Modeling and Damping Controller Design for Static Synchronous Compensator

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Abstract - **A STATCOM can be used for voltage regulation in a power system, having as an ultimate goal the increase in transmittable power, and improvements of steady-state transmission characteristics and of the overall stability of the system. In this paper a model of a SMIB with STATCOM which is suitable for both steady state analysis and dynamic stability analysis systems is developed. A damping controller is also designed for the STATCOM using root locus methods.**

I. INTRODUCTION

Transmission lines in a modern interconnected power system are more heavily loaded then ever before to meet the growing demand. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. Flexible ac transmission system (FACTS) controllers can provide feasible solutions to reinforce the transmission systems to better utilize the existing power systems [1]. Some of the functions of FACTS devices are control the power transfer between the power utility companies and to avoid unwanted power loop flows, increase the maximum power carrying capacity of existing transmission systems, secure loadings of lines near their thermal limits and prevention of cascading outages by contributing to emergency control. It can also improve the damping of oscillations which can threaten security or limit the usable line capacity and improve system stability in general [2, 3]. FACTS devices can be connected to a transmissions line in various ways, such as in series, shunt, or a combination of series and shunt. A static synchronous compensator (STATCOM) operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. In addition, STATCOM can also increase power system stability by damping power oscillations [4].

Various approaches have been down and proposed to design damping controllers for different FACTS devices [5, 6]. A comparative study of two damping controllers, power system stabilizer (PSS) and STATCOM for damping enhancement of oscillations occurring in a power system subject to disturbances by employing PID controller is presented in [7]. A third order dynamic model of the power system to incorporate STATCOM in the system to study its damping properties proposed in [8]. A current injection model of FACTS controllers for power system dynamic stability studies which can be easily applied to the linear and the nonlinear analysis, and adopt any kind of FACTS controllers regardless of model types, proposed in [9].

Linear analysis techniques have been used to study the dynamic behavior of power systems. This paper using the state space theory deduces the mathematical model for the single-machine infinite-bus (SMIB) systems with STATCOM. The eigenvalue method is employed to analyze the damping ability of STATCOM. Finally, simulation results have been reported and discussed.

II. SIMPLIFIED SYSTEM MODEL

Power system oscillations are generally associated with the dynamics of generators, turbine governors and excitation systems and can be represented by the linearized swing equation of a synchronous generator around an operating condition. Dynamic model of SMIB with STATCOM controller is shown in Fig. 1. The model neglects the active losses of the line and transformer, switching losses of the inverter and the power loss in the capacitor. In general, a STATCOM system can be divided into three key parts: the converter power stage, the passive components and the control system. The basic principle of operation of a STATCOM is the generation of a controllable ac voltage source (U_C) behind a transformer leakage reactance (X_S) by a voltage source inverter connected to a dc capacitor (C_{DC}). The V-I characteristic of STATCOM are shown in Fig. 2.

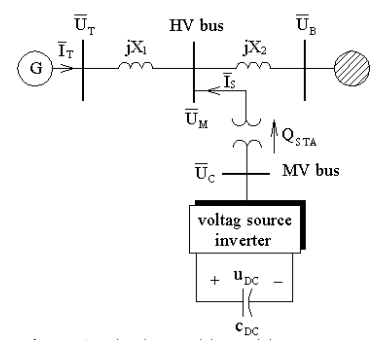

Figure 1. Single machine with STATCOM

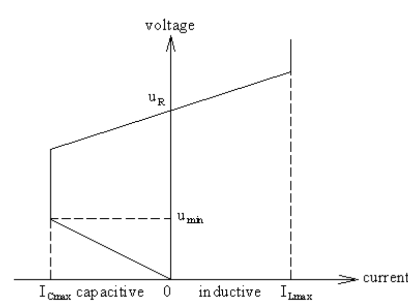

Figure 2. Terminal characteristic of STATCOM.

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The controller can provide both capacitive and inductive compensation and is able to control output current over the rated maximum capacitive or inductive range independent of the AC system voltage. The dynamic behavior of the system was studied considering the controller combined voltage $G_W(s)$ and speed $G_S(s)$ loop. In the equivalent model STATCOM assumed that the terminal voltage can be controlled by first order delay of input U_S. If $\Delta\omega$ is the per unit speed deviation of the generator and amplitude of STATCOM voltage U_M, K_U and K_W are the control transfer function in the voltage and damping control loop, respectively, the output of the STATCOM controller is:

$$\Delta U_S = -K_U\,\Delta U_M + K_W\,\Delta\omega \quad (1)$$

The STATCOM is modeled as a reactive current source I_S absorbed from the system with a time delay T_{STA}:

$$\frac{d}{dt} I_S = \frac{1}{T_{STA}}(-I_S + K_{STA}\,U_S) \quad (2)$$

The dynamics of the machine is expressed in terms of the second order electromechanical swing equation (classical model). If $\Delta\delta$ is the rotor angle deviation, the change of delivered electrical power P_E is:

$$\Delta P_E = K_{ED}\Delta\delta + K_{ES}\Delta I_S \quad (3)$$

The change in amplitude of STATCOM voltage and the angle of voltage at bus M is given by:

$$\Delta U_M = K_{UD}\Delta\delta + K_{US}\Delta I_S \quad (4)$$

$$tg\theta = d_1 \frac{d_2 \sin\delta + d_3 I_S \sin\theta}{d_4 + d_5\cos\delta + d_6 I_S \cos\theta} \quad (5)$$

The coefficients $d_1 \ldots d_6$ are dependent on not only the system parameters such as line reactance (X_1 and X_2), transient emf in the quadrature axis (E'_q), quadrature axis reactance (X_q), direct axis transient reactance (X'_d) and infinite bus voltage magnitude (U_B), but also the location of the STATCOM in system. X_1 represents the equivalent reactance between the machine internal bus and the intermediate bus M, and X_2 represents the equivalent reactance between bus m and the infinite bus. The change of the direct and quadrature axis components (i_d and i_q) of armature current (I_T) are expressed as:

$$\Delta i_d = K_{DD}\Delta\delta + K_{DS}\Delta I_S \quad (6)$$

$$\Delta i_q = K_{QD}\Delta\delta + K_{QS}\Delta I_S \quad (7)$$

where:

$$K_{DD} = \frac{K_{UD}\sin\theta_o - K_{TD} U_{Mo}\cos\theta_o}{X_1 + X'_d} \quad (8)$$

$$K_{DS} = \frac{K_{US}\sin\theta_o - K_{TS} U_{Mo}\cos\theta_o}{X_1 + X'_d} \quad (9)$$

$$K_{QD} = \frac{K_{UD}\sin\theta_o + K_{TD} U_{Mo}\cos\theta_o}{X_1 + X_q} \quad (10)$$

$$K_{QS} = \frac{K_{US}\sin\theta_o + K_{TS} U_{Mo}\cos\theta_o}{X_1 + X_q} \quad (11)$$

If ω_o is the base electrical angular velocity, H is generator inertia constant, K_D is inherent damping constant, ΔP_M is change in mechanical electrical output, X is the state vector and U is the input vector, the close loop state space equation of linearized model of the system can be written as:

$$\frac{d}{dt}X = \begin{bmatrix} 0 & \omega_o & 0 \\ -\frac{K_1}{2H} & -\frac{K_D}{2H} & -\frac{K_2}{2H} \\ -K_4K_U & K_5K_W & -K_6 - K_3K_U \end{bmatrix} X + \begin{bmatrix} 0 \\ \frac{1}{2H} \\ 0 \end{bmatrix} U \quad (12)$$

where:

$$X = [\Delta\delta \quad \Delta\omega \quad \Delta I_S]^T \quad (13)$$

$$U = [\Delta P_M] \quad (14)$$

and K_1 and K_2 are the constant derived from electrical torque, K_3 and K_4 are the constant derived from STATCOM terminal voltage magnitude and K_5 and K_6 are the constant derived from STATCOM model equation:

$$K_1 = K_{ED} \quad (15)$$

$$K_2 = K_{ES} \quad (16)$$

$$K_3 = \frac{K_{STA}K_{US}}{T_{STA}} \quad (17)$$

$$K_4 = \frac{K_{STA}K_{UD}}{T_{STA}} \quad (18)$$

$$K_5 = \frac{K_{STA}}{T_{STA}} \quad (19)$$

$$K_6 = \frac{1}{T_{STA}} \quad (20)$$

The dynamic response of a linear system defined by (12) is determined by its characteristic equation given in (21).

$$\Delta(s) = s^3 + (K_6 + K_3K_U + \frac{D}{J})s^2 + \frac{1}{J}[D(K_6 + K_3K_U) + K_2K_5K_W + K_1\omega_o]s + \frac{1}{J}[\omega_o K_1(K_6 + K_3K_U) - K_2K_4K_U] \quad (21)$$

Therefore, there are three eigenvalue for the SMIB with STATCOM and proportional controller in speed and voltage loops. The transfer functions of the closed loop system from the variable states to the mechanical power are:

$$H_{DM}(s) = \frac{\Delta\delta(s)}{\Delta P_M(s)} = \frac{\omega_o}{2H}\left(\frac{s + K_6 + K_3K_U}{\Delta(s)}\right) \quad (22)$$

$$H_{SM}(s) = \frac{\Delta\omega(s)}{\Delta P_M(s)} = \frac{1}{2H}\left(\frac{s(s + K_6 + K_3K_U)}{\Delta(s)}\right) \quad (23)$$

$$H_{CM}(s) = \frac{\Delta I_S(s)}{\Delta P_M(s)} = \frac{1}{2H}\left(\frac{K_5K_W s - K_4K_U\omega_o}{\Delta(s)}\right) \quad (24)$$

III. SIMULATION RESULTS

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. 3 in the SIMULINK/MATLAB. The data of the system is given in the Table I.

TABLE I
PARAMETERS SYSTEM

transmission line	X_l=0.3, X_2=0.3
STATCOM	K_{STA}=1, T_{STA}=0.02
steady state condition	P_{Eo}=1, Q_{Eo}=0.150, U_{To}=1
generator	X_q=0.6, X_d=1.6, X'_d=0.3, J=3, D=0

The small-signal model of the system is used to study the incremental dynamics. Using root-locus technique, appropriate feedback variables that result in stable closed-loop operation of the system are selected. The closed loop poles are roots of the characteristic equation. A necessary condition for stability of the system is that all the roots in characteristic equation have a negative real part. Typical performance goals for controlled plants are given in the time domain, normally in terms of step response characteristics (rise time, overshoot, steady state tracking error, etc.). The proportional gains of the PID controllers in Fig. 3 were tuned and the effect of each of the K_W and K_U has been studied

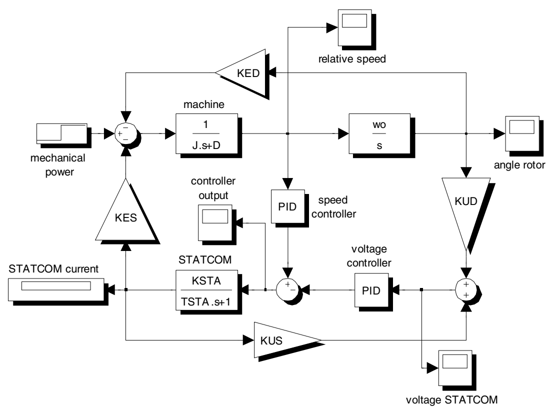


Figure 3. System model in SIMULINK/MATLA

The root-locus plot for the change of K_U in the system with proportional controller in voltage loop is shown in Fig. 4, where assumed K_W=0. The root-locus plot for the change of K_W in the system with proportional controller in speed loop is shown in Fig. 5, where assumed K_U=0. It is observed that by increasing the value of K_W the system damping improves. But the changes in K_U have no impact on system damping.

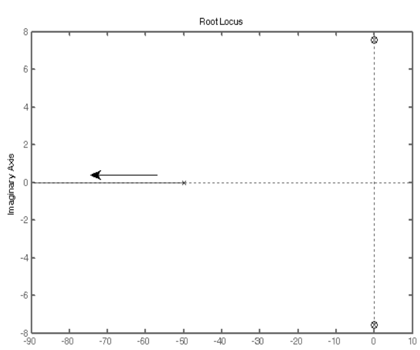


Figure 4. Locus of the roots of the change voltage controller

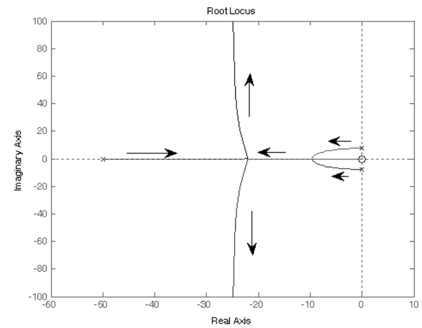


Figure 5. Locus of the roots of the change speed controller

A 10% input torque pulse is applied to simulate the disturbance. The step response with different controller gains is presented in Figs. 6 and 7, respectively. Fig. 8 show step response of load angle and relative speed for change in K_W and Fig. 9 show the stator terminal voltage in change of K_W. The uncontrolled system response is oscillatory.

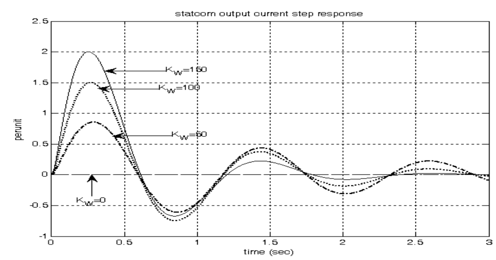


Figure 6. Step response of STATCOM output current

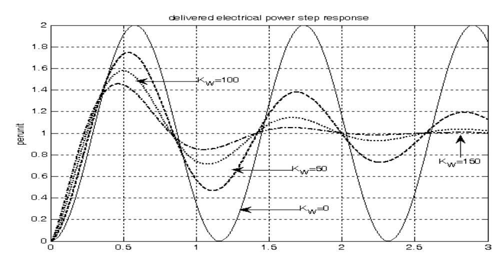


Figure 7. Step response of delivered electrical power

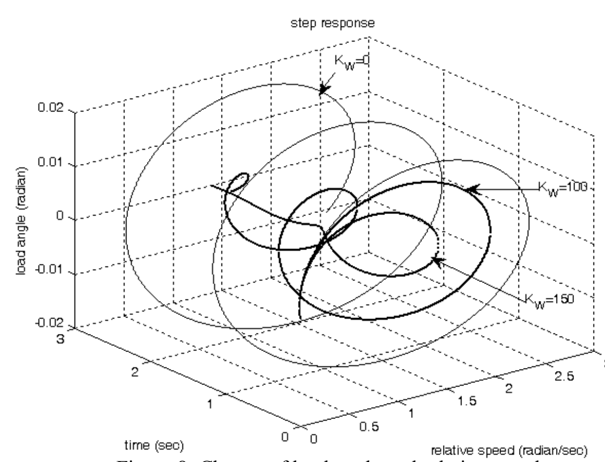


Figure 8. Change of load angle and relative speed

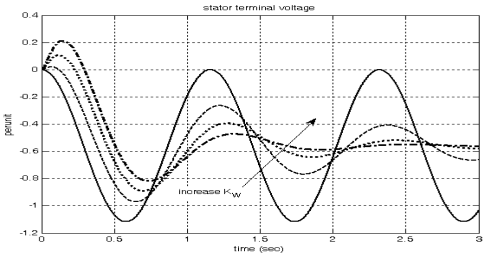


Figure 9. Step response of stator terminal voltage

The dominant eigenvalues for change in STATCOM parameters K_{STA} and T_{STA} are show in Tables II and III, respectively. Fig. 10 shows the STATCOM step response for change in reactive power with only speed controller and the dominant eigenvalues for this case are shown in Table IV.

TABLE II
EIGNEVALUE CHANGE OF K_{STA}

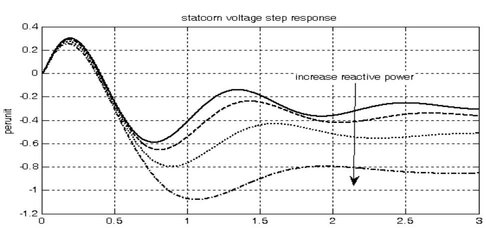
K_{STA}=0.8	K_{STA}=1	K_{STA}=1.2	K_{STA}=1.4
-48.10	-47.60	-47.08	-46.56
-0.95±j 5.44	-1.20±j5.42	-1.46±j5.39	-1.72±j5.35

TABLE III
EIGNEVALUE IN CHANGE OF T_{STA}

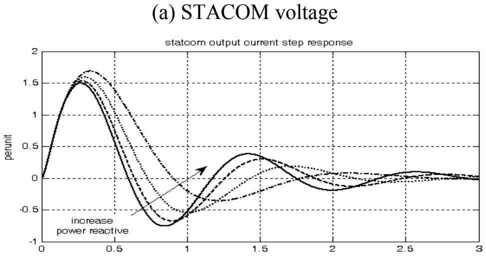
T_{STA}=0.01	T_{STA}=0.02	T_{STA}=0.03	T_{STA}=0.04
-97.63	-47.60	-30.91	-22.57
-1.18±j 5.36	-1.20±j5.42	-1.21±j5.50	-1.21±j5.57

TABLE IV
EIGNEVALUE IN CHANGE OF REACTIVE POWER WITH ACTIVE POWER CONSTANT

Q_{Eo}=0	Q_{Eo}=0.15	Q_{Eo}=0.35	Q_{Eo}=0.55
-47.62	-47.36	-46.96	-46.50
-1.19±j 5.46	-1.32±j5.08	-1.52±j5.08	-1.75±j3.56



(a) STACOM voltage



(b) STACOM current

Figure 10. STATCOM step response for change in reactive power

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. From the results, we see that the controller in the voltage loop does not contribute to system damping but its presence is found to be necessary for the voltage regulation.

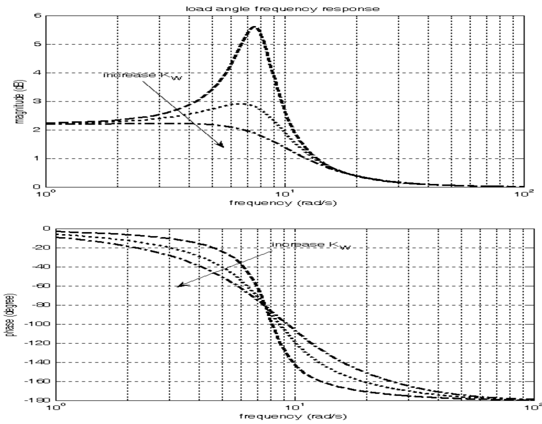


Figure 11. Comparison of the load angle frequency response characteristics for change in K_W

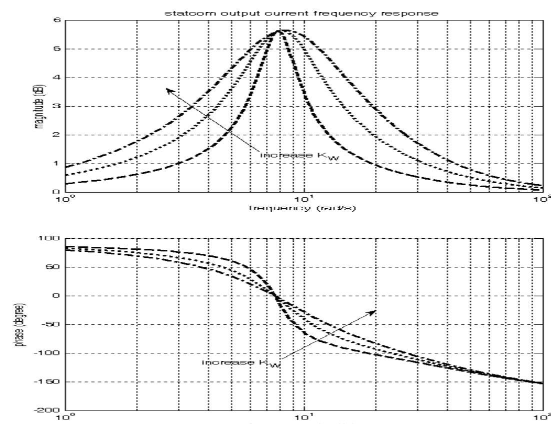


Figure 12. Comparison of the STATCOM output current frequency response characteristics for change in K_W

IV. 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 damping controller is also designed for the STATCOM using root locus methods. Simulations are performed on a single area system for reference change and load change.

REFERENCES

[1] M.H.Haque, "Stability improvement by FACTS devices: A comparision between STATCOM and SSSC", IEEE/PES, 2005.

[2] M.M.Farsangi, Y.H.Song, K.Y.Lee, "Choice of FACTS devices control inputs for damping interarea oscillations", IEEE Trans. On Pow. Sys., Vol.19, No.2, pp.1135-1143, May 2004.

[3] L.Saribulut, M.Tumay, Đ.Eker, "Performance analysis of fuzzy logic based unified power flow controller",PWASET, Vol.35, pp.321-326, November 2008.

[4] P.B.Sankar, C.S.Babu, “Transient stability enhancement of power system using STATCOM”, Inter. Jour. of Elec. and Pow. Engi., No.2, Vol.4, pp.271-276, 2008.
[5] G.Shahgholian, S.Eshtehardiha, H.Mahdavinasab, M.R.Yousefi, “A novel approach in automatic control based on the genetic algorithm in STATCOM for improvement power system transient stability”, IEEE/ICIS, pp.14-19, 2008.
[6] K.Vijayakumar, R.P.Kumudinidevi, “A hybrid genetic algorithm for optimal power flow incorporating FACTS devices”, Asia. Jour. Of Scie. Rese., No.4, pp.403-411, 2008.
[7] L.Wang, Z.Y.Tsai, “Stabilization of generator oscillations using PID STATCON damping controllers and PID power system stabilizers”, IEEE/PESW, Vol.1, No.31, pp.616-621, Jan./Feb. 1999.
[8]] Y.YU, H.Yimgoduo, “STATCOM modeling and analysis in damping power system oscillations”, IEEE/IECE, Vol.2, pp.756-762, July 2001.
[9] J.Park, G.Jang, K.M. Son, “Modeling and control of VSI type FACTS controllers for power system dynamic stability using the current injection method”, Inter. Jour. of Con., Aut., and Sys., Vol. 6, No.4, pp.495-505, August 2008.