Improvement of Dynamic Behavior and System Stability by Using STATCOM

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***Abstract*- Static synchronous compensator (STATCOM) controls are known to enhance damping of a power system. This paper investigates the effect of the STATCOM on small signal power system stability in a single-machine infinite-system (SMIB). Non-linear and linear models of a single machine have been derived. The STATCOM is modeled as the voltage source converter behind a step down transformer by a first order differential equation. 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.**

I. INTRODUCTION

FACTS controllers have the flexibility of controlling both real and reactive power, which in addition can be used for various applications to enhance power system performance. The major contributions of the FACTS devices analysis have been addressing the following basic issues: system dynamic and transient stability, increasing power transmission capacity, damping power oscillations, maintaining network voltage [1, 2].

The shunt FACTS devices play an important role in controlling of generating and absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. A static synchronous compensator (STATCOM) is one of the shunt FACTS devices that can play a significant role in reactive power compensation [3, 4].

Many papers have been published on modeling, operation and control fundamentals of the FACTS devices [5-6]. In [7] to reduce overall financial losses in the network due to voltage sags for three most widely used FACTS based devices are optimally placed using a genetic algorithm. A feedback control strategy based on the detailed small-signal model for balancing individual dc capacitor voltages in a three-phase cascade multilevel inverter-based static synchronous compensator is presented in [8]. A multivariable design of STATCOM ac and dc voltage PI control was presented in [9], but the structural complexity of the presented multivariable PI controllers with different channels reduces their applicability. A robust control for a SMIB with a STATCOM in [10] is designed using the recently developed nonlinear H_∞ theory. The effects of STATCOM using eigenvalues analysis on power systems small signal stability presented in [11], which the simulation of system dynamic behavior is mainly done in the following two cases: classical model and classical flux-decay model equipped with automatic voltage regulator (AVR). In [12] the proposed STATCOM stability models are justified based on the basic operational characteristics for both phase and PWM control strategies, hence could not be applied to system under the impact of large disturbance that have voltage and current with high harmonic content. In [13], the STATCOM-based controllers' parameters are optimized over a wide range of operating conditions and system parameter uncertainties in order to enhancing dynamic stability, which it is tested through eigenvalue analysis and time domain simulation.

A power system is composed of many dynamic devices connected buses and loads. Power system controllers are often used to enhance the small signal stability performance of power systems during severe or stressed operating conditions. Small signal stability is best analyzed by linearizing the system differential equations about equilibrium operating point.

Damping the oscillations is not only important in increasing the transmission capability but also for stabilization of power system conditions after critical faults. A STATCOM control has been found to enhance the damping of the power system. This paper consists of five parts. The first part, the operation and application of STATCOM is reviewed. In the second part presented the modeling of power system under study. In the third part a model of the system which is suitable for dynamic stability analysis systems is developed, the last part to prove the effectiveness of the proposed technique, various simulation results using Matlab Simulink are shown under both change of parameters and deferent conditions of load.

II. STATIC SYNCHRONOUS COMPENSATOR

STATCOM is a shunt connected solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. The simplified diagram and equivalent model of the STATCOM connected to the power system are shown in Figure 1, which the STATCOM is modeled as a voltage source converter behind a step down transformer with a leakage reactance X_S.

The STATCOM is a shunt compensation component which injects leading or lagging current into the ac system. It is

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originally designed for voltage maintenance in power systems by reactive power shunt compensation.

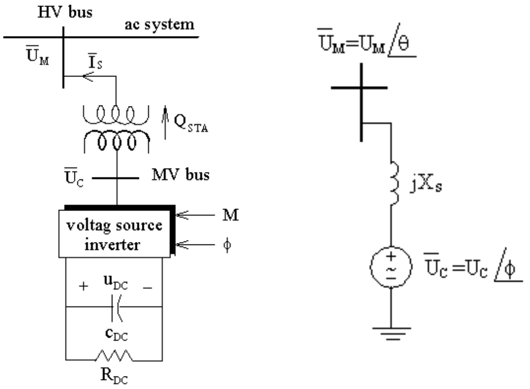


Fig. 1. STATCOM connected to the power system and equivalent model

The voltage source inverter generates a controllable ac voltage U_C given by [14]:

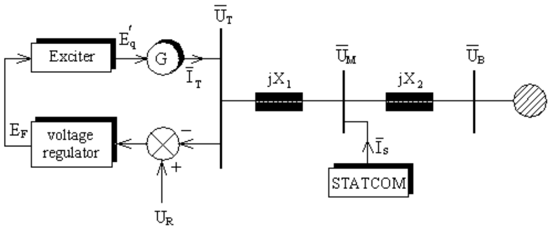
$$\overline{U}_C = M\,U_{DC}\,\angle\Phi \tag{1}$$

where U_{DC} is the dc voltage, Φ is the phase defined by PWM, and M is proportion with the modulation ratio (m), defined by the PWM, and the ratio between the ac and dc voltage (k), depending on the inverter structure. The magnitude and the phase of U_C can be controlled through m and Φ respectively. The most common methods used for controlling the ac voltage generated by the inverter are: dc variable voltage with a full wave inverter and constant dc voltage with a pulse-width modulated inverter. The DC voltage across the DC capacitor of the STATCOM is controlled to be constant for normal operation of the PWM inverter. The output of reactive current strongly depends on the thyristor firing angle that is given by the phase shift between the STATCOM-voltage U_C and the bus voltage U_M. Control of the susceptance presented to power system is possible by variation of the magnitude of U_C with respect to bus voltage U_M. Ideally the inverter output voltage is phase with the voltage at the common connection point. The capacitor is used to maintain a constant dc voltage in order to allow the operation of the voltage-source converter, which is charged with power taken from the network. In ideal steady state analysis, the active power exchange between ac system and the STATCOM can be neglected and only reactive power can be exchanged between them.

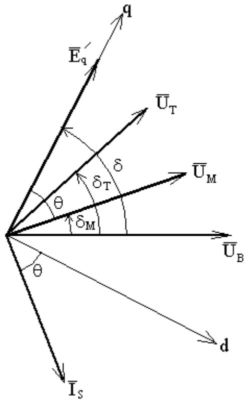
III. MATHEMATICL MODELING

The single line diagram of the single machine infinite bus (SMIB) power system under investigation in this paper is shown in Figure 2. A STATCOM is connected to the bus M between the generator terminal (bus T) and the infinite bus (bus B). The reactance of the line from the bus T to the bus M is X_1 and the reactance of the line from the bus M to the bus B is X_2. The resistance of the line is neglected. The magnitude of the machine internal voltage, terminal voltage and infinite bus voltage is represented by E'_q, U_T and U_B, respectively. The excitation voltage E_F is supplied the exciter and is controlled by the AVR. The torque angle δ is defined as the angle between the infinite bus voltage and the internal voltage of quadrature axis. The relationships shown in Figure 2 are used to transform variables from one reference frame to the other. The system has a STATCOM installed in the transmission line. The synchronous generator connected an infinite bus is a multivariable nonlinear dynamic system, described by a well known set of equations.

A typical variation of reactive power supplied by the STATCOM (when it operates at full inductive and capacitive ratings) is shown in Figure 3. In practice, the STATCOM can operate anywhere in between the two curves. When a shunt FACTS devices is connected to a long line to increase the power transfer capability.



(a) Power system configuration



(b) Phasor diagram

Fig. 2. Power system with a STATCOM

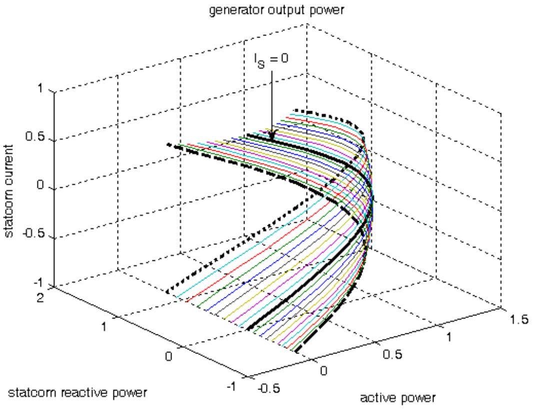


Fig. 3. Effect of STATCOM current on output power of the machine

In the detailed model of the power system with STACOM, in addition to the swing equation of the generator, the field and excitation system dynamics are considered. The STATCOM is represented by a first order differential equation relating the STATCOM dc capacitor voltage and current. The non linear model of the SMIB system is given as [15, 16]:

$$\frac{d}{dt}\delta = 2\pi f_o \omega \tag{2}$$

$$\frac{d}{dt}\omega = \frac{1}{2H}(P_M - P_E - K_D \omega) \tag{3}$$

$$\frac{d}{dt}E_q' = \frac{1}{T_{do}'}[E_F - E_q' + (X_d' - X_d)i_d] \tag{4}$$

$$\frac{d}{dt}E_F = \frac{1}{T_E}[-E_F + K_E(U_R - U_T)] \tag{5}$$

$$\frac{d}{dt}U_{DC} = \frac{1}{C_{DC}}i_{DC} - \frac{1}{R_{DC}C_{DC}}U_{DC} \tag{6}$$

Here δ is the rotor angle, ω is rotor speed, , E_F is internal voltage, P_E is generator output power, P_M is input mechanical power, U_R is reference voltage, T'_{do} is d-axis open circuit transient time constant, X'_d and X_q are the direct and quadrature reactance of the generator.

Therefore model for SMIB system with STATCOM is given with five state variables and two inputs:

$$X = [\delta \quad \omega \quad E_q' \quad E_F \quad U_{DC}]^T \tag{7}$$

$$U = [P_M \quad U_R]^T \tag{8}$$

IV. LINEAR DYNAMIC MODEL

Power system is a typical dynamic system. In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed. In this section a linearized incremental model including the voltage regulator and exciter of SMIB is obtained. The d and q components of terminal current can be written as:

$$\Delta i_d = m_d\, \Delta E_q' + n_d \Delta\phi + q_d \Delta U_{DC} + p_d \Delta\delta + k_d \Delta M \tag{9}$$

$$\Delta i_q = n_q \Delta\phi + q_q \Delta U_{DC} + p_q \Delta\delta + k_q \Delta M \tag{10}$$

The sensitivity constants are functions of the system parameters and the initial operating condition. With due attention to the equation linearizing, the sensitivity constants are given by:

$$p_q = \frac{U_{Bo} \cos\delta_o}{Y_Q} \tag{11}$$

$$n_q = \frac{-X_2}{Y_Q X_S} M_o \sin\phi_o U_{DCo} \tag{12}$$

$$k_q = \frac{X_2}{Y_Q X_S} U_{DCo} \cos\phi_o \tag{13}$$

$$q_q = \frac{X_2}{Y_Q X_S} M_o \cos\phi_o \tag{14}$$

$$p_d = \frac{U_{Bo} \sin\delta_o}{Y_D} \tag{15}$$

$$n_d = \frac{-X_2}{Y_D X_S} M_o \cos\phi_o U_{DCo} \tag{16}$$

$$k_d = \frac{-X_2}{Y_D X_S} U_{DCo} \sin\phi_o \tag{17}$$

$$q_d = \frac{-X_2}{Y_D X_S} M_o \sin\phi_o \tag{18}$$

$$m_d = \frac{1}{Y_D}(1 + \frac{X_2}{X_S}) \tag{19}$$

where:

$$Y_D = X_1 + X_2 + \frac{X_1 X_2}{X_S} + (1 + \frac{X_2}{X_S}) X_d' \tag{20}$$

$$Y_Q = X_1 + X_2 + \frac{X_1 X_2}{X_S} + (1 + \frac{X_2}{X_S}) X_q \tag{21}$$

The real power output of the generator is describes as:

$$\Delta P_E = K_1 \Delta\delta + K_2 \Delta E_q' + K_{EC} \Delta U_{DC} + K_{EM} \Delta M + K_{EF} \Delta\phi \tag{22}$$

where:

$$K_1 = p_q K_{Eq} + p_d K_{Ed} \tag{23}$$

$$K_2 = I_{qo}[1 + (X_q - X_d') m_d] \tag{24}$$

$$K_{EC} = q_q K_{Eq} + q_d K_{Ed} \tag{25}$$

$$K_{EM} = k_q K_{Eq} + k_d K_{Ed} \tag{26}$$

$$K_{EF} = n_q K_{Eq} + n_d K_{Ed} \tag{27}$$

The terminal voltage is given by:

$$\Delta U_T = K_5 \Delta\delta + K_6\, \Delta E_q' + K_{TC} \Delta U_{DC} + K_{TM}\, \Delta M + K_{TF} \Delta\phi \tag{28}$$

where:

$$K_5 = \frac{1}{U_{To}}(-X_d' U_{qo} p_d + X_q U_{do} p_q) \tag{29}$$

$$K_6 = \frac{U_{qo}}{U_{To}}(1 - X_d' m_d) \tag{30}$$

$$K_{TF} = \frac{1}{U_{To}}(-X_d' U_{qo} n_d + X_q U_{do} n_q) \tag{31}$$

$$K_{TC} = \frac{1}{U_{To}}(-X_d' U_{qo} q_d + X_q U_{do} q_q) \tag{32}$$

$$K_{TM} = \frac{1}{U_{To}}(-X_d' U_{qo} k_d + X_q U_{do} k_q \tag{33}$$

The components of STATCOM current can be expressed as follows:

$$\Delta I_{sd} = m_{sd}\Delta E_q' + n_{sd}\Delta\phi + q_{sd}\Delta U_{DC} + p_{sd}\Delta\delta + k_{sd}\Delta M \tag{34}$$

$$\Delta I_{sq} = n_{sq}\Delta\phi + q_{sq}\Delta U_{DC} + p_{sq}\Delta\delta + k_{sq}\Delta M \tag{35}$$

By linearizing about an output point, the total linearized system model including SMIB and shunt FACTS can be represent by the following equation:

$$\frac{d}{dt}\Delta X = A\,\Delta X + B\,\Delta U \tag{36}$$

$$\Delta Y = C\,\Delta X + D\,\Delta U \tag{37}$$

where ΔX is the state vector, ΔY is the output vector, ΔU is the input vector, A is the state matrix, B is the control or input matrix, C is the output matrix and D is the feed forward matrix.

The following is a summary of the linearizing the equation of the system with respect to an equilibrium point as a set of first order differential equations, with time t in seconds, rotor angle δ in electrical radians, and all other quantities in per unit.

$$\frac{d}{dt}\Delta X = \begin{bmatrix} 0 & \omega_o & 0 & 0 & 0 \\ \frac{-K_1}{2H} & \frac{-K_D}{2H} & \frac{-K_2}{2H} & 0 & \frac{-K_{EC}}{2H} \\ \frac{-K_4}{T_{do}'} & 0 & \frac{-K_3}{T_{do}'} & \frac{1}{T_{do}'} & \frac{-K_{DC}}{T_{do}'} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{-1}{T_A} & \frac{-K_A K_{TC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix} \Delta X + \begin{bmatrix} 0 & 0 \\ \frac{-K_{EM}}{2H} & \frac{-K_{EF}}{2H} \\ \frac{-K_{DM}}{T_{do}'} & \frac{-K_{DF}}{T_{do}'} \\ \frac{-K_A K_{TM}}{T_A} & \frac{-K_A K_{TF}}{T_A} \\ K_{CM} & K_{CF} \end{bmatrix} \begin{bmatrix} \Delta M \\ \Delta\phi \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{2H} & 0 \\ 0 & 0 \\ 0 & \frac{K_A}{T_A} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P_M \\ \Delta U_R \end{bmatrix} \tag{38}$$

The deviations of state variables and the control vector are:

$$\Delta X = [\Delta\delta \quad \Delta\omega \quad \Delta E_q' \quad \Delta E_F \quad \Delta U_{DC}]^T \tag{39}$$

$$\Delta X = [\Delta M \quad \Delta\phi]^T \tag{40}$$

A STATCOM is a multiple input multiple output variables. Figure 4 shows the block diagram representation of the small signal performance of the SMIB installed with a STATCOM, where $G_M(s)$, $G_A(s)$, $G_F(s)$ and $G_D(s)$ are the transfer functions of machine, AVR, exciter and compensator, respectively, and:

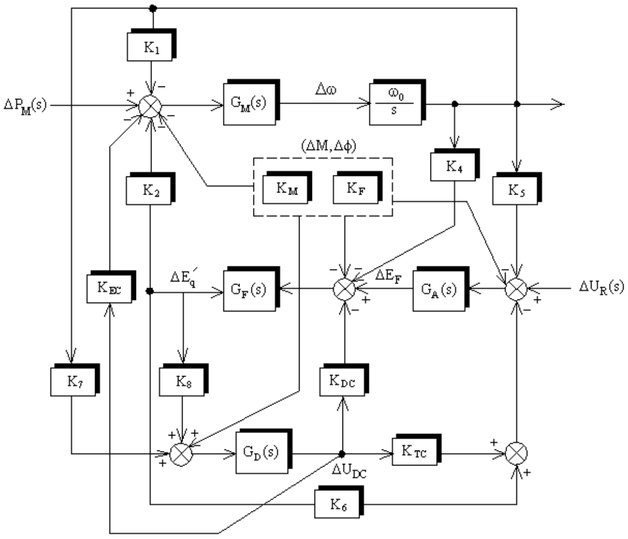


Fig. 4. Linearised model of a SMIB installed with STATCOM

$$K_M = \left[-\frac{K_{EM}}{2H} \quad -\frac{K_{DM}}{T_{do}'} \quad -\frac{K_A K_{TM}}{T_A} \quad K_{CM} \right]^T \tag{41}$$

$$K_F = \left[-\frac{K_{EF}}{2H} \quad -\frac{K_{DF}}{T_{do}'} \quad -\frac{K_A K_{TF}}{T_A} \quad K_{CF} \right]^T \tag{42}$$

The block diagram of Figure 5 can be used in small signal stability investigations of the power system. Let a two-input and two-output process be represented by the block diagram shown in Figure 5 for which the transfer function is:

$$\begin{bmatrix} \Delta U_T \\ \Delta U_{DC} \end{bmatrix} = \underbrace{\begin{bmatrix} H_{TM}(s) & H_{FF}(s) \\ H_{DM}(s) & H_{DF}(s) \end{bmatrix}}_{H(s)} \begin{bmatrix} \Delta M \\ \Delta\phi \end{bmatrix} \tag{43}$$

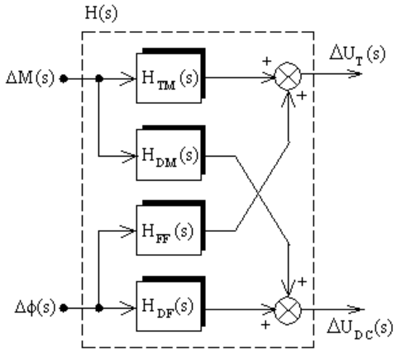


Fig. 5. Two-input and two-output of the system

V. DESIGN CONTROLLER

There are three basic controllers implemented in a STATCOM, the ac voltage regulation of the power system, the dc voltage regulation across the capacitor and power oscillation damping. The ac voltage controller regulates the reactive power exchange while the dc controller regulates the active power exchange with the power system. Figure 6 show the ac and dc voltage control using PI controller.

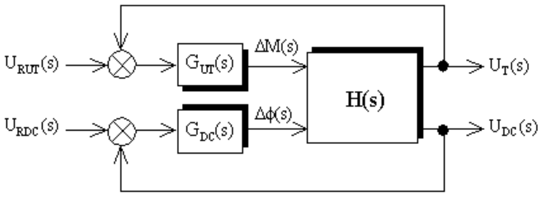


Figure 6. Voltage control using PI controller

Two control signals can be applied to the STATCOM, magnitude control (ΔM) and phase angle control (ΔΦ). The block diagram of the ac voltage regulator and the dc voltage regulator with a lead-lag damping stabilizer are shown in Figure 7 and Figure 8, respectively. The proportional and integral gains are K_{PDC}, K_{IDC} and K_{PAC}, K_{IAC} for dc and ac voltages respectively.

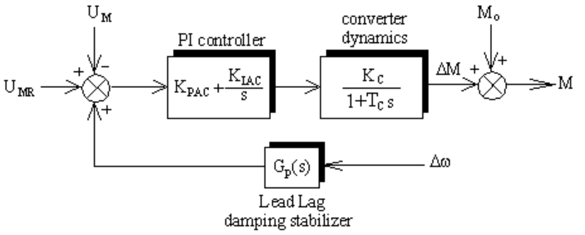


Figure 7. The magnitude control circuit block diagram

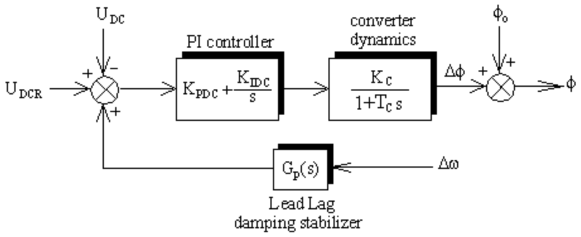


Figure 8. The phase control block diagram

VI. SIMULATION RESULTS

The state equation and transfer function developed to describe a plant may change due to change of load. Thus plant parameter variations often occur in practice.

Digital simulation is carried out by the MATLAB software. For the simulation, different loading conditions with change of parameters in the SMIB system are considered.

The data used in this study are given in the Table I. The value of the sensitivity constant of model power system for normal operating conditions with STATCOM is show in Table II. The undamped natural mechanical mode frequency (ω_n) and damping ratio (η) for normal loading in open loop system is shown in Tables III.

The desired eigenvalues are depends on the performance criteria, such as settling time, rise time and overshoot, used in the design.

TABLE I
DATA OF THE SMIB POWER SYSTEM

Components	Item	Value
Generator	X_q	0.6
	X_d	1
	X'_d	0.3
	J	6
	K_D	4
	T'_{do}	6.3
	f	50
Transmission line	X_1	0.3
	X_2	0.3
Loading normal	U_{To}	1
	P_{Eo}	0.9
	Q_{Eo}	0
STATCOM	C_{DC}	1
	U_{DCO}	1
	X_S	0.15
	M_o	0.25
	Φ_o	45.52°
AVR	K_A	10
	T_A	0.01

TABLE II
SENSITIVITY CONSTANT OF MODEL POWER SYSTEM FOR NORMAL LOADING

Constant	Value	Constant	Value
K_1	0.8996	K_{EF}	-0.1748
K_2	1.1313	K_{DF}	-0.1168
K_3	2	K_{TF}	0.0101
K_4	0.6751	K_{CF}	-3.8658
K_5	-0.0864	K_{EM}	0.3694
K_6	0.5028	K_{DM}	-0.4757
K_7	-1.2958	K_{TM}	0.3125
K_8	0.2501	K_{CM}	0.0843
K_9	-0.0075		

TABLE II
EIGENVALUES OF OPEN LOOP SYSTEM

Loading condition	Eigenvalues	ω_n	η
Normal	-0.0607 -0.9766 -99.1923 -0.3810±j6.8423	6.8529	0.0556

In this section, a Simulink model of the control scheme as shown in Figure 9 are developed to study the performance and dynamic system simulation with a number of disturbances. The power system dynamic performances due to a step change in the M (-) and Φ (…) in the system without controller are show in Figures 10 and 11.

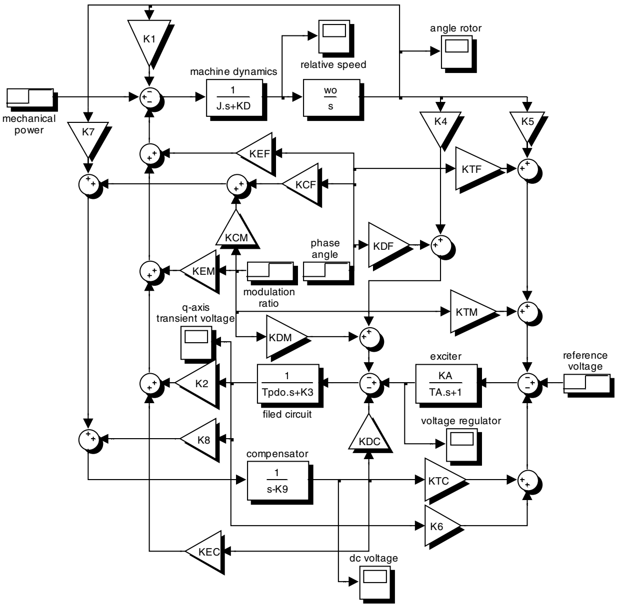


Fig. 9. System model in Matlab/Simulink

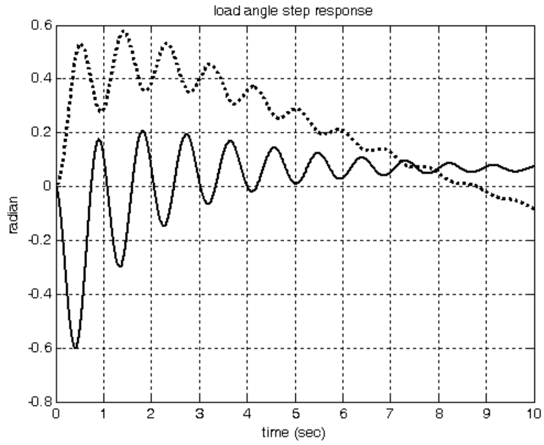


Fig. 10. Load angle deviation during a step change in the input

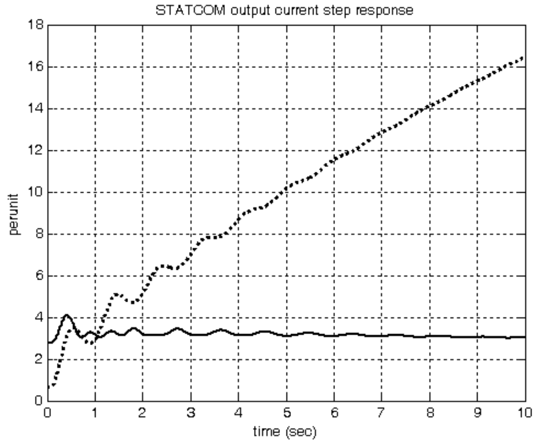


Fig. 11. STATCOM output current deviation during a step change in the input

VII. CONCLUSION

The problem of small signal stability is usually one of insufficient damping of system oscillations. The LFO of a large electric power system are due to the mechanical mode oscillations of the machines in the system. This paper presented studies on the performance of the STATCOM controllers for the damping of LFO in a SMIB. Simulation studies on a simple power system indicate that the designed controller provides very good damping properties.

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