Stability Enhancement of a Multi-Machine Power System using Static VAR Compensator

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Abstract —**This paper deals with the use of a shunt FACTS device (SVC) to improve the stability of the system. In this paper, a multi-machine power system has been considered for describing the impact of SVC for enhancement of voltage stability, small signal stability and transient stability of the power system. Analysis also consists of various results found for the different locations of shunt FACTS device and best location is found out. Power system analysis toolbox (PSAT) has been used for the analysis and simulation.**

***Keywords*— Power system stability; SVC; PSAT; CPF**

I. INTRODUCTION

The inevitable globalization and liberalization of energy markets associated with growing deregulation and privatization are increasingly resulting in bottlenecks, uncontrolled load flows, instabilities, and even power transmission failures. Power supplies are increasingly dependent on distributed power plants with higher voltage levels, a greater exchange within meshed systems, and transport to large load centres. This type of power transmission must be implemented safely and cost effectively with a view to the future. The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. In recent years, new types of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems This means that with FACTS, power companies will be able to better utilize their existing transmission networks, substantially increase the availability and reliability of their line networks, and improve both dynamic and transient network stability while ensuring a better quality of supply. The voltage stability, small signal stability and transient stability of a complex power system can be effectively improved by the use of FACTS devices [2-3]. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to improve the transient stability of a system.

Reactive power compensation is an important issue in electrical power systems and shunt FACTS devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and transient stability. SVC and STATCOM are members of FACTS family that are connected in shunt with the system. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, they are also capable of improving the transient stability by increasing (decreasing) the power transfer capability.

In this paper we are investigating two type of stability i.e. voltage and rotor angle stability, with the shunt FACTS device SVC [2]. SVC is a first generation FACTS device, can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation but it can also be used for transient and small signal stability. A simple and effective method based on power flow analysis has been employed to locate the weak buses in the system for effective compensation. Eigen value analysis technique has been used for small signal stability analysis. This paper uses PSAT tool in MATLAB to analyze the best suitable location of SVC for power system stability enhancement [9].

II. STATIC VAR COMPENSATOR (SVC)

A. Basic Concept

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 thyristor controlled reactor (L). The firing angle control of the thyristor banks determines the equivalent shunt admittance presented to the power system [6]. In general, the two thyristor valve controlled/switched concepts used with SVCs are the thyristor controlled reactor (TCR) and the thyristor-switched capacitor (TSC). The TSC provides a "stepped" response and the TCR provides a "smooth" or continuously variable susceptance. When system voltage is low, the SVC generates capacitive reactive power. When system voltage is high, it absorbs inductive reactive power. The reactive power is changed by switching on three-phase capacitor and reactor banks connected to the secondary side of the transformer. Each capacitor bank is switched on and off by thyristor valves (TSC). Reactors can be either switched (TSR) or controlled (TCR).

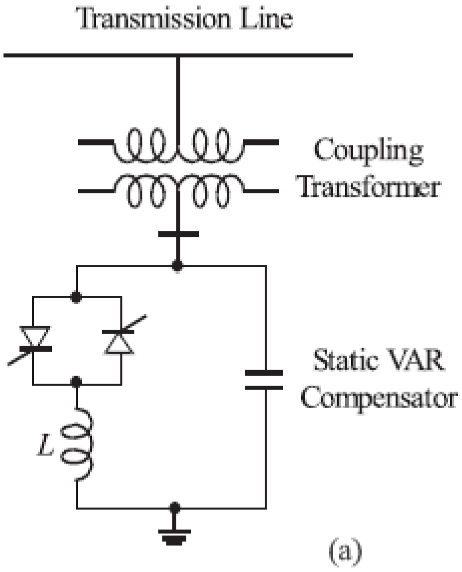


Figure1: Basic configuration of SVC

Static Var systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually for rapid control of voltage at weak points in a network. Installations may be at the midpoint of transmission interconnections or at the line ends. Static Var Compensators are shunt connected static generators and or absorbers whose outputs are varied so as to control voltage of the electric power systems. In its simple form SVC is connected of FC-TCR configuration as shown in Fig 2(a). The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated. The effective reactance of the FC-TCR is varied by firing angle control of the anti parallel thyristors. The firing angle can be controlled through a PI controller in such a way that the voltage bus where the SVC is connected is maintained at the reference value.

Static compensation systems perform the following tasks:

- Stabilize voltage
- Control dynamic reactive power
- Improve transient stability
- Damp active power oscillations
- Increase power transfer capability
- Balance system voltages

The design and configuration of an SVC including the size of the installation, operating conditions and losses, depend on individual circumstances and the tasks to be performed.

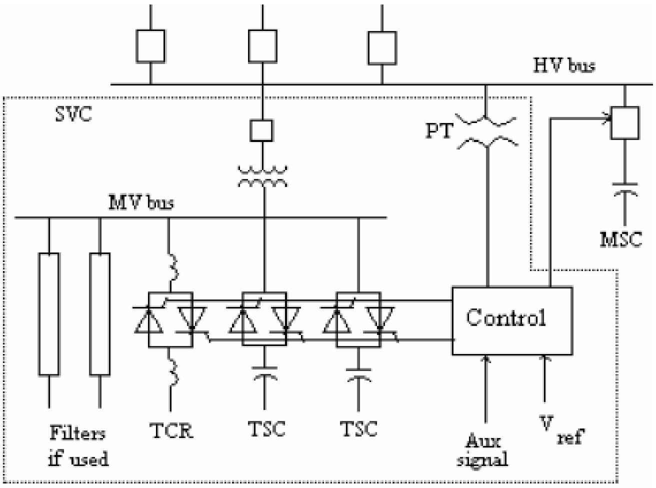


Figure 2(a): A typical SVC system

B. Modelling of SVC

SVC firing angle model: The equivalent reactance XSVC, which is function of a changing firing angle α, is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 2 (b). This model provides information on the SVC firing angle required to achieve a given level of compensation.

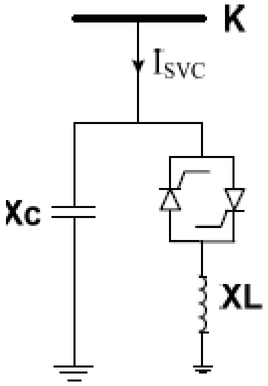


Fig 2(b): SVC Firing Angle Model

The model can be developed with respect to a sinusoidal voltage, differential and algebraic equations can be written as

$I_{svc} = -jB_{svc}V_k$ ……………………………………… (1)

The fundamental frequency TCR equivalent reactance X_{TCR}

$X_{TCR} = \pi X_L / \sigma - \sin\sigma$……………………….………..… (2)

Where $\sigma = 2(\pi-\alpha)$, $X_L = wL$

And in terms of firing angle

$X_{TCR} = \pi X_L / 2(\pi - \alpha) + \sin 2(\alpha)$……….…………….... (3)

Where σ and α are conduction and firing angles respectively.

At $\alpha=90^0$, TCR conducts fully and the equivalent reactance X_{TCR} becomes X_L, while at $\alpha=180^0$, TCR is blocked and its equivalent reactance becomes infinite.

The SVC effective reactance X_{SVC} is determined by the parallel combination of X_C and X_{TCR} as

$X_{SVC} = \pi X_C X_L / (X_C [2(\pi - \alpha)+\sin 2\alpha] - \pi X_L)$…............….. (4)

Where $X_C = 1/wC$

$Q_k = -V_k^2\{ X_C[2(\pi - \alpha) + \sin 2\alpha] - \pi X_L\} / \pi X_C X_L$.......... (5)

The SVC equivalent reactance is given by (4). It is shown in Fig. 2(c) that the SVC equivalent susceptance (BSVC=-1/XSVC) profile, as function of firing angle, does not present discontinuities, i.e., BSVC varies in a continuous, smooth fashion in both operative regions. Hence, linearization of the SVC power flow equations, based on BSVC with respect to firing angle, will exhibit a better numerical behaviour than the linearized model based on X_{SVC}.

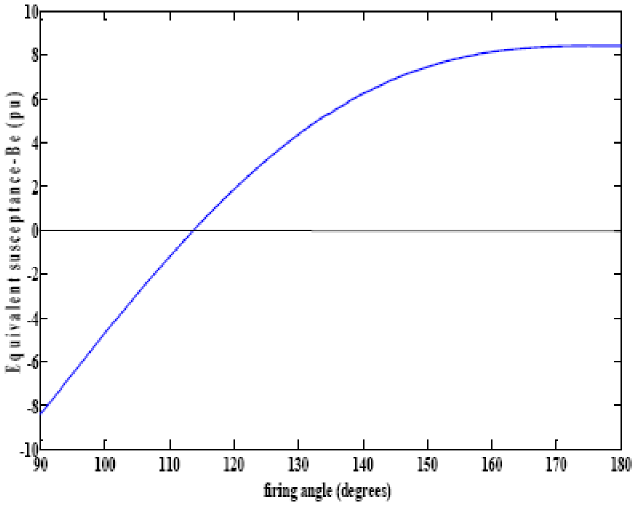


Fig 2(c): SVC Equivalent Susceptance Profile

The initialization of the SVC variables based on the initial values of ac variables and the characteristic of the equivalent susceptance (Fig.2(c)), thus the impedance is initialized at the resonance point $X_{TCR}=X_C$, i.e. $Q_{SVC}=0$, corresponding to firing angle 115^0, for chosen parameters of L and C i.e. $X_L=0.1134\ \Omega$ and $X_c = 0.2267\ \Omega$.

Proposed SVC power flow model:

The proposed model takes firing angle as the state variable in power flow formulation. From equation (5) the SVC linearized power flow equation can be written as:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^{(i)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{2V_k^2}{\pi X_L}\left[\cos\left(2\alpha\right)-1\right] \end{bmatrix}^{(i)} \begin{bmatrix} \Delta \theta_k \\ \Delta \alpha \end{bmatrix}^{(i)} \quad ....(6)$$

At the end of iteration i, the variable firing angle α is updated according to the following equation:

$$\alpha^{(i)} = \alpha^{(i-1)} + \Delta\alpha^{(i)} \quad ....(7)$$

III. VOLTAGE STABILITY

A. *Basic Concept*

The root cause of voltage instability is the lack of supply of sufficient reactive power. The major problem is mainly the voltage drop that occurs due to the flow of active power and reactive in the transmission line. A system enters into the state of voltage instability when voltage magnitude at a bus decreases in spite of reactive power injection at that bus. A system is set to be voltage unstable if V-Q sensitivity is negative for at least one bus [8]. Voltage instability occurs locally but its consequences may have a vast impact on the system. Voltage collapse occurs due to the voltage instability in the system which causes a low voltage profile in the larger areas of the power system [1].

B. Classification of Voltage Stability

The voltage stability is classified into the following two subclasses:

a) Large-disturbance voltage stability

b) Small-disturbance voltage stability

Large-disturbance voltage stability is related with the control of voltages after large disturbances such as system faults, loss of generation, or circuit contingencies.

Small- disturbance voltage stability is related with the control of system voltages after small and slow disturbances.

IV. ROTOR ANGLE STABILITY

Rotor Angle Stability is the study of rotor oscillations of the machine. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor oscillate. Rotor Angle Stability is mainly of two types:

(1) Small Signal Stability

(2) Transient Stability

Small Signal Stability is the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of analysis. Instability that may result can be of two forms:

(i) Steady increase in rotor angle due to lack of sufficient synchronizing torque, or

(ii) Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

Transient Stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The important severe disturbances are a short circuit or a sudden loss of load. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship.

V. STABILITY ENHANCEMENT OF A MULTI-MACHINE POWER SYSTEM : A CASE STUDY

A Multi Machine Bus system shown in fig 3 is considered for analysis of best location of SVC so as to enhance the stability in the system. The multimachine system consists of 9 buses and 3 generators placed at bus #1, 2 and 3. Bus #1 is a slack bus, bus #2 and 3 are the PQ buses and rest all are PV buses. Load is connected on the bus #5,6 and 8.

The system is modelled in PSAT i.e. power system analysis toolbox and Fig 4 shows the network visualization. Here, the system is tested under both the disturbances i.e. small and large in order to study the stability margins and dynamic behaviour. First of all we will study the performance of the basic system in PSAT in order to obtain the PV curves as well to obtain the Eigen value and time domain analysis. Then the FACTS device which is SVC in our case, is added to the system and again the system is studied to find the effect of the facts device SVC on the system on all the three types of stabilities i.e. voltage stability, small signal stability and rotor angle stability.

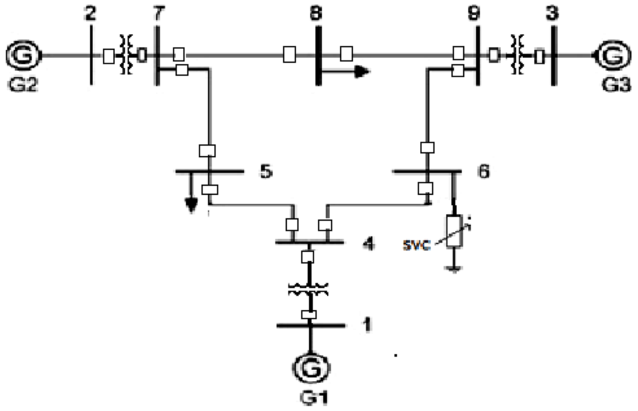


Figure 3: Single line diagram of multi machine bus system (shown with a SVC connected at bus 6)

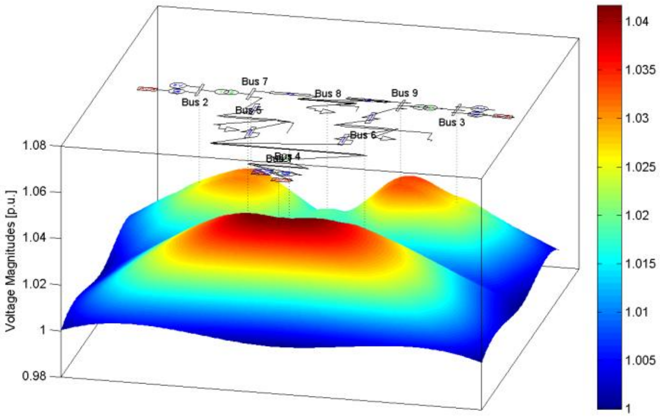


Figure 4: Network Visualization

VI. SIMULATION RESULTS

A. *Voltage Stability Analysis*

A multi machine test system (fig 3) is considered which includes 9 buses ,3 generators,6 lines ,3 transformers and 3 loads is simulated using PSAT.

The profile of the bus voltage magnitudes with the variation in loading are plotted with the use of continuation power flow and it is shown in fig 5. For the base case, the maximum loading point where the system jacobion is singular, is at λ =2.505 p.u.

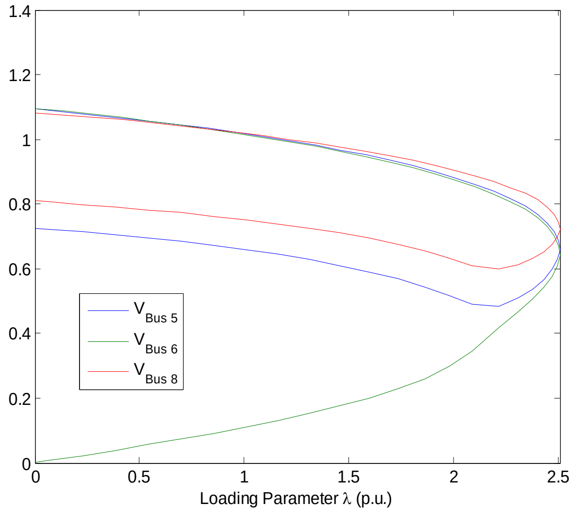


Figure 5: CPF for the base case (without SVC)

In the test bus system based on voltage magnitude profile (fig 6) bus 5, 6, and 8 are identified as the weakest buses needing Mvar support [5].

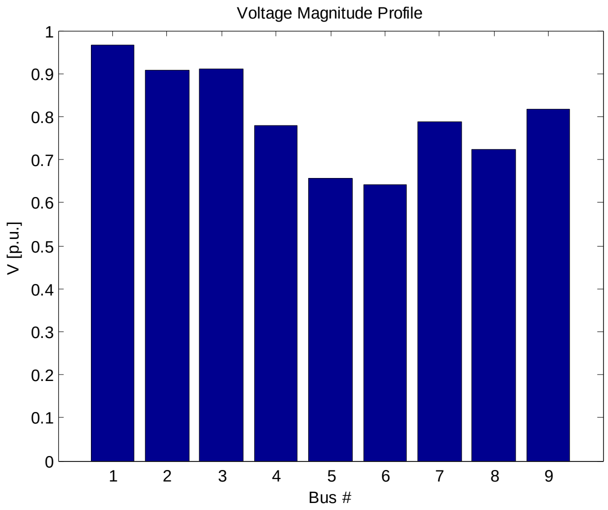


Figure 6: voltage magnitude profile without SVC

Now SVC is connected at these locations one by one and the maximum loading parameter was observed when SVC was connected at bus 5. The new maximum loading condition is λ= 2.7346 p.u. Corresponding PV curve and voltage magnitude profile obtained can be shown in the fig 7 and fig 8 respectively:

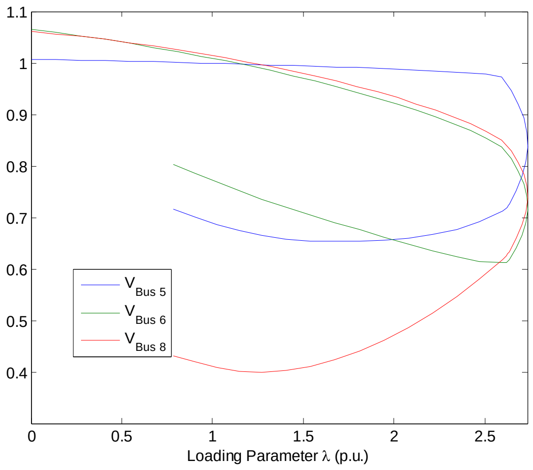


Figure 7: CPF with SVC at bus 5

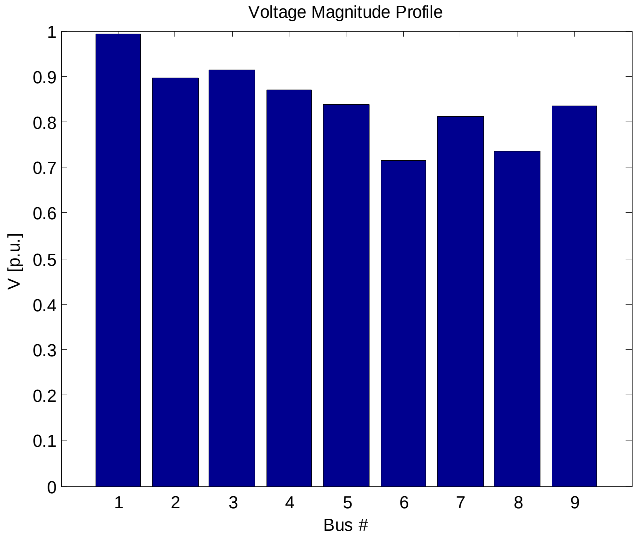


Figure 8: voltage magnitude profile with SVC at bus 5

It is found that the SVC increases the critical voltage point of the bus and also the range of the loading parameter. The loading parameter is increased from 2.505p.u. without SVC to 2.7346 p.u. with SVC. Hence the voltage stability of the multi machine power system is enhanced.

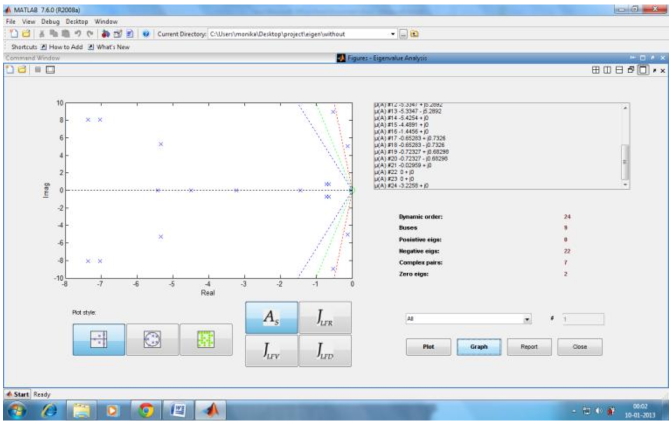
B. *Rotor angle stability*

Eigen value analysis

To obtain the small signal stability analysis we use Eigen value analysis. Eigen values are of two types: real or complex. When Real Eigen values lie at the left half of the s plane, system is stable.

Complex Eigen values contain two parts i.e. one is real part that provides damping and second is imaginary that provides frequency.

Figure 9 shows the Eigen value analysis of the test system without SVC.

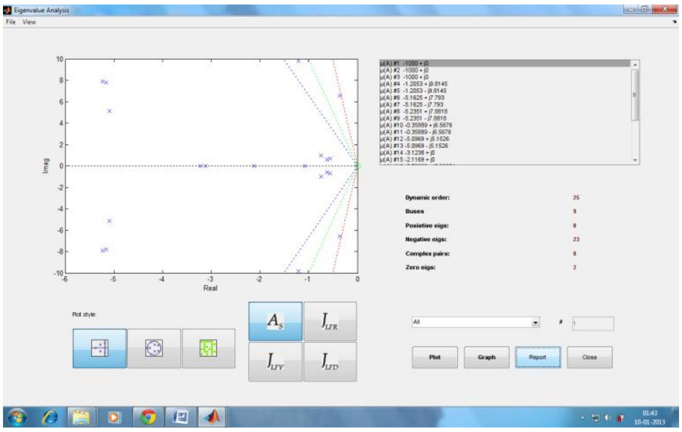


```
μ(A) #12 -5.3347 + j5.2892
μ(A) #13 -5.3347 - j5.2892
μ(A) #14 -5.4254 + j0
μ(A) #15 -4.4891 + j0
μ(A) #16 -1.4456 + j0
μ(A) #17 -0.65283 + j0.7326
μ(A) #18 -0.65283 - j0.7326
μ(A) #19 -0.72327 + j0.68298
μ(A) #20 -0.72327 - j0.68298
μ(A) #21 -0.02959 + j0
μ(A) #22  0 + j0
μ(A) #23  0 + j0
μ(A) #24 -3.2256 + j0

Dynamic order:      24
Buses               9
Posistive eigs:     0
Negative eigs:      22
Complex pairs:      7
Zero eigs:          2
```

Figure 9: Eigen Value Analysis without SVC

Now we will take the case of SVC, figure 10 shows the Eigen value analysis of the test system using SVC at bus #5.



```
μ(A) #1  -1000 + j0
μ(A) #2  -1000 + j0
μ(A) #3  -1000 + j0
μ(A) #4  -1.2053 + j9.8145
μ(A) #5  -1.2053 - j9.8145
μ(A) #6  -5.1625 + j7.793
μ(A) #7  -5.1625 - j7.793
μ(A) #8  -5.2351 + j7.8818
μ(A) #9  -5.2351 - j7.8818
μ(A) #10 -0.35889 + j6.5676
μ(A) #11 -0.35889 - j6.5676
μ(A) #12 -5.0969 + j5.1526
μ(A) #13 -5.0969 - j5.1526
μ(A) #14 -3.1238 + j0
μ(A) #15 -2.1169 + j0

Dynamic order:      25
Buses               9
Posistive eigs:     0
Negative eigs:      23
Complex pairs:      8
Zero eigs:          2
```

Figure 10: Eigen Value Analysis with SVC

Comparison of the statistics of both the cases i.e. with and without SVC is given in the table 1.

STATISTICS	**WITHOUT SVC**	**WITH SVC**
Dynamic Order	**24**	**25**
Negative Eigen	**22**	**23**
Positive Eigen	**0**	**0**
Real Eigen	**10**	**9**
Complex Pair	**7**	**8**
Zero Eigen	**2**	**2**

Table 1: Comparison of Eigen Value Report with and without SVC

In the Table 1, we can see that dynamic order of the system increases after incorporating SVC in the system. Here we notice that the no of negative Eigen value increases when SVC is placed in the system which in turn increases the small signal stability of the system. So we can say that small signal stability is enhanced using SVC in the system.

C. *Transient Stability Analysis*

For transient analysis, the fault is applied at bus 8 in the multi machine system for time duration of 0.250 second. Figure 11 (a) to (d) depicts the system response simulation curves of the system for oscillations in terms of power angle, speed, voltage and active power without SVC and Figure 12 (a) to (d) depicts the system simulation response curves with SVC.

In case of delta3-delta2 graph, we observe that the oscillations are damped out at 10sec with the use of SVC (fig 12(a)). Similarly in case of omega1 Vs time, oscillations are damped out at 14sec (fig 12(b)); in case of vf1 Vs time, at 7sec (fig 12(c)).; and in case of P2 Vs time, at 18sec (fig 12(d)) with the use of SVC.

It can be concluded from the response curves that the oscillations are damped out effectively and settling time is reduced considerably using SVC. Hence, with SVC we can enhance the transient performance of the system.

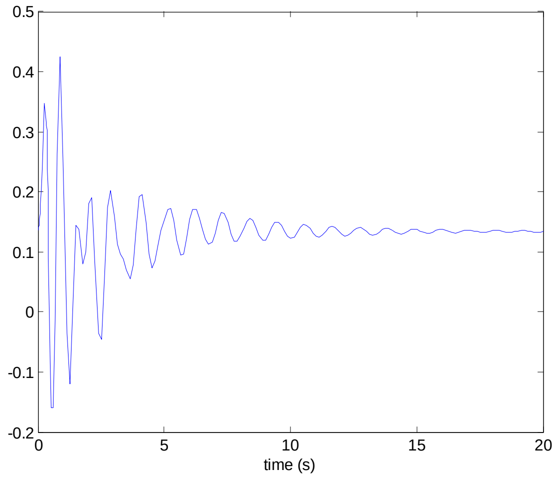


Fig 11(a): delta3-delta2 Vs time (without SVC)

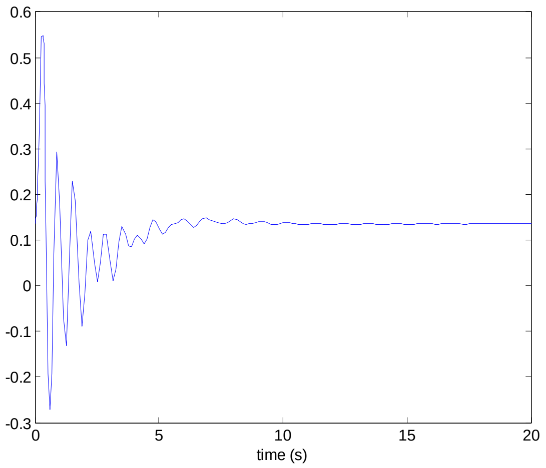


Fig 12(a): delta3-delta2 Vs time (with SVC)

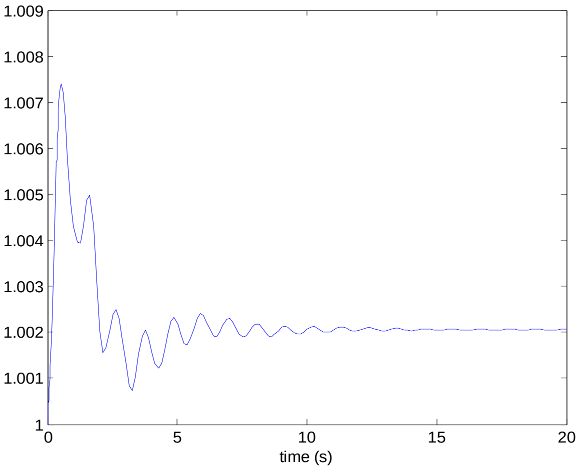


Fig 11(b):omega1 Vs time graph (without SVC)

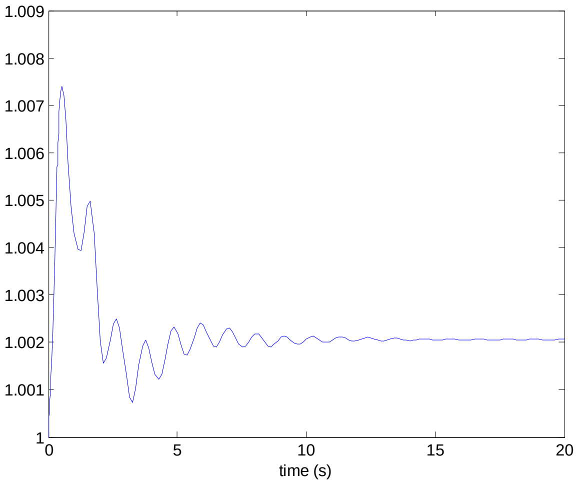


Fig 12(b): omega1 Vs time (with SVC)

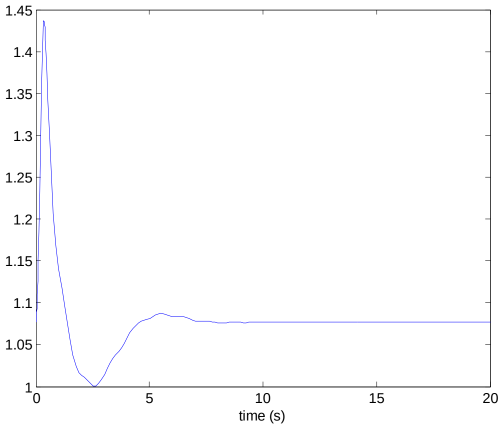


Fig 11(c) vf1 Vs time graph (without SVC)

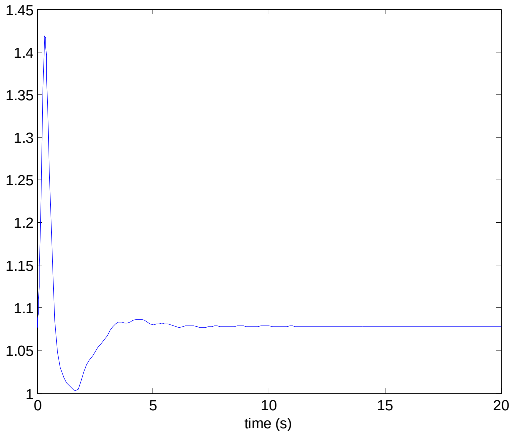


Fig 12(c): vf1 Vs time graph (with SVC)

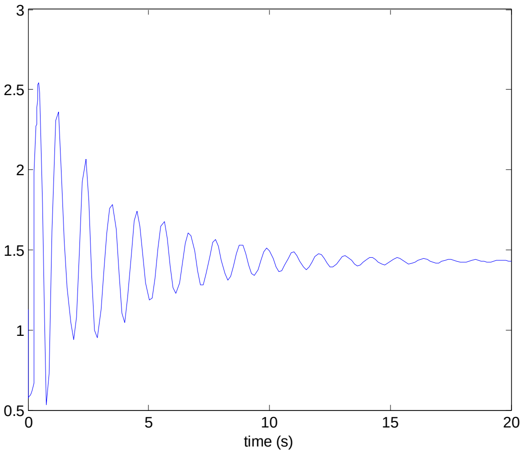


Fig 11(d): P2 Vs time graph (without SVC)

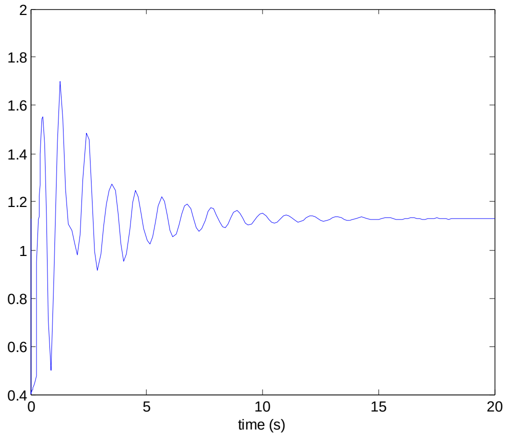


Fig 12(d): P2 Vs time graph (with SVC)

VII. CONCLUSION

The effects of SVC on voltage stability, small signal stability and transient stability are presented using PSAT (power system analysis toolbox) software. It was observed that SVC increases the loadability of the system which means voltage stability is increased. Based on simulation results in case of transient stability, the response curves show that the oscillations are damped out effectively with SVC. Using Eigen value analysis, we can enhance the small signal stability of the system. The results presented in this paper clearly show that SVC can be used to enhance the system stability in practical power systems with the use of simulink model. In future by designing the SVC controller ourselves we can have better results for the same system.

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