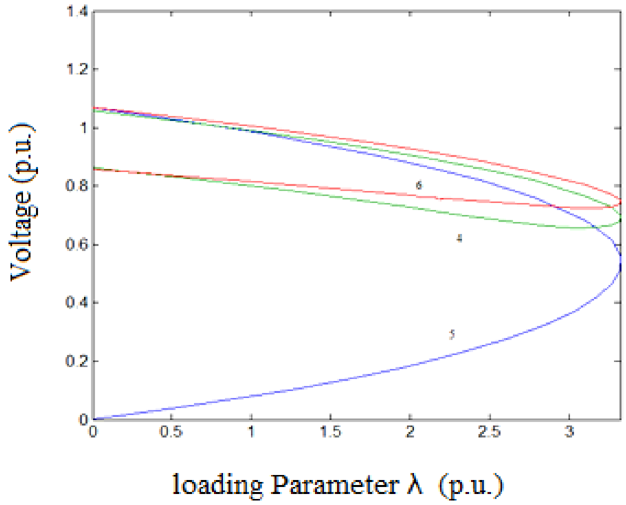

Figure5.P-V curve of critical bus without SVC

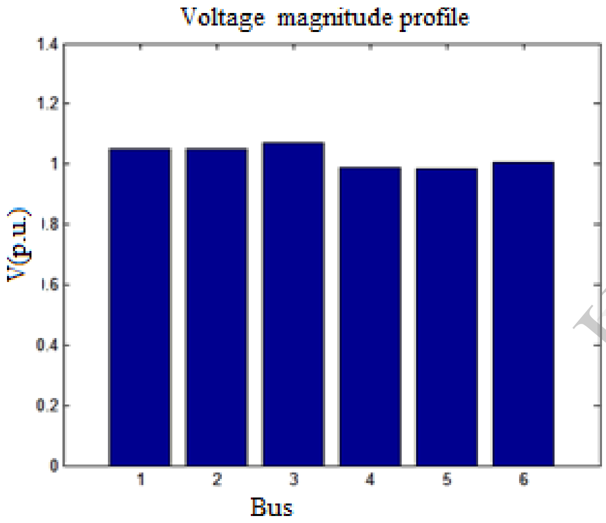

Figure 6.Voltage magnitude after power flow

Figure5 shows the variation of voltage with respect to change in load in critical buses 4, 5 and 6.without SVC having maximum loading point is λ_{max} = 3.3208

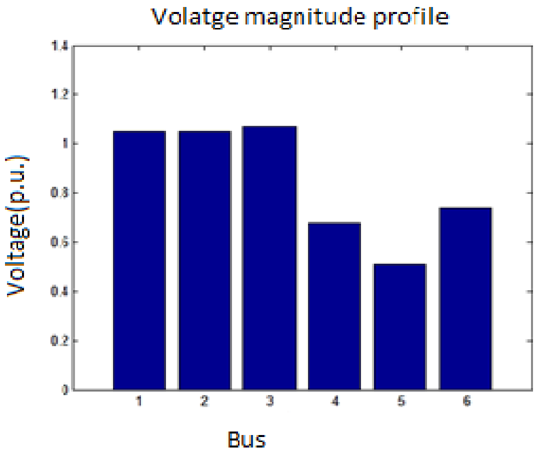

Figure7.Voltage magnitude after continuation power flow

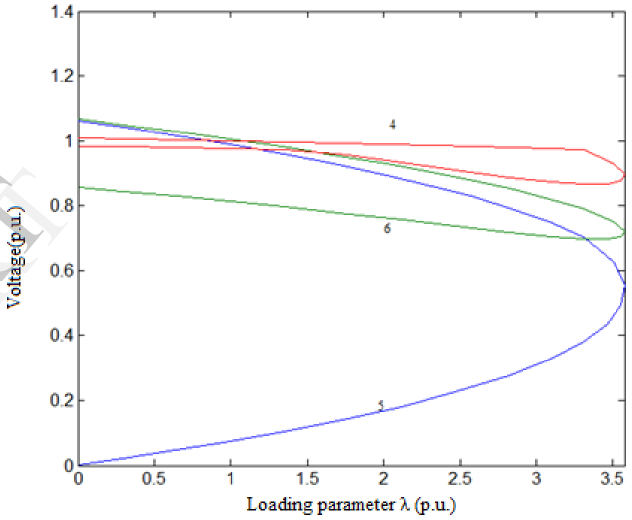

Figure 8.P-V curve with SVC at bus 4.

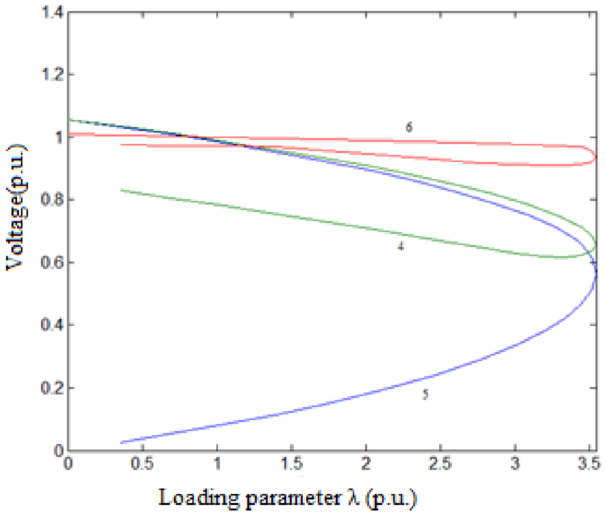

Figure 10.P-V curve with SVC at bus 6.

Table2: Loading parameter for different cases

S.NO	Without SVC	SVC at bus 4	SVC at bus 5	SVC at bus 6
Λ	3.3208	3.5772	3.0772	3.5429

From Table2 it is shown that with SVC maximum loading value is 3.5772 and real power losses are 0.07875,which is obtain when SVC is at bus 4,but losses

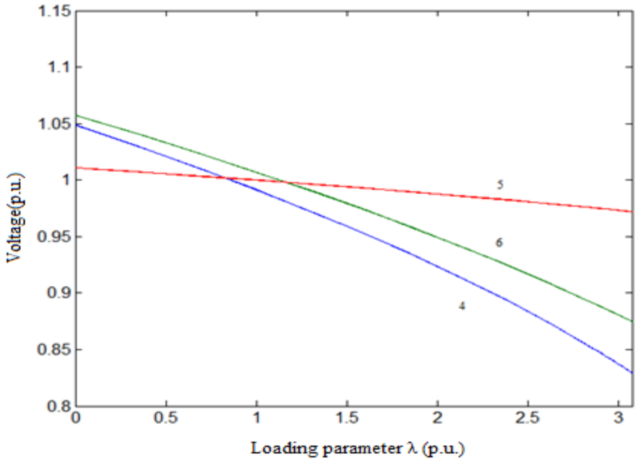

Figure 9.P-V curve with SVC at bus 5.

S.No.	Total losses	Result of Pf without svc	Result of pf with svc at bus 4	Result of pf with svc at bus 5	Result of pf with svc at bus 6
1	Real Power [p.u.]	0.07875	0.07217	0.07084	0.08078

8. Conclusion

In this paper, the current status of power system stability enhancement using SVC controllers was discussed .All the results obtain from power system analysis toolbox (psat) with Six bus test system, from the result it is clear that svc increase the voltage of the bus in which it is connected, and will also increase maximum loading point.

As from table 1 with SVC connection voltage at bus 4,5,6 is improved hence voltage stability is improved with SVC connection.

Best location for SVC is that where voltage stability increases along with minimum losses are obtained with increased value of maximum loading point in comparison when SVC is not connected.

Hence bus 4 is the best location for SVC connection because with SVC loading value is

are minimum when SVC is connected at bus 5,as given in table3 but maximum loading value is 3.0772 which is minimum at this bus so bus 5 can not be cosiderd a best location for SVC.

At bus 6 maximum loading value is 3.5429 which is less than loading value obtain with SVC at bus 4,but loss increases so this bus can not be a best location for SVC.

Table3.Losses obtain form four cases

maximum i.e. 3.5077 and real power losses are also minimum i.e. 0.07217.

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