State Space Analysis of Power System Stability Enhancement with Used the STATCOM

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Abstract- **FACTS devices can regulate the active and reactive power as well as voltage-magnitude. Static synchronous compensator (STATCOM) is taking place as of the new generation FACTS devices. The effects of STATCOM using eigenvalues analysis on power systems small signal stability presented in this paper. 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).**

I. INTRODUCTION

With the increasing electric power demand, power systems can reach stressed conditions, resulting in undesirable voltage and frequency conditions. Power system is a non-linear object and its stability depends on the type, location and duration of a disturbance. Shunts FACTS devices such as SVC and STATCOM are used for controlling transmission voltage, power flow, reducing reactive loss, and damping of power system oscillations for high power transfer levels. The STATCOM can offer a number of performance advantages for reactive power control applications over the conventional SVC because of its greater reactive current output at depressed voltage, faster response, better control stability, lower harmonics and smaller size [1].

Power systems are experiencing low frequency oscillation (LFO) due to disturbances. Main causes of LFO are: (i) A long distance from load center of power generator, (ii) Lack of transmission lines compared to load growth, (iii) Use of high reactance electric equipment, (iv) Use of a high gain exciter to compensate synchronous stability reduction, and (v) 0.1-2.0 Hz low frequency oscillation due to lack of brake torque. Application of STATCOM and several control strategies for stability improvement has been discussed in the literature [2-3]. An adaptive fuzzy controller is incorporated into the supplementary control of a STATCOM to enhance the damping of an inter-area oscillation exhibited by a two-area four-machine interconnected power system presented in [4]. A current injection model of FACTS controllers is adopted for studying dynamic stability of power system which can be easily applied to the linear and the nonlinear analysis, and adopt any kind of VSI type FACTS controllers regardless of model types, proposed in [5].

This paper presents a study of the effect of a STATCOM on power system low frequency oscillations damping. The simulation of system dynamic behavior is mainly done in the following two cases: classical model [model (0,0)] and third-order model [model (1,0)] equipped with AVR. Moreover, the effect of the system loading on system damping is also explored.

II. MATHEMATICAL MODEL OF THE STUDY SYSTEM

The power system modeling plays an important role in the small signal stability problem of power systems. In this study, a single machine infinite bus (SMIB) power system as shown in Figure 1 is considered. The generator is equipped with an excitation system and the system has a STATCOM installed. The transmission line has parameters of $A_{L1}B_{L1}C_{L1}D_{L1}$ and $A_{L2}B_{L2}C_{L2}D_{L2}$ for the first and the second sections respectively. In principle, a STATCOM is a shunt-connected device which injects reactive current into the AC system. The STATCOM has only two possible steady-state operating modes: lagging (inductive) and leading (capacitive), therefore it is not possible to significantly impact both active and reactive power simultaneously. The STATCOM here is modeled as a first-order shunt controllable reactive current source with time delay (T_{STA}). The approximate model of the STATCOM is show in Figure 2. In the voltage phasor diagram shown in Figure 3, the rotor angle δ is the angle by which the q-axis leads the infinite bus the voltage [6].

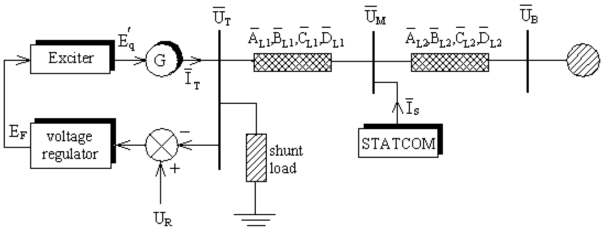


Figure 1. STACOM installed in SMIB power system

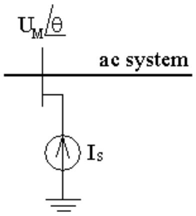


Figure 2. Mathematical model of STATCOM

When the STACOM operates in capacitive mode, the injected current can be expressed as:

$$\bar{I}_S = I_S\, e^{j(\theta - \frac{\pi}{2})} \tag{1}$$

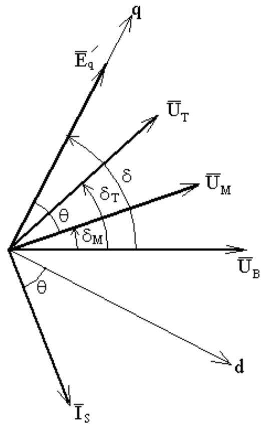


Figure 3. Voltage phasor diagram

The angles between the infinite bus voltage with the terminal voltage and STATCOM voltage are δ_T and δ_M, respectively:

$$\mathrm{tg}\delta_M = \mathrm{tg}(\delta-\theta) = \frac{X_2 U_T \sin\delta_T}{X_2 U_T \cos\delta_T + X_1 U_B} \tag{2}$$

where the magnitude of the generator terminal voltage and the infinite bus voltage is represented by U_T and U_B, respectively. X_1 and X_2 represents the equivalent reactance of the line for two sections. That is the STATCOM current does not change the angle of the voltage at bus M. The voltage magnitude at bus M can be expressed as:

$$U_M = \frac{X_1X_2I_S + X_2U_T\cos(\delta_T-\delta_M) + X_1U_B\cos\delta_M}{X_1+X_2} \tag{3}$$

$$U_M = \frac{X_1X_2}{X_1+X_2}I_S + \frac{1}{X_1+X_2}\sqrt{(X_1U_B)^2+(X_2U_T)^2+2X_1X_2U_TU_B\cos\delta_T} \tag{4}$$

Here the angle of voltage at bus M is defined as the angle between the STATCOM bus voltage and the internal voltage and is given by:

$$\mathrm{tg}\theta = \frac{X_1+X_2+X'_d}{X_1+X_2+X_q}\,\frac{(X_1+X_q)(U_B\sin\delta + X_2\sin\theta)}{X_2E'_q + (X_1+X'_d)(U_B\cos\delta + X_2\cos\theta)} \tag{5}$$

where E'_q is the voltage proportional to the d-axis flux linkages, X_d is the direct axis reactance, X'_d is the direct axis transient reactance and X_q is the quadrature reactance. That is the voltage magnitude of bus M depends on the STATCOM current, but the angle voltage at bus M is independent of STATCOM current. STATCOM can control the terminal voltage without influence of the voltage at the installation bus. A lossless STATCOM does not supply or absorb any active power. The reactive power supplied by the STATCOM is given by:

$$Q_{STA} = U_M I_S \tag{6}$$

Figures 4 and 5 shows the variation of reactive power supplied by the STATCOM and the voltage magnitude at bus M when it operates at full capacitive rating ($I_S=I_{Smax}$) and at full inductive rating ($I_S=-I_{Smin}$).

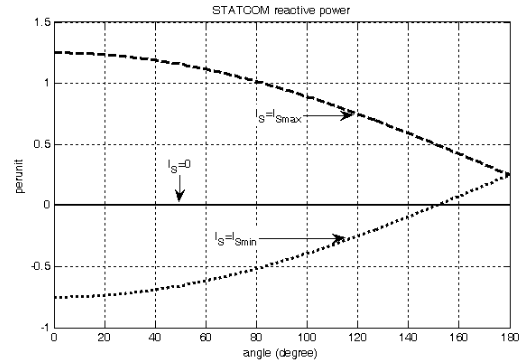


Figure 4. Reactive power supplied by the STATCOM

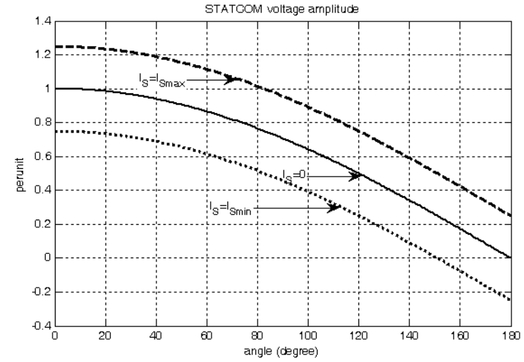


Figure 5. Amplitude of STATCOM bus voltage

Basic linear differential equations describing dynamics of the single machine infinite bus power system with installed STATCOM are:

$$\frac{d}{dt}\Delta\delta = \omega_0\,\Delta\omega \tag{7}$$

$$\frac{d}{dt}\Delta\omega = -\frac{K_D}{J}\Delta\omega - \frac{K_1}{J}\Delta\delta - \frac{K_2}{J}\Delta E'_q - \frac{K_{ES}}{J}\Delta I_S + \frac{1}{J}\Delta P_M \tag{8}$$

$$\frac{d}{dt}\Delta E'_q = \frac{1}{T'_{do}}[\Delta E_F - \Delta E'_q + (X'_d - X_d)\Delta i_d] \tag{9}$$

$$\frac{d}{dt}\Delta E_F = -\frac{1}{T_A}\Delta E_F + \frac{K_A}{T_A}(\Delta U_R - \Delta U_T) \tag{10}$$

$$\frac{d}{dt}\Delta I_S = \frac{1}{T_{STA}}(-\Delta I_S + K_{STA}\,\Delta U_S) \tag{11}$$

where J and K_D are respectively the inertia coefficient and damping coefficient, P_M denotes the mechanical input power, P_E the electrical output, E_F the stator voltage which corresponds to the generator field voltage and T'_{do} the field open circuit time constant, U_R the reference voltage, T_A the transient time constant for AVR, K_A the transient gain for AVR.

III. DYNAMIC PERFORMANCE ANALYSIS

Dynamic control of generator output power is the key point in improving damping of a power system. Performances of dynamical systems are usually defined with their transient responses. With the help of a FACTS device, the output electrical power of the machine can dynamically be controlled to improve the dynamic performance of the system. The approximate continuous time model typically employed for dynamic analysis is summarized in this section. The dynamic response of a linear system is governed by the magnitude and location of its eigenvalues, or poles. For oscillation damping, the controller should be located to efficiently bring the critical eigenvalues into the open left half plane.

The dynamic analysis is verified by transfer function simulation using Matlab and time domain simulation of the power supply system. The dynamic characteristics of the system for low frequency oscillation studies are expressed by the block diagram shown in Figure 6 with the sensitivity constants. The resulting linear model is expressed in terms of the sensitivity parameters which are dependent upon the operating point considered.

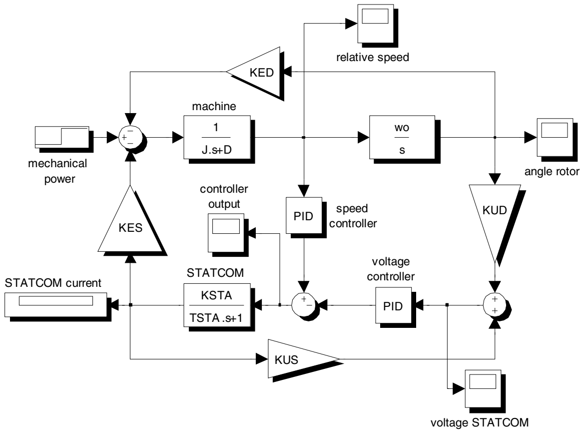
Constant K_1, K_2 and K_{ES} are derived from the electric torque expression, K_3, K_4 and K_{EI} from the field winding circuit equation, K_5, K_6 and K_{VS} from the generator terminal voltage magnitude, K_{UD}, K_{US} and K_{UE} from the STATCOM bus voltage magnitude, K_{TD}, K_{TS} and K_{TE} from the STATCOM bus voltage angle, K_{ID}, K_{IS} and K_{IE}, K_{DD}, K_{DS} and K_{DE}, K_{QD}, K_{QS} and K_{QQ} from the generator terminal current and dq components. K_U and K_W are proportional coefficient of PID controller in the voltage and speed loops respectively.

IV. SIMULATION RESULTS

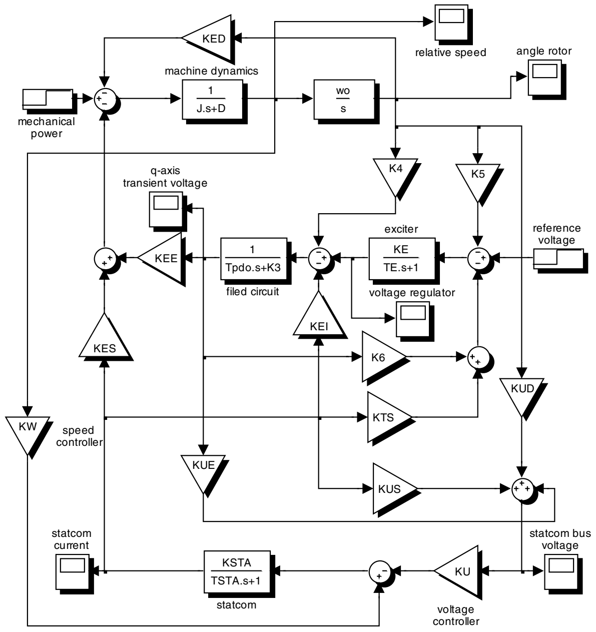
Simulation studies for the evaluation of damping effects by the STATCOM and the proposed control schemes have been performed on a SMIB system. The data used in this study are given in Table I. The loading in a power system is never constant. The four cases (listed in Table II) were simulated. Nominal parameters of the system for the initial dq current and voltage components and torque angle for loading different condition are shown in Table III.

By varying the operating point, the sensitivity parameter values also vary. Tables IV and V summarize the value of the sensitivity constant of model power system for different load conditions for without and with STATCOM, respectively.

The system modes for different loading condition are shown in Tables VI and VII. This confirms the well-known facts that STATCOM have little effect on electromechanical oscillations at light load and leading power factor. The damping ratio, corresponding to the electromechanical mode of oscillations, increased from 0.0141 (without STATCOM) to 0.2421 (with STATCOM) for the system with normal load, and increased from 0.0531 (without STATCOM) to 0.4613 (with STATCOM) for the system with light load.



(a) Classical model for synchronous machine



(b) Classical flux-decay model for synchronous machine
Figure 6. Mathematical model of SMIB system with STACOM in Simulink/Matlab

TABLE I
DATA OF THE SMIB SYSTEM

Components	Item	Value
Generator	X_q	1.66
	X_d	1.68
	X'_d	0.32
	J	4.62
	K_D	4
	T'_{do}	4
	f	60
Transmission line	X_1	0.3
	X_2	0.3
Loading normal	U_{To}	1
	P_{Eo}	0.8
	Q_{Eo}	0.6
STATCOM	K_{STA}	1
	T_{STA}	0.02
	I_{So}	2
Controller	K_W	100
	K_U	0
AVR	K_E	30
	T_E	0.05

TABLE II
SIMULATION CASES

Case	Load condition	P_{Eo}	Q_{Eo}	U_{To}
A	Normal	0.8	0.6	1
B	Heavy	1	0.2	1
C	Light	0.6	-0.3	1

TABLE III
STEADY STATE OPERATING POINT OF MODEL POWER SYSTEM

Parameter	A	B	C
U_{do}	0.5539	0.7800	0.8930
U_{qo}	0.8326	0.6258	0.4501
U_{Bo}	0.8000	1.0651	1.2337
I_{do}	0.9427	0.9051	0.4008
I_{qo}	0.3337	0.4699	0.5379
θ_o	50.44	67.32	72.83
δ_o	70.51	85.54	80.22

TABLE IV
SENSITIVITY CONSTANT OF MODEL POWER SYSTEM WITHOUT STATCOM

Constant	A	B	C
K_1	0.6497	0.8046	1.0560
K_2	0.8197	1.1542	1.3215
K_3	2.4783	2.4783	2.4783
K_4	1.1148	1.5697	1.7972
K_5	-0.1098	-0.1837	-0.0528
K_6	0.5430	0.4082	0.2935

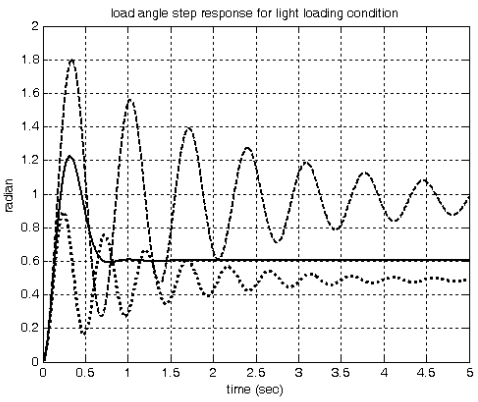
TABLE V
SENSITIVITY CONSTANT OF MODEL POWER SYSTEM WITH STATCOM

Constant	A	B	C
K_1	1.2883	1.7081	2.0421
K_2	1.2245	1.6775	1.9200
K_3	2.1488	2.0884	2.0983
K_4	1.5754	2.1334	2.4442
K_5	-0.0953	-0.1754	-0.0327
K_6	0.5326	0.4024	0.2817
K_{EI}	-0.3268	-0.1924	-0.1479
K_{VS}	0.2008	0.2455	0.2700
K_{ID}	1.1694	1.4416	1.1961
K_{IS}	-0.1769	-0.0483	0.0726
K_{IE}	0.7691	0.6878	0.4543

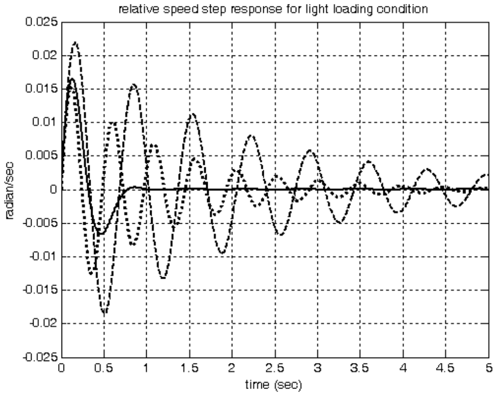
TABLE VI
EIGENVALUES OF LINEAR MODEL FOR DIFFERENT LOADING CONDITIONS WITHOUT STATCOM

Load	Electrical mode	Mechanical mode	Control mode
A	-9.6599±j 4.9674	-1.8721±j7.5022	-48.3390
B	-9.8392±j 9.3071	-2.1961±j6.7001	-47.3174
C	-5.5466±j 3.2823	-5.0104±j 9.6381	-50.2764

Figure 7, the step response of power system with STATCOM during a step change in the mechanical power using the classical model (dot line), the third order model (solid line) and without STATCOM (dash line) for light loading is shown. Also the Bode diagram of load angle is shown in Figure 8. The step response of the system for normal load condition is shown in Figures 9 and 10.



(a) Load angle



(b) Relative speed rotor

Figure 7. Step response for light load during a step change in the mechanical power

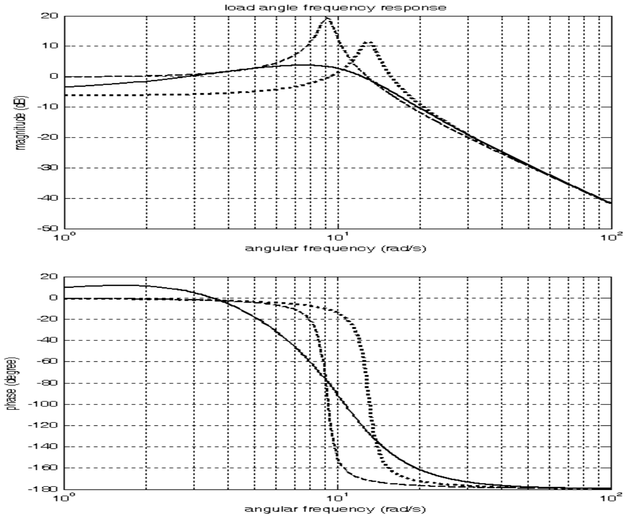
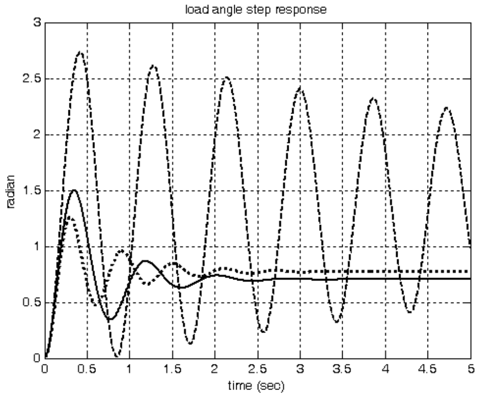
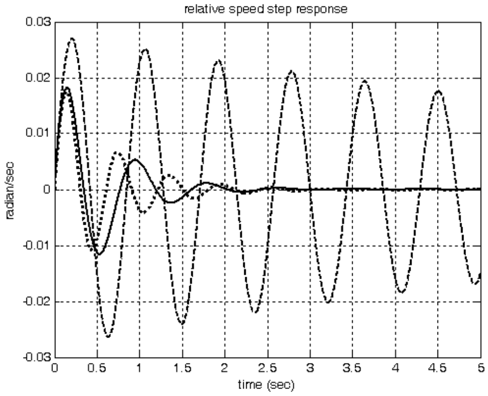


Figure 8. Bode diagram of load angle for light load

Figure 11 show the reactive power delivered deviation and output current of STATCOM according to load angle for different load conditions in the system.



(a) Load angle



(b) Relative speed rotor

Figure 9. Step response for normal load during a step change in the mechanical power

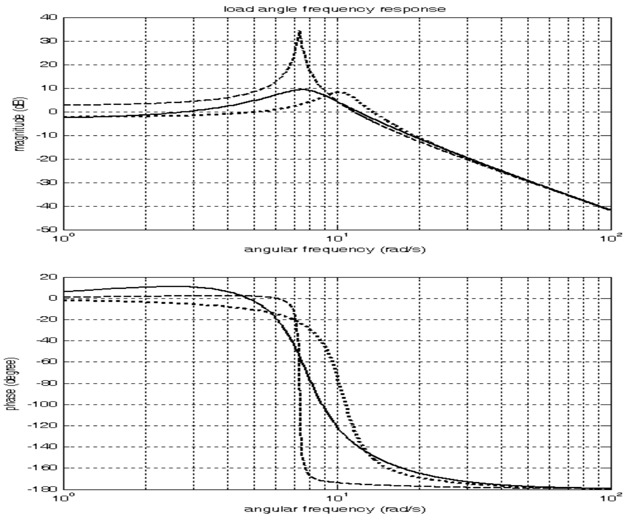
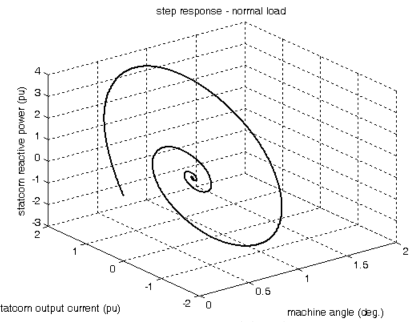


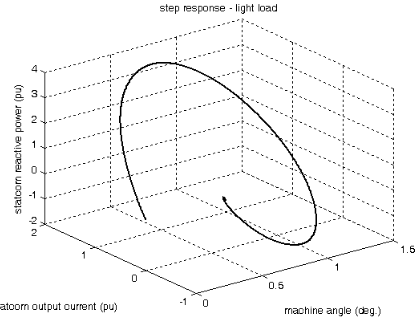
Figure 10. Bode diagram of load angle for normal load

V. CONCLUSION

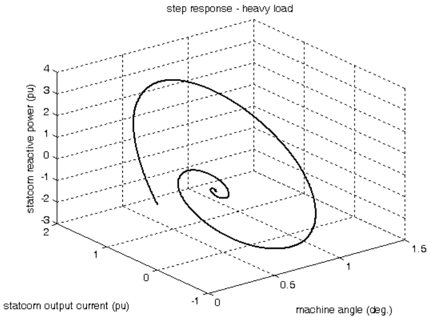
Electromechanical oscillations have been observed in many power systems worldwide. That is generally studied by modal analysis of a linearized system model. This paper has examined the effects of the STATCOM using eigenvalues analysis on damping power systems electromechanical oscillations.



(a) Normal load



(b) Light load



(c) Heavy load

Figure 11. Reactive power and output current of STATCOM according to load angle

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