Damping Power System Oscillations in Single-Machine Infinite-Bus Power System Using a STATCOM

Ghazanfar Shahgholian, Pegah Shafaghi, Sepehr Moalem,Mehdi Mahdavian
Department of Electrical Engineering - Islamic Azad University
Najaf Abad Branch
Esfahan, Iran
shahgholian@iaun.ac.ir, p_shafaghi@iaun.ac.ir

***Abstract*— The aim of this paper is dynamic modeling and analysis of STATCOM for a single-machine infinite-bus (SMIB) power system. Also the study the applicability of PID type in dynamic performance enhancement with eigenvalue analysis is shown. Non-linear and linear models of a single machine have been derived. The STATCOM is modeled as a reactive current source with a time delay. A comparative study for two control inputs, one in the speed loop and the other in the voltage loop, for STATCOM controller using eigenvalues analysis is shown.**

Keywords- static synchronous compensator; PID controller; damping power system oscillations; small signal stability.

I. INTRODUCTION

There has been a surge of interest in the development and use of flexible ac transmission system (FACTS) controllers in power transmission systems in recent years. FACTS controllers can improve the security of a power system by enhancing its steady-state and transient stability or by damping the sub-synchronous resonance oscillations. An important FACTS device is the Static synchronous compensator (SATCOM), which can control all three principle parameters (voltage, impedance and phase angle) and used for dynamic compensation of power system to provide voltage support and stability improvement [1].

STATCOM is a flexible ac transmission system device, which is connected as a shunt to the network, for generating or absorbing reactive power. A number of studies have been performed about the dynamic behavior of STATCOM and its application to improve the transient performance of power systems [2, 3]. A nonlinear PID controller on STATCOM with differential tracker for damping the inter-area oscillations proposed in [4], where simulation results showed good performance of the suggested differential tracker under large disturbances. In [5] proposed a technique based on neural network algorithm to define the switching instants for control the harmonic output of a STATCOM using a PWM scheme with a minimal number of additional switching. A study comparing the effects of four FACTS controllers using eigenvalues analysis on power systems small signal angle stability presented in [6]. In [7] a study and compares different control techniques for damping undesirable electromechanical oscillations in power system by using series and shunt FACTS controllers is discussed. A comparative study between the conventional SVC and STATCOM in damping power system oscillation is show the superiorly of STATCOM-based controller over SVC-based controller in increasing the damping of low frequency oscillations.

Small signal stability is one of the mandatory requirements for a secure power system operation. In this paper the dynamic behavior of a single machine infinite bus system installed with STATCOM has been investigated. Non-linear and linear models of a single machine have been derived. The STATCOM is modeled as a reactive current source with a time delay. Finally, the role STATCOM played in enlarging transmission capacity and improving transient stability is showed by simulation results and parameters variation on system response are discussed.

II. SYSTEM DESCRIPTION

A STATCOM is a voltage-source converter (VSC) based shunt FACTS device. It is capable of injecting controllable reactive power into the system. Fig. 1 show a STATCOM is placed at bus M which consists of a step down transformer (SDT) and a dc capacitor. The VSC generates a controllable ac voltage $u_C(t)$.

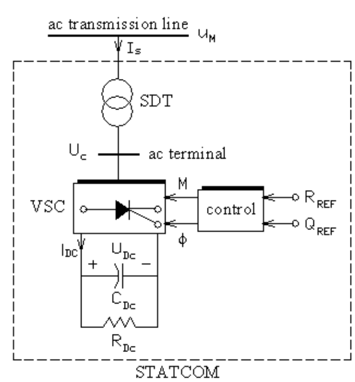

Figure 1. Circuit diagram of STATCOM

Two control signals are M (modulation ratio defined by PWM) and ϕ (phase angle defined by PWM). The dc capacitor (C_{DC}) has the function of establishing an energy

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balance between the input and output during the dynamic change of the var output. The size of the capacitor is primarily determined by the ripple input current encountered with the particular converter design. The reference signal Q_{REF} and P_{REF} can control the amplitude and phase angle of output voltage, respectively. The reactive power output of STATCOM is inversely proportional to bus voltage and thus is less affected by voltage reduction than the other FACTS devices. The reactive power is varied by varying the magnitude of the converter output voltages. The equivalent circuit of STATCOM is represented by a shunt reactive current source I_S as shown in Fig. 2. The STATCOM operation is illustrated by the phasor diagrams shown in Fig. 3 [8, 9].

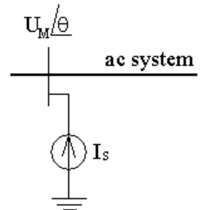
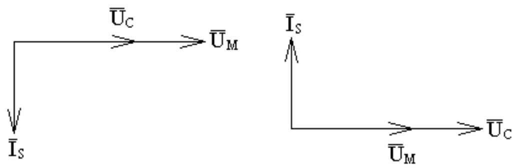


Figure 2. Mathematical model of STATCOM



(a) Inductive (b) Capacitive

Figure 3. STATCOM operation

III. DYNAMIC PERFORMANCE ANALYSIS

The power system model consists of a synchronous machine connected to an infinite bus through a transmission line with a STATCOM as shown in Fig. 4.

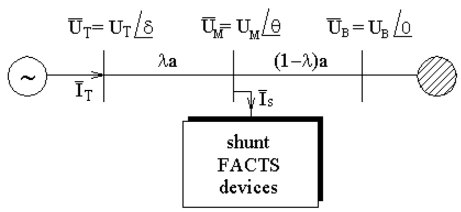


Figure 4. Transmission line with a shunt FACTS device

The cylindrical rotor machine is simulated by electromechanical swing equation in broken into two first order differential equations. A parameter λ is used to show the fraction of line length at which the FACTS device is placed.

A. Transmission line model

The transmission line parameters are uniformly distributed and the line can be represented with a two-port, four-terminal network as shown in Fig. 5, where U_{SE} and I_{SE} are the sending-end voltage and current, and U_{RE} and I_{RE} are the receiving-end voltage and current. The relation between the sending end (SE) and receiving end (RE) quantities can be written as [10]:

$$\begin{bmatrix} \overline{U}_{SE} \\ \overline{I}_{SE} \end{bmatrix} = \begin{bmatrix} \overline{A} & \overline{B} \\ \overline{C} & \overline{D} \end{bmatrix} \begin{bmatrix} \overline{U}_{RE} \\ \overline{I}_{RE} \end{bmatrix} \quad (1)$$

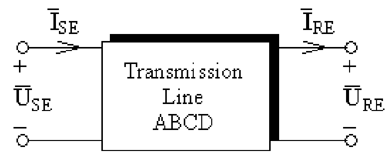


Figure 5. Representation of two-port network

where generalized circuit constants (ABCD) of a line of length a, are parameters that depend on the transmission-line constants and given by:

$$\begin{cases} \overline{A} = \overline{D} = \cosh(\gamma a) \\ \overline{B} = \overline{Z}_C \sinh(\gamma a) \\ \overline{C} = \dfrac{1}{\overline{Z}_C} \sinh(\gamma a) \end{cases} \quad (2)$$

where Z_C characteristic impedance of the line, γ is the line propagation constant:

$$\begin{cases} \overline{Z}_C = \sqrt{\dfrac{\overline{z}}{\overline{y}}} \\ \overline{\gamma} = \sqrt{\overline{z}\,\overline{y}} \end{cases} \quad (3)$$

where $\overline{z}$ is series impedance per unit length/phase and $\overline{y}$ is shunt admittance of per unit length/phase. If $\overline{A}\,\overline{D} - \overline{B}\,\overline{C} = 1$ and $\overline{A} = \overline{D}$ the currents at the SE and RE of the line can be written as:

$$\begin{cases} \overline{I}_{SE} = \dfrac{\overline{A}}{\overline{B}} \overline{U}_{SE} - \dfrac{1}{\overline{B}} \overline{U}_{RE} \\ \overline{I}_{SR} = \dfrac{1}{\overline{B}} \overline{U}_{SE} - \dfrac{\overline{A}}{\overline{B}} \overline{U}_{RE} \end{cases} \quad (4)$$

where $\overline{A} = A\angle\alpha$ and $\overline{B} = B\angle\beta$.

B. system equation

The dynamic of the generator is expressed in terms of the second order electromechanical swing and the model of STATCOM is a controllable reactive current source with time delay. The nonlinear model of the SMIB system is given as [11]:

$$\frac{d}{dt}\delta = \omega_o\,\omega \quad (5)$$

$$\frac{d}{dt}\omega = -\frac{K_D}{2H}\omega - \frac{1}{2H}P_E + \frac{1}{2H}P_M \quad (6)$$

$$\frac{d}{dt}I_S = \frac{1}{T_{STA}}(-I_S + K_{STA}\,u_S) \quad (7)$$

where K_D is the damping constant, H is the inertia constant in second, ω is the relative speed, P_M is the mechanical power input, ω_o is the synchronous speed, P_E is the electrical power output, δ is load angle in radian, I_S is output current drained by STATCOM and u_S is STATCOM controller output.

C. linearization equations

The dynamic equations governing the performance of the power system are nonlinear. They are linearized about steady state condition for small signal stability studies. The linearized model for SMIB with STACOM is obtained by perturbing the set of equations (1)-(3) around a nominal point. In steady state

$$\begin{cases} u_d = X_q\, i_q \\ u_q = E_q^{'} - X_d^{'}\, i_d \end{cases} \quad (8)$$

where u_d, u_q direct and quadrature axis stator terminal voltage (U_T) components, respectively, $E^{'}_q$ is transient emf in the quadrature axis, X'_d is direct axis transient reactance and X_q is quadrature axis reactance. The transmission line in Fig.3 has parameters $A_1B_1C_1D_1$ and $A_2B_2C_2D_2$ for the first and the second sections respectively. The STATCOM voltage is:

$$\overline{U}_M = U_{Md} + j\,U_{Mq} \quad (9)$$

where U_{Md} and U_{Mq} are the direct and quadrature axis components of U_M, respectively, and θ is phase difference between quadrature axis of the generator and U_M as shown Fig. 6. The voltage and current relationship for the power system with STATCOM are expressed as:

$$\underbrace{\begin{bmatrix} F_1 & F_2 \\ F_3 & F_4 \end{bmatrix}}_{X_{dq}} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} U_{Md} - A_1E_q^{'}\cos\alpha_1 \\ U_{Mq} + A_1E_q^{'}\sin\alpha_1 \end{bmatrix} \quad (10)$$

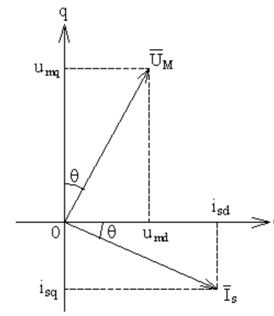


Figure 6. Phasor diagram of the voltage and current at the bus M

$$i_d = \frac{1}{|X_{dq}|}[-F_2U_{Md} + F_4U_{Mq} - A_1E_q^{'}(F_2\sin\alpha_1 + F_4\cos\alpha_1)] \quad (11)$$

$$i_q = \frac{1}{|X_{dq}|}[F_1U_{Md} - F_3U_{Mq} + A_1E_q^{'}(F_1\sin\alpha_1 + F_3\cos\alpha_1)] \quad (12)$$

$$|X_{dq}| = A_1B_1(X_q + X_d^{'})\sin(\alpha_1 - \beta_1) - A_1^2X_qX_d^{'} - B_1^2 \quad (13)$$

$$\overline{U}_M = \frac{1}{A_2}\overline{U}_B + \frac{\overline{B}_2}{A_2}[\overline{I}_S + \frac{1}{A_1}\overline{I}_T - \frac{\overline{C}_1}{A_1}\overline{U}_M] \quad (14)$$

Change in amplitude and phase of STATCOM voltage are:

$$\Delta\theta = K_{TD}\Delta\delta + K_{TS}\,\Delta I_S \quad (15)$$

$$\Delta U_M = K_{UD}\Delta\delta + K_{US}\Delta I_S \quad (16)$$

The change of delivered electrical power is:

$$\Delta P_E = K_{ET}\Delta\theta + K_{EM}\Delta U_M \quad (17)$$

$$\Delta P_E = \underbrace{(K_{ET}K_{TD} + K_{EM}K_{md})}_{K_{ED}}\Delta\delta + \underbrace{(K_{ET}K_{TS} + K_{EM}K_{mq})}_{K_{ES}}\Delta I_S \quad (18)$$

The change of generator current terminal is:

$$\Delta i_d = K_{DD}\Delta\delta + K_{DS}\Delta I_S \quad (19)$$

$$\Delta i_q = K_{QD}\Delta\delta + K_{QS}\Delta I_S \quad (20)$$

where i_d and i_q are direct and quadrature axis terminal current components, respectively. The block diagram of the entire linearized system with PID controller in the speed $G_S(s)$ and the voltage $G_U(s)$ loop can be described by the block diagram shown in Fig. 7.

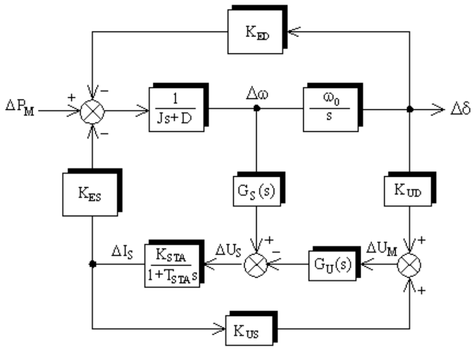


Figure 7. Block diagram of the linearized system

They are linearized about steady state condition for small signal stability studies. The linearized model for SMIB with STACOM is obtained by perturbing the set of equations (1)-(3) around a nominal point:

$$\frac{d}{dt}\Delta\delta = \omega_o\,\Delta\omega \tag{21}$$

$$\frac{d}{dt}\Delta\omega = -\frac{D}{J}\Delta\omega - \frac{K_{ED}}{J}\Delta\delta - \frac{K_{ES}}{J}\Delta I_S + \frac{1}{J}\Delta P_M \tag{22}$$

$$\frac{d}{dt}\Delta I_S = \frac{K_{STA}K_W}{T_{STA}}\Delta\omega - \frac{K_{UD}K_UK_{STA}}{T_{STA}}\Delta\delta - \left(\frac{1+K_UK_{US}K_{STA}}{T_{STA}}\right)\Delta I_S \tag{23}$$

The closed loop poles are roots of the characteristic equation:

$$\Delta(s) = s^3 + \left(\frac{1+K_UK_{US}K_{STA}}{T_{STA}} + \frac{D}{J}\right)s^2 + \left(\frac{K_{ES}K_{ST}K_W)}{J\,T_{STA}} + \frac{D}{T_{STA}}(1+K_{STA}K_UK_{US}) + K_{ED}\omega_o\right)s + \frac{\omega_oK_{ED}}{J}\left(\frac{1+K_{STA}K_UK_{US}}{T_{STA}}\right) - \frac{K_{ES}\omega_oK_{STA}K_UK_{UD}}{J\,T_{STA}} \tag{24}$$

D. Reactive power

The angle of voltage at bus M is given by:

$$tg\delta_M = \frac{X_2U_T\sin\delta_T}{X_2U_T\cos\delta_T + X_1U_B} \tag{25}$$

The voltage of bus M can be written as:

$$U_M = \lambda(1-\lambda)I_S + \sqrt{(1-\lambda)^2U_T^2 + \lambda^2U_B^2 + 2\lambda(1-\lambda)U_TU_B\cos\delta_T} \tag{26}$$

The reactive power (Q_{STA}) supplied by the STATCOM And the active power of the generator can be written as:

$$Q_{STA} = I_S\,U_M \tag{27}$$

$$P_T = \frac{E_q'U_B}{X_T+X_d'}\sin\delta - \frac{X_q-X_d'}{(X_T+X_q)(X_T+X_d')}\frac{U_B^2}{2}\sin 2\delta + \frac{X_2I_S}{X_T+X_d'}E_q'\sin\theta - \frac{I_S(X_q-X_d')}{(X_T+X_q)(X_T+X_d')}[U_B\sin(\delta+\theta) - \frac{X_S^2}{2}I_S\sin\theta] \tag{28}$$

IV. Simulation Results

The dynamic behavior of the system was studied considering the following three controller configurations: controller in speed loop only, controller in voltage loop only and controller in combined voltage-speed loop. The power system model given in Fig. 5 was simulated to test the STATCOM controller. The data of the system is given in the Table I. The effect of both K_W and K_U on the dynamic performance was evaluated. The dominant eigenvalues for several of K_U and K_W are shown in Table II. The effects of K_W on dominant eigenvalues are shown in Table III. Figs. 8 and 9 show the generator speed and mid-bus voltage variations with control only in the speed (K_W) loop. In Fig.9, the step response is highly oscillatory with decrease of K_W and decrease in overshoot. If the gains are increased the damping characteristics improve but there is an overshoot initially both in the voltage response and controller current output.

TABLE I. Data of the SMIB system

generator	X_q=0.6, X_d=1.6, X'_d=0.3, J=3, D=0
statcom	K_{STA}=1, T_{STA}=0.02
transmission line	X_1=0.3, X_2=0.3
steady state condition	I_{do}=0.8342, I_{qo}=0.4518, U_{do}=0.8211 U_{qo}=0.5708, U_B=1, δ_o=77°, I_{So}=0

TABLE II. Dominant eigenvalues for several K_U and K_W

K_U=0 K_W=0	K_U=50 K_W=0	K_U=0 K_W=50	K_U=50 K_W=50
-50 ±j7.86	-597.5 -0.01±j8.87	-46.89 -1.55±j7.96	-597.29 -0.11±j8.87

TABLE III. The effects of K_W on dominant eigenvalues

K_W=0	K_W=50	K_W=100	K_W=150
-50 ±j7.86	-46.89 -1.55±j7.96	-43.31 -3.35±j7.75	-38.91 -5.55±j6.97

Fig. 10 show speed deviation and angle load deviation with two location of STATCOM, near generator bus and near infinite bus. The comparison of the load angle and STATCOM output current frequency response characteristics for change in K_W are shown in Figs. 11 and 12, respectively. This confirms the well known fact that controller in voltage loop have little on electromechanical oscillations.

V. Conclusion

FACTS devices can help the damping of power system oscillations. Linear analysis techniques have been used to study the dynamic behavior of SMIB system with STATCOM. A comparative study for two control inputs, one in the speed loop and the other in the voltage loop, for STATCOM controller using eigenvalues analysis has been investigated. A controller in the speed loop has effective control over the electrical and electromechanical transient.

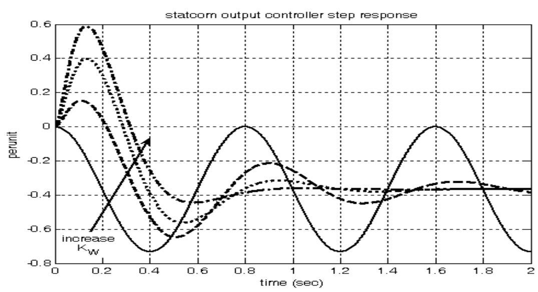


Figure 8. Output controller with controller in the speed loop

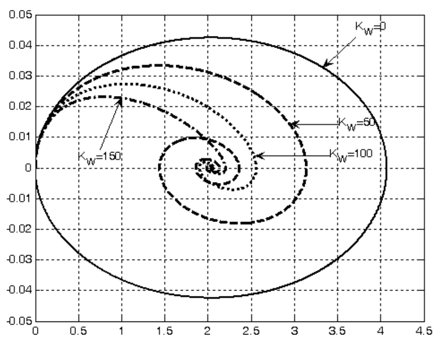


Figure 9. Speed deviation and angle load deviation with change of K_W

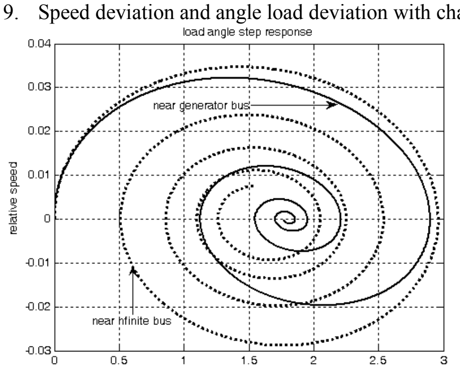


Figure 10. Speed deviation and angle load deviation with two location of STATCOM

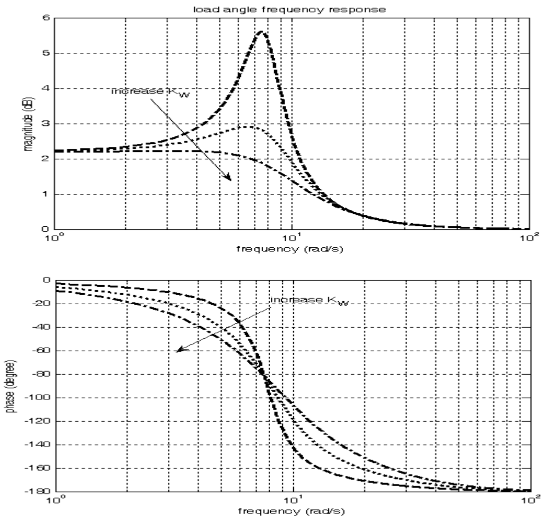


Figure 11. Comparison of the load angle frequency response characteristics for change in K_W

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