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# Impact of FACTS Controllers on the Dynamic Stability of Power Systems

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*The availability of flexible A.C. transmission system (FACTs) devices such as Static Var compensators (SVCs) and Static Compensators (STATCOMs), has led their use to control reactive power flows in transmission lines and system bus voltage. In addition to voltage control these devices can also be used effectively for improving the small signal stability of the power system and improve system damping. The objective of this paper is to explore the impact of the shunt connected FACTS devices namely Static Var Compensator (SVC) and Static Compensator (STATCOM), on the small signal stability of a single machine infinite bus system. A single machine infinite bus system is chosen to analyze the damping capabilities in a detailed manner.*

***Keywords:*** *Small Signal Stability, SVC, STATCOM, Damping Controller, Transient Stability.*

## 1.0 INTRODUCTION

As power systems became interconnected, areas of generation were found to be prone to electromechanical oscillations**.** These oscillations have been observed in many power systems worldwide. With increased loading conditions and interconnections the transmission system became weak and inadequate, also load characteristics added to the problem causing spontaneous oscillations. These oscillations may be local to a single generator or a generator plant (local oscillations, 0.8 – 2 Hz), or they may involve different groups of generators widely separated geographically (inter-area oscillations, 0.2 –0.8 Hz).These uncontrolled electro mechanical oscillation may lead to total or partial power interruption [1].

The recent advances in power electronics technology have led to the development of FACTS controllers which are effective candidates for providing secure loading, power flow control and voltage control in transmission systems. These controllers when placed effectively with supplementary stabilizing loops are found to be effective for damping out power system oscillations was discussed in [2].

Ref. [3] presents the basic Static Var Compensator (SVC) control strategies for enhancing the dynamic and transient stability of a simple two machine system. The design of a SVC based robust controller to damp power swings was presented in Ref. [4]. Ref [5] demonstrated a basic design procedure for the design of FACTS Controllers against power swings. The design of controllers was based on modal decomposition technique and the paper also addressed the issue of selecting feedback signals. The measurement signal used in the numerical example was the synthesized angular difference between the bus voltages of the two areas.

The dynamic behavior of voltage source converter based FACTS devices for simulation studies was discussed in ref. [6].These devices were modeled as current injections for dynamic analysis.

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The following section presents the mathematical modeling details of SVC and STATCOM for the enhancement of dynamic stability.

## 2.0 SYNCHRONOUS MACHINE MODELING

In stability analysis of a multi-machine system, modeling of all the machines in a more detailed manner is exceedingly complex in view of the large number of synchronous machines to be simulated. Therefore simplifying assumptions and approximations are usually made in modeling the system. Often only a few machines are modeled in detail, usually those machines located near the disturbances, while other machines are represented by simpler models. In the two-axis machine model, the transient effects are accounted for, while the sub-transient effects are neglected [7].

The amortisseur winding effects are neglected. The assumption is based on the fact that the effect of damper windings on the transient is small enough to be negligible. Additional assumptions are made in this model are that in the stator voltage equations, voltages proportional to flux linkages ($\dot{\lambda}_d$ and $\dot{\lambda}_q$) are negligible compared to the speed voltage terms and that $\omega = \omega_R = 1.0$ p.u. where $\omega$ is the angular velocity of the rotor and $\omega_R$ is the generator rated speed.

The linearized state equations in per unit form are given below. [7]

$$\Delta \dot{E}'_{di} = \frac{1}{\tau'_{qoi}}\left(-\Delta E'_{di} - \left(x_{qi} - x'_{qi}\right)\Delta I_{qi}\right)$$

$$\Delta \dot{E}'_{qi} = \frac{1}{\tau'_{doi}}\left(\Delta E_{FDi} - \Delta E'_{qi} + \left(x_{di} - x'_{di}\right)\Delta I_{di}\right)$$

$$\Delta \dot{\omega}_i = \frac{1}{\tau_{ji}}\{\Delta T_{mi} - D\Delta\omega_i - \Delta T_{ei})$$

$$\Delta \dot{\delta}_i = \Delta\omega_i$$

$$i = 1, 2 - - n \qquad ....(1)$$

where the state variables are

$E'_d$ - direct axis component of voltage behind transient reactance.

$E'_q$- quadrature axis component of voltage behind transient reactance.

$\omega$ - Angular velocity of rotor

$\delta$ – Rotor angle.

### 2.1 Network Equation in System dq coordinates with SVC

For the purpose of developing the small signal stability program the SVC is modeled in the network equations as shown in Figure 1.

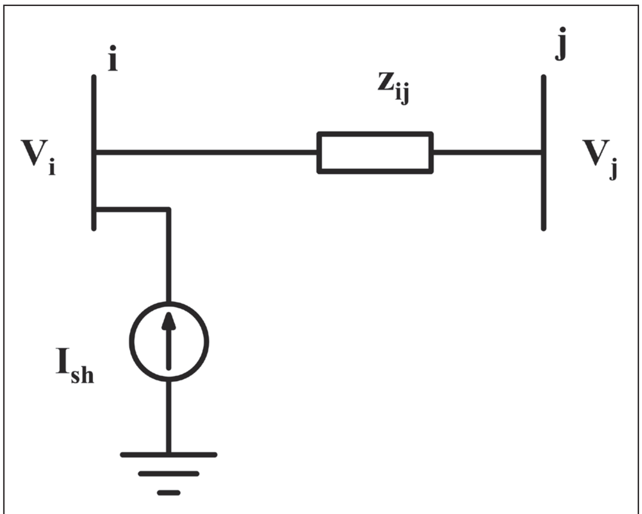


FIG. 1 CURRENT INJECTIONS - SVC

The change in bus voltage $_S$) ($\Delta V_i$ due to shunt connected FACTS device in the network is expressed in terms of the state variables from the last row of the matrix equation is given by

$$\begin{bmatrix}\Delta\bar{I}_1\\ \Delta\bar{I}_2\\ \Delta\bar{I}_{sh}\end{bmatrix} = \begin{pmatrix} Y_{11}e^{j\theta_{11}} & Y_{12}e^{j(\theta_{12}-\delta_{120})} & Y_{13}e^{j(\theta_{13}-\delta_{130})} \\ Y_{21}e^{j(\theta_{21}-\delta_{210})} & Y_{22}e^{j\theta_{22}} & Y_{23}e^{j(\theta_{23}-\delta_{230})} \\ Y_{31}e^{j(\theta_{31}-\delta_{310})} & Y_{32}e^{j(\theta_{32}-\delta_{320})} & Y_{33}e^{j\theta_{33}} \end{pmatrix}\begin{bmatrix}\Delta\bar{E}_1\\ \Delta E_2\\ \Delta\bar{V}_s\end{bmatrix}$$

$$-j\sum_{k=1}^{n}\begin{bmatrix}\bar{V}_{k0}Y_{1k}e^{j(\theta_{1k}-\delta_{1k0})} & 1k\\ \bar{V}_{k0}Y_{2k}e^{j(\theta_{2k}-\delta_{2k0})} & 2k\\ \bar{V}_{k0}Y_{3k}e^{j(\theta_{3k}-\delta_{3k0})} & 3k\end{bmatrix} \qquad ....(2)$$

## 2.2 Dynamic Model of SVC

The SVC dynamic model used for linear analysis is shown in Figure 2. With an additional stabilizing signal, supplementary control superimposed on the voltage control loop of an SVC can provide damping of system oscillations [3].

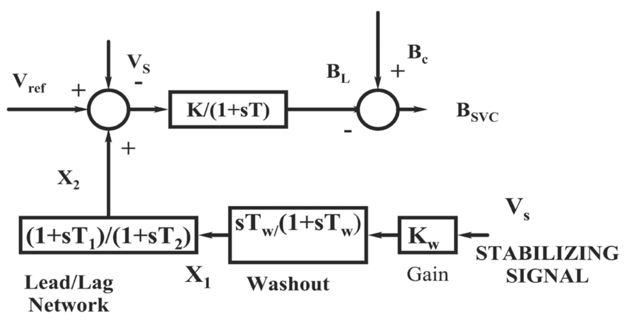


FIG. 2 DYNAMIC MODEL OF SVC

From the matrix equation (2), the change in network current with the introduction of SVC in the system d-q reference frame is given below. [9]

$$\begin{aligned}
\Delta I_{qi} = {} & G_{ii}\Delta E'_{qi} - B_{ii}\Delta E'_{di} \\
& + \sum_{k \neq i,j} [(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta E'_{qk} \\
& -(B_{ki}\cos\delta_{kio} + G_{ki}\sin\delta_{kio})\Delta E'_{dk} \\
& -(G_{ki}\sin\delta_{kio} + B_{ki}\cos\delta_{kio})\Delta\delta_{ki}E'_{qko} \\
& +(B_{ki}\sin\delta_{kio} - G_{ki}\cos\delta_{kio})\Delta\delta_{ki}E'_{dko}] \\
& + \sum_{j} \begin{matrix} [(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta V_{srj} \\ -(B_{ji}\cos\delta_{jio} + G_{ji}\sin\delta_{jio})\Delta V_{smj} \end{matrix} \\
& -(G_{ji}\sin\delta_{jio} + B_{ji}\cos\delta_{jio})\Delta\delta_{ji}V_{srjo} \\
& +(B_{ji}\sin\delta_{jio} - G_{ji}\cos\delta_{jio})\Delta\delta_{ji}V_{smjo}]
\end{aligned} \qquad ....(3)$$

$$\begin{aligned}
\Delta I_{di} = {} & B_{ii}\Delta E'_{qi} + G_{ii}\Delta E'_{di} \\
& + \sum_{k \neq i,j} [(G_{ki}\sin\delta_{kio} + B_{ki}\cos\delta_{kio})\Delta E'_{qk} \\
& +(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta E'_{dk} \\
& +(G_{ki}\cos\delta_{kio} - B_{ki}\sin\delta_{kio})\Delta\delta_{ki}E'_{qko} \\
& -(B_{ki}\cos\delta_{kio} + G_{ki}\sin\delta_{kio})\Delta\delta_{ki}E'_{dko}] \\
& + \sum_{j} \begin{matrix} [(G_{ji}\sin\delta_{jio} + B_{ji}\cos\delta_{jio})\Delta V_{srj} \\ +(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta V_{smj} \end{matrix} \\
& +(G_{ji}\cos\delta_{jio} - B_{ji}\sin\delta_{jio})\Delta\delta_{ji}V_{srjo} \\
& -(B_{ji}\cos\delta_{jio} + G_{ji}\sin\delta_{jio})\Delta\delta_{ji}V_{smjo}]
\end{aligned} \qquad ....(4)$$

The linearized state equations of the SVC for small signal analysis is given below

$$\Delta\dot{B}_L = \frac{K}{T}\Delta X_L + \frac{K}{T}\left[\left(\frac{T_1}{T_2}\right)K_W - 1\right]\Delta V_S - \frac{\Delta B_L}{T} - \frac{K}{T}\left(\frac{T_1}{T_2}\right)\Delta X_W \qquad ....(5)$$

The differential equations connected with the washout and lead lag filter are [9]

$$\Delta\dot{X}_W = \frac{K_W}{T_W}\Delta V_S - \frac{\Delta X_W}{T_W} \qquad ....(6)$$

$$\Delta\dot{X}_L = \frac{1}{T_2}\left(1 - \frac{T_1}{T_2}\right)(K_W\Delta V_S - \Delta X_W) - \frac{\Delta X_L}{T_2} \qquad ....(7)$$

Substituting (3) and (4) in the differential of the synchronous machine (1) and linearized differential equations of SVC (5-7) yields the system state space matrix.

The complete set of state variables describing the dynamics of the synchronous machine with the inclusion of the SVC in the network is as follows.

$$x^T = [E'_d, E'_q, \omega, \delta, B_L, X_W, X_L] \qquad ....(8)$$

## 2.3 Dynamic Modeling of STATCOM

The STATCOM resembles in many respects a synchronous compensator, but without inertia. The schematic diagram of a STATCOM is as shown in Figure 3. The basic electronic block of a STATCOM is the voltage source converter (VSC), which in general converts an input dc voltage into a three-phase output voltage ($V = kV_{dc}\angle\alpha$) at fundamental frequency, with rapidly controllable amplitude and phase. α is the phase shift between the controller VSC voltage and the bus voltage $V_s$.

The STATCOM is replaced with an equivalent current injection as shown in the Figure 4.

$Z_{ij}$ in Figure 4 includes only the impedance of line. The admittance ($Y_{sh}$) of the STATCOM device is pushed into the bus admittance matrix at node i.

The basic STATCOM circuit connected to a HT bus is shown Figure 5 [8].

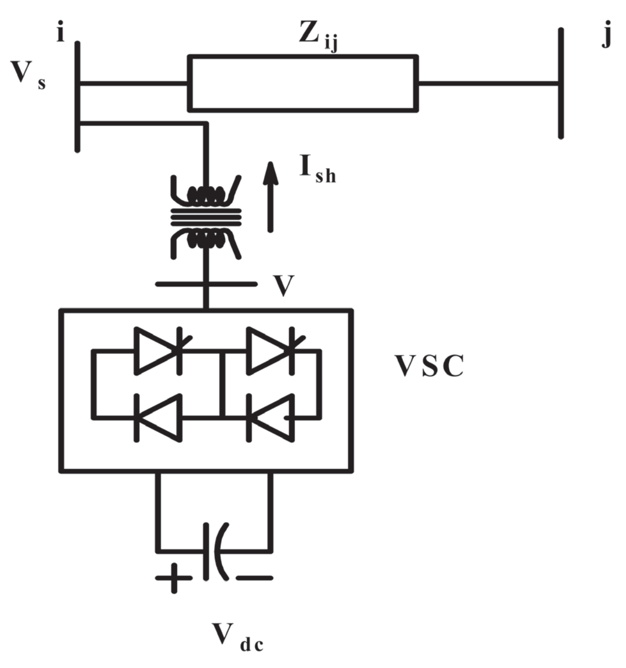


FIG. 3 STATCOM CONNECTED TO A MEDIUM VOLTAGE BUS

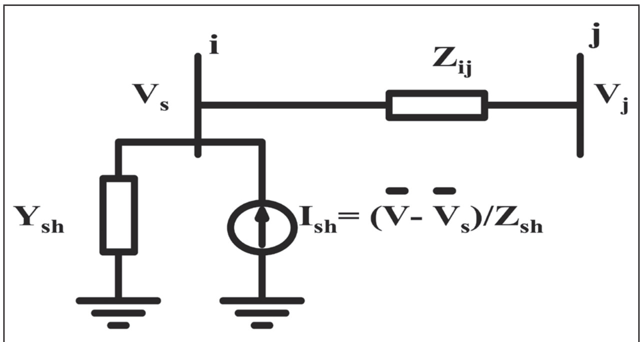


FIG. 4 CURRENT INJECTION MODEL OF STATCOM

From Figure 5, R+ j X is the coupling transformer impedance. k is a constant given by $\sqrt{3/8}$ $m_{sh}$. $V_s$ is the bus voltage to be controlled.Rc is the resistance to account for switching losses. Vdc is the DC voltage across the STATCOM capacitor. α - output of phase angle regulator. C - Capacitor connected to the terminals of the voltage source converter.

The shunt controller of the STATCOM includes a pulse width modulation (PWM) based AC voltage magnitude controller and a Proportional Integral (PI) phase angle regulator or the DC voltage magnitude controller (Figure 6). The AC voltage magnitude is controlled by the modulation index $m_{sh}$ as this has a direct effect on the Voltage Source Converter (VSC) voltage magnitude. The DC voltage magnitude controller is directly controlled by the phase angle, α which basically determines the active power flowing into the controller and the charging and discharging of the DC capacitor (Figure 7).

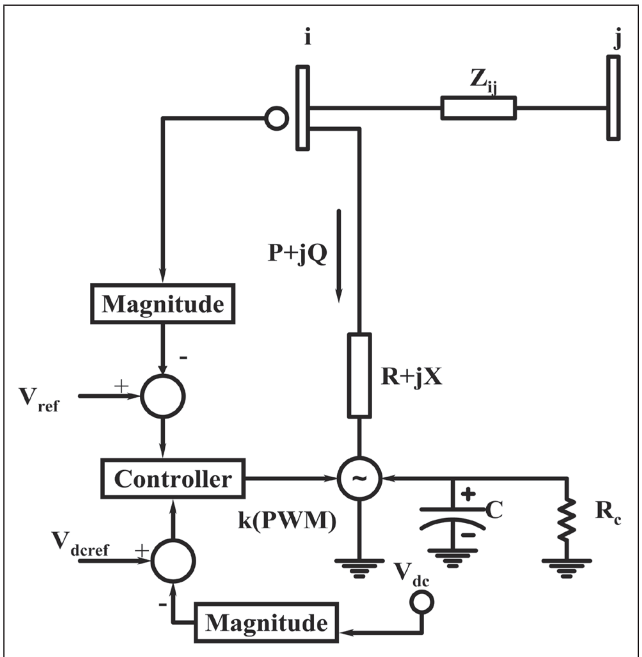


FIG. 5 STATCOM CIRCUIT

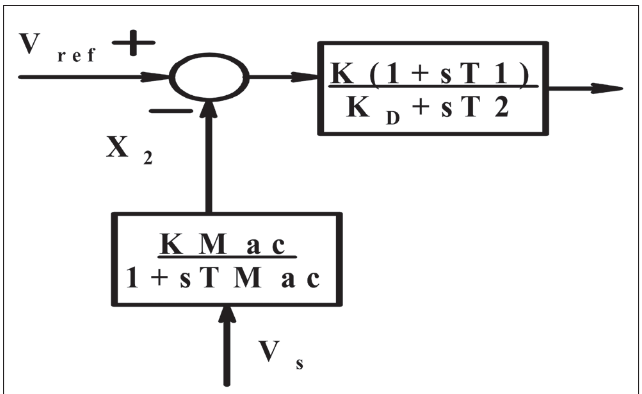


FIG. 6 VOLTAGE MAGNITUDE CONTROLLER – STATCOM

The following linearized differential equations can be written from the block diagrams given in Figure (6) and (7) for the STATCOM dynamic model.

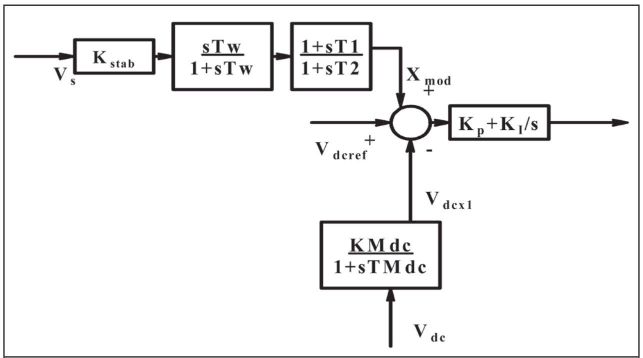


FIG. 7 PHASE ANGLE CONTROLLER

$$\Delta\dot{X}_2 = \frac{[K_{Mac}\Delta V_s - \Delta X_2]}{T_{Mac}} \quad ....(9)$$

$$\Delta \dot{m}_{sh} = -\frac{K_D}{T_2}\Delta m_{sh} + \frac{K}{T_2}\left(\frac{T_1}{T_{Mac}} - 1\right)\Delta X_2 - \frac{K}{T_2}\left(\frac{K_{Mac}T_1}{T_{Mac}}\right)\Delta V_s \quad ....(10)$$

$$\Delta\dot{V}_{dcx1} = \frac{[K_{M_{dc}}\Delta V_{dc} - \Delta V_{dcx1}]}{T_{M_{dc}}} \quad ....(11)$$

$$\Delta\dot{\alpha} = -\frac{K_pK_{Mdc}}{T_{Mdc}}\Delta V_{dc} + \left(\frac{K_p}{T_{Mdc}} - K_I\right)\Delta V_{dcx1} + \left(\frac{-K_p}{T2} + K_I\right)\Delta X_{le} + \left[\frac{K_p}{T_2}\left(1-\frac{T_1}{T_2}\right) + K_I\left(\frac{T_1}{T_2}\right)\right]K_{stab}\Delta V_s - \left[\frac{K_p}{T_2}\left(1-\frac{T_1}{T_2}\right) + K_I\left(\frac{T_1}{T_2}\right)\right]\Delta X_w \quad ....(12)$$

$X_2$ is the output of the AC voltage measuring circuit. $V_{dcx1}$ is the output of the DC voltage measuring circuit. $\alpha$ is the output of the phase angle controller block. From the power balance equation $P_{ac}=P_{dc}$+Losses, the change in capacitor dc voltage is obtained as given below

$$\Delta\dot{V}_{dc} = \frac{P_{aco}}{CV_{dc}^2}\Delta V_{dc} - \frac{\Delta V_{dc}}{R_cC} - \frac{RI^2}{CV_{dc}^2}\Delta V_{dc} + \frac{1}{CV_{dc}}\Delta P_{ac} \quad ....(13)$$

The differential equation connected with the washout block circuit is. [9]

$$\Delta\dot{X}_W = \left(\frac{K_{stab}}{T_W}\right)\Delta V_s - \frac{\Delta X_W}{T_W} \quad ....(14)$$

The equation associated with the lead lag block is given by [9]

$$\Delta\dot{X}_{le} = \frac{1}{T_2}\left(1 - \frac{T_1}{T_2}\right)(K_{stab}\Delta V_s - \Delta X_W) - \frac{\Delta X_{le}}{T_2} \quad ....(15)$$

The change in network current with STATCOM in the circuit can be obtained similar to equations (3) and (4) as obtained for SVC. Substituting (3) and (4) in the differential and algebraic equation of the synchronous machine (1), exciter state equation and STATCOM dynamic equations (9-15) yields the system state space matrix.

The complete set of state variables describing the dynamics of the multimachine power system with STATCOM is given by

$$x^T = [\Delta E_d', \Delta E_q', \Delta\omega, \Delta\delta, \Delta E_{FD}, \Delta X_W, \Delta X_{le}, \Delta X_2, \Delta m_{sh}, \Delta V_{dcx1}, \Delta\alpha, \Delta V_{dc}] \quad ....(16)$$

## 3.0 NUMERICAL EXAMPLE AND RESULTS

The test system taken up for small signal stability enhancement with FACTS /PSS controllers is shown in Figure 8 [1].

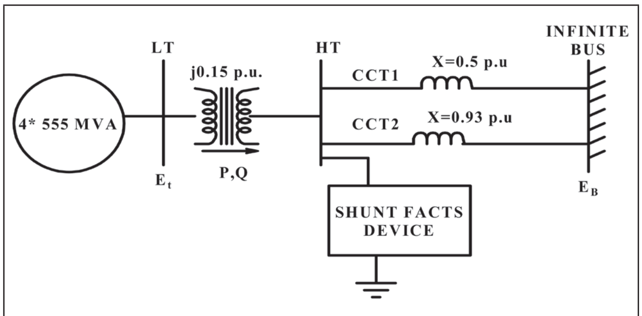


FIG. 8 SINGLE MACHINE INFINITE BUS SYSTEM WITH SVC/STATCOM CONNECTED AT HT BUS

From Table 1 it can be observed that the damping ratio of the swing mode with PSS is 0.1405 and with SVC is 0.1774.

TABLE 1

EIGENVALUE ANALYSIS OF THE SMIB SYSTEM WITH PSS / SHUNT FACTS DEVICE

| WITHOUT DAMPING CONTROLLER | WITH PSS | WITH SVC | WITH STATCOM |
|---|---|---|---|
| 0.4146 ± 6.8083i $\zeta$=-0.060783 f=1.0841 Hz | -1.0604 ± 7.4717i $\zeta$ =0.1405 | -1.3571 ± 7.5297i $\zeta$ = 0.1774 | -1.8471 ± 7.2934i $\zeta$ = 0.2455 |

The damping ratio of the SMIB system is 0.1774 with SVC and 0.2455 with STATCOM in the HT bus. This is because that STATCOM is a voltage source converter based FACTS device, which has a faster transient response than a SVC, which is a passive thyristor switched device.

To check the robustness of the FACTS stabilizers following a major disturbance a three-phase fault is simulated in line CCT 2 near the HT bus at 1 sec, which is subsequently cleared by tripping the line in 1.1 seconds. It can be observed that the rotor angle oscillations settle down with PSS in the excitation system after 4 seconds (Figure 9).

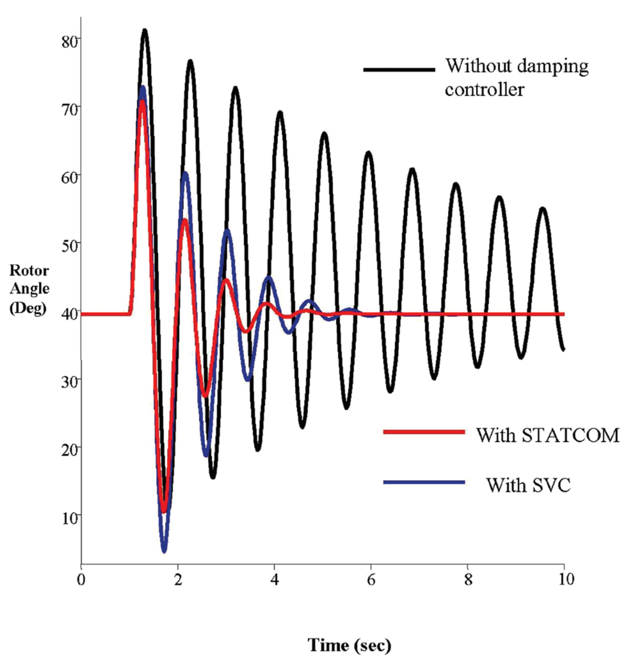


FIG. 9 DYNAMIC RESPONSE OF THE SMIB SYSTEM

## 4.0 CONCLUSION

This paper presented the mathematical model for analyzing the small signal stability of a power system with shunt connected FACTS devices which could be generalized for a multi-machine power system. A single machine infinite bus (SMIB) system was chosen for carrying out detailed investigations on different FACTS based stabilizers. A generalized small signal stability model based on current injections of FACTS devices is developed for the SMIB system. From the results it is observed that among shunt connected devices, STATCOM is effective in enhancing the small signal stability compared to SVC.

## APPENDIX

The Table 2 and 3 give below presents the data related to the dynamic data of SVC and STATCOM.

TABLE 2

SVC DATA

| VARIABLE | VALUE |
|---|---|
| $B_{Lo}$ | -0.974 |
| $B_{co}$ | 0.8772 |
| K | 10 |
| $T_w$ | 5 |
| $T_2$ | 0.05 |

TABLE 3

STATCOM DATA

| VARIABLE | VALUE |
|---|---|
| R | 0 |
| X | 0.025 |
| $R_C$ | .077 |
| C | 0.2592 |
| K | 10 |
| $T_1$ | 1.1 |
| $T_2$ | 0.05 |
| $K_d$ | 10 |
| $K_{Mac}$ | 1 |
| $T_{Mac}$ | 0.01 |
| $K_p$ | 10 |
| $K_I$ | 1 |
| $K_{Mdc}$ | 10 |
| $T_{Mdc}$ | 0.01 |

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