Modeling and Dynamic Analysis of a STATCOM for System Damping Enhancement

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***Abstract-* A static synchronous compensator (STATCOM) control is presented to enhance the damping of the power system. The aim of this paper is dynamic modeling and analysis of STATCOM for a single-machine infinite-bus (SMIB) power system. Also the applicability of PID type control in dynamic performance enhancement with eigenvalue analysis is studied and shown to be feasible. The model is then used to investigate the damping improvement of a SMIB and the results obtained are systematically described.**

I. INTRODUCTION

Power systems are non linear systems with a wide range of operating conditions and time varying configurations and parameters. Large interconnected power networks are for increasingly heavier loads especially if new lines cannot be built because of the lack of right of way. Continuous advances in power electronic technologies have made the application of FACTS devices very popular in power systems. Generally, the main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes. Dynamic application of FACTS controllers includes transient stability improvement, oscillation damping and voltage stability enhancement [1, 2].

A good number of papers are available on modeling, simulation, operation and control fundamental of the FACTS devices [3-8]. Simulation of FACTS controllers is mainly done in the following two ways: (a) detailed calculations in 3 phase systems and (b) steady state and stability analyses [9]. The theoretical analysis and experimental verification of voltage regulation stability problems of STATCOM were presented in [10]. The authors propose phase compensation method to achieve larger phase margin of the control loop to enhance the stability of STATCOM voltage regulating loop. An approach for comprehensively assessing the financial benefits to the network of three most widely used FACTS based devices for voltage sag mitigation FACTS presented in [11]. A STATCOM-based var generator for medium power applications, utilizing one-cycle control is proposed in [12], which the switching frequency of the devices is constant. The design of a space vector pulse width modulated two-leg four-switch STATCOM to provide satisfactory performances in performing various reactive power flow control functions during steady-state and transient operations of power systems in [13] presented.

Damping the oscillations is not only important in increasing the transmission capability but also for stabilization of power system conditions after critical faults. One of the methods of damping of power system oscillations is control of the transmission line reactance. Reactance control can be achieved by series or shunt compensation. There are various shunt-connected FACTS devices. The STATCOM is shunt connected reactive compensation equipment. A STATCOM is one of the fundamental FACTS devices that can be used for voltage regulation and dynamic voltage control, because of its attractive steady state performance and operating characteristics [14, 15].

In this paper control of power system with STATCOM is investigated. A linear small-signal dynamic model of the SMIB was derived using state-space. A newly linearized block diagram which represents the dynamics of power system is described. Simulation results show the effect of the STATCOM on the damping of the power system oscillations.

II. SMALL SIGNAL MODEL

In this section we will study the small signal performance of a single machine connected to a large system through transmission lines. The studied system, shown in Figure 1, is a single-machine infinite-bus (SMIB) power system equipped with the STATCOM at the bus bar M of transmission line, where X_1 represents the equivalent reactance between the machine bus and the intermediate bus M, and X_2 represents the equivalent reactance between bus M and the infinite bus.

A STATCOM operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

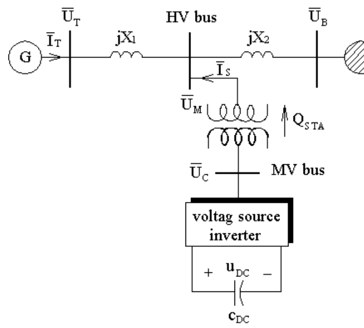

Fig. 1. STATCOM installed in SMIB power system with shunt load

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 converter connected to a dc capacitor (C_{DC}).

The relationships shown in Figure 2 are used to transform variables from xy reference frame to the dq. The rotor angle δ is the angle by which internal voltage (E'_q) leads the x-axis. δ_M is the angle of STATCOM bus voltage and δ_T is the angle of generator terminal voltage. The V-I characteristic of a STATCOM is limited only by the maximum voltage and current rating as depicted in Figure 3. Inductive current generated by STATCOM is considered positive. This controller can be operated over its full output current range even at very low voltages. Modeling of STATCOM as a controllable reactive current source with time delay is show in Figure 4. The following equations can be derived from voltage equation:

$$tg\delta_M = \frac{X_2 U_T \sin\delta_T}{X_2 U_T \cos\delta_T + X_1 U_B} \quad (1)$$

$$tg\delta_T = \frac{[X_T U_M - X_1 X_2 I_S]\sin\delta_M}{[X_T U_M - X_1 X_2 I_S]\cos\delta_M - X_1 U_B} \quad (2)$$

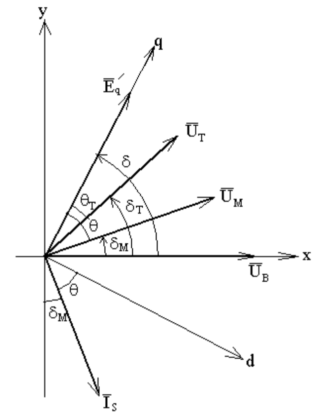

Fig. 2. Two frames reference for phasor quantities

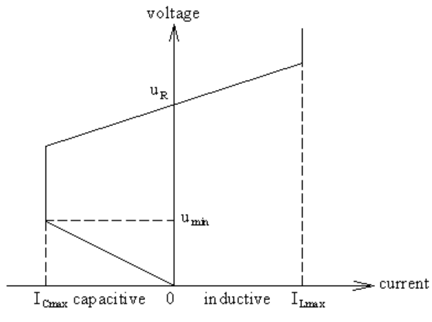

Fig. 3. The V-I characteristic of STATCOM

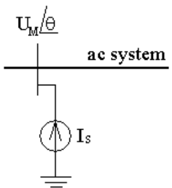

Fig. 4. STATCOM model

where U_B , U_M and U_T are voltage magnitude at is infinite bus, STATCOM bus and generator terminal, respectively. The voltage magnitude at bus M can be written as:

$$U_M = \frac{X_1 X_2 I_S + X_2 U_T \cos(\delta_T - \delta_M) + X_1 U_B \cos\delta_M}{X_T} \quad (3)$$

where $X_T=X_1+X_2$ is total reactance of line. The voltage of bus M can be written as:

$$U_M = \lambda(1-\lambda) X_L I_S + \sqrt{(1-\lambda)^2 U_T^2 + \lambda^2 U_B^2 + 2\lambda(1-\lambda) U_T U_B \cos\delta_T} \quad (4)$$

where λ is used to show the fraction of line length at which the STATCOM is placed. From the phasor diagram, the angle between the U_M and q-axis is θ and can be written as:

$$tg\theta = \frac{X_T + X'_d}{X_T + X_q} \frac{(X_1 + X_q)(U_B \sin\delta + X_2 I_S \sin\theta)}{X_2 E'_q + (X_1 + X'_d)(U_B \cos\delta + X_2 I_S \cos\theta)} \quad (5)$$

The d and q components of STATCOM bus voltage can be written as:

$$U_{Md} = \frac{X_1 + X_q}{X_T + X_q}[U_B \sin\delta + X_2 I_S \sin\theta] \quad (6)$$

$$U_{Mq} = \frac{X_1 + X'_d}{X_T + X'_d}[U_B \cos\delta + X_2 I_S \cos\theta] + \frac{X_2}{X_T + X'_d} E'_q \quad (7)$$

The generator output power in presence of STATCOM can be expressed in terms of the δ_M, δ_T, U_B and U_T, as:

$$P_E = \underbrace{\frac{U_T U_B}{X_T}\sin(\delta_T)}_{I} + \underbrace{\frac{X_2 U_T}{X_T} I_S \sin(\delta_T - \delta_M)}_{II} \quad (8)$$

$$Q_E = \underbrace{\frac{U_T(U_T - U_B)}{X_T}\cos\delta_T}_{I} - \underbrace{\frac{U_T X_2}{X_T} I_S \cos(\delta_T - \delta_M)}_{II} \quad (9)$$

The output power has been decomposed into two components. The second term shows the effect of STATCOM and change with I_S. Note that the coefficient of the second term often is numerically positive because δ_T for a normal system is greater than δ_M. Amplitude and angle of STATCOM voltage in term of generator terminal voltage angle show in Figure 5. The equations of the system are nonlinear and have to be linearized for small signal analysis. The following is a summary of the system linear equations as a set of first order differential equations, with time t in seconds, rotor angle δ in electrical radians, J_M is the inertia constant in seconds and all other quantities in per unit [16].

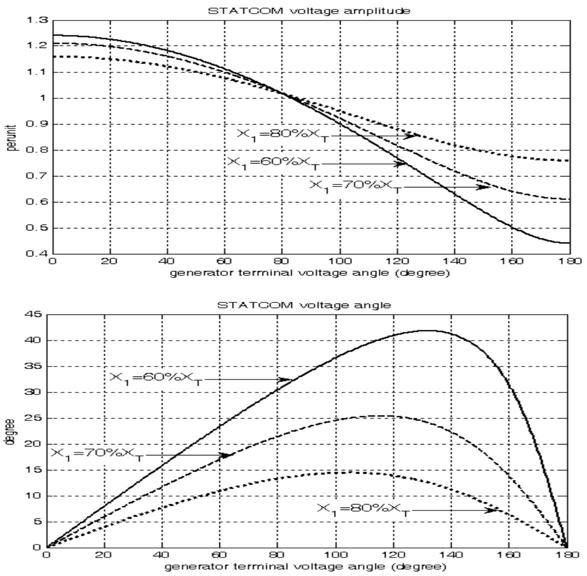

Fig. 5. STATCOM voltage in term of generator terminal voltage angle

$$\frac{d}{dt}\delta = \omega_o\,\delta \tag{10}$$

$$\frac{d}{dt}\omega = \frac{1}{J_M}(P_M - P_E - K_D\,\omega) \tag{11}$$

$$\frac{d}{dt}I_S = \frac{1}{T_{STA}}(-I_S + K_{STA}\,U_S) \tag{12}$$

where ω is relative speed, K_D is the damping constant, Is, K_{STA}, T_{STA} and U_S are the output current, gain, time constant and controller output of the STATCOM, P_M is the input mechanical power, respectively.

III. Control Design and Dynamic Analysis

An open loop dynamic analysis has been made using the linear small signal model. This analysis, based on transfer functions and Bode plots, is similar to the analysis for SISO (single input-single output) systems.

Proportional integral (PI) and proportional integral derivative (PID) controllers are widely utilized in industrial control systems. The PID controller is used to improve the dynamic response as well as reduce or eliminate the steady state error. The damping of the system is improved by decreasing (increasing) the output power of the machine when its speed deviation is negative (positive). Figure 6 shows the block diagram representation of the small signal performance of the system model with PID controller in the speed, $G_W(s)$, and the voltage, $G_U(s)$, loop. Constant K_{ED} and K_{ES} are derived from the electric torque expression, K_{ID} and K_{IS} from the terminal current of generator, K_{UD} and K_{US} from the STATCOM bus voltage magnitude, K_{TD} and K_{TS} from the STATCOM bus voltage angle. The basis for the block diagram and the expressions for the associated constants are developed below:

$$\Delta P_E = K_{ED}\,\Delta\delta + K_{ES}\,\Delta I_S \tag{13}$$

$$\Delta I_T = K_{ID}\Delta\delta + K_{IS}\Delta I_S \tag{14}$$

$$\Delta U_M = K_{UD}\Delta\delta + K_{US}\Delta I_S \tag{15}$$

$$\Delta\theta = K_{TD}\Delta\delta + K_{TS}\,\Delta I_S \tag{16}$$

$$\Delta\delta_M = (1 - K_{TD})\Delta\delta - K_{TS}\,\Delta I_S \tag{17}$$

$$\Delta Q_{STA} = (U_{Mo} + K_{US} I_{So})\,\Delta I_S + K_{UD} I_{So}\Delta\delta \tag{18}$$

The s domain form of PID controller transfer function is as follows:

$$G_U(s) = K_{VP} + \frac{K_{VI}}{s} + K_{VD}\,s \tag{19}$$

$$G_W(s) = K_{WP} + \frac{K_{WI}}{s} + K_{WD}\,s \tag{20}$$

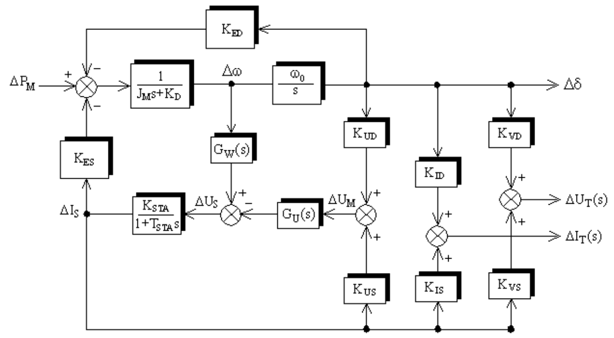

Fig. 6. Function scheme for the STATCOM control

IV. Simulation Results

The nominal parameters of the system and the operating conditions used for the sample problem investigated are given in Table I. All data are given in per unit of value on the 2220 MVA, 24KV base, except that J_M and time constants are in seconds while frequency is in hertz. The shunt load is represented by the constant admittances.

TABLE I
DATA OF SMIB SYSTEM

Components	Parameters	Value
GENERATOR	X_q	1.76
	X_d	1.81
	X'_d	0.30
	J_M	7
	K_D	0
	f	60
TRANSMISSION LINE	X_1	0.2
	X_2	0.2
STATCOM	K_{STA}	1
	T_{STA}	0.02
	I_{SO}	2

At very light loading the system generates reactive power that must be absorbed, while at heavy loading the system consumers a large amount of reactive power that must be replaced. Three operating conditions for the time response studies are as shown in Table II. Table III summarizes the value of the sensitivity constant under the system condition. The steady state operating points of the model power system as a function load conditions is shown in Table IV.

TABLE II
OPERATING CONDITIONS

Loading	P_{EO}	Q_{EO}	U_{TO}
Nominal	0.90	0.30	1
Light	0.60	-0.30	1
Heavy	1.10	0.02	1

TABLE III
SENSITIVITY CONSTANT OF MODEL POWER SYSTEM

Loading Constant	Normal	Heavy	Light
K_{ES}	0.1611	0.1796	0.0661
K_{ED}	0.7557	0.8018	0.8779
K_{US}	0.2108	0.2153	0.2074
K_{UD}	-0.1611	-0.1796	-0.0661

TABLE IV
STEADY STATE OPERATING POINT OF MODEL POWER SYSTEM

Steady state	LOADING		
	Normal	Heavy	Light
U_{do}	0.4161	0.5463	0.4020
U_{qo}	0.9093	0.8376	0.9560
U_{BO}	0.9818	1.1882	1.2337
I_{do}	0.6473	0.6176	-0.0335
I_{qo}	0.6935	0.9104	0.6700
θ_o	41.12	51.48	33.08
δ_0	58.00	66.85	40.67

The root-locus plot for the change of K_{WP} in the system with proportional controller in speed loop is shown in Figure 7. Figures 8 and 9 show the swing curve of the generator and the STATCOM output current for various values of controller proportional gain. We can see that without STATCOM, generator has undamped oscillations. Also, it is observed that by increasing the value of K_{WP} the system damping improves.

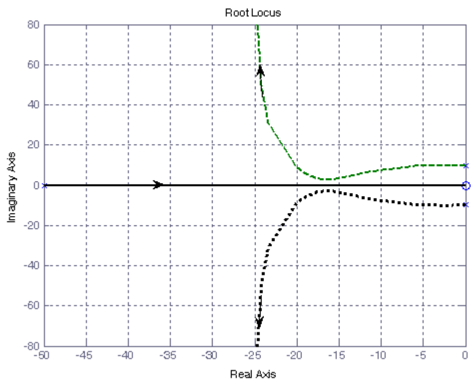

Fig. 7. Locus of the roots of the change proportional gain of controller in speed loop

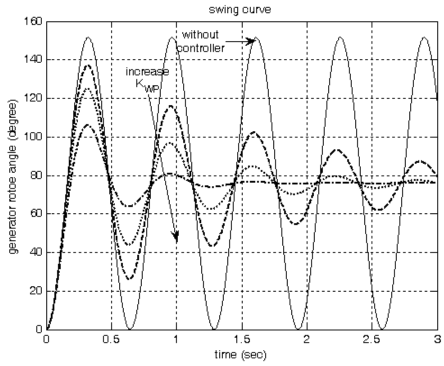

Fig. 8. Swing curve of the generator for various values of K_{WP}

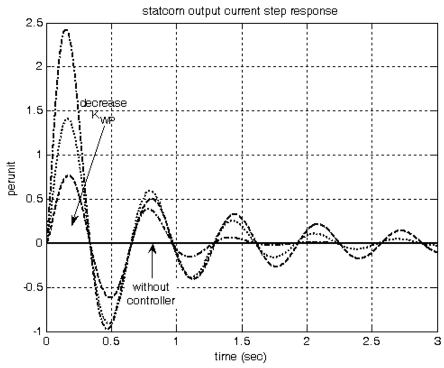

Fig. 9. The STATCOM output current for various values of K_{WP}

The effect of gains on system damping with controller in speed loop for normal loading summarizes in Tables V and VI.

TABLE V
THE EFFECT OF K_{WI} ON SYSTEM PERFORMANCE WITH K_{WP}=100 and K_{WD}=0

K_{WI}	Eigenvalues	Damping ratio	Natural frequency
0	-44.2085 -2.89±j9.95	0.2794	10.3639
20	-44.2382 -2.88±j10.01	0.2765	10.4188
100	-44.3562 -2.82±j10.25	0.2653	10.6348

TABLE VI
THE EFFECT OF K_{WD} ON SYSTEM PERFORMANCE WITH K_{WP}=100 AND K_{WI}=0

K_{WD}	Eigenvalues	Damping ratio	Natural frequency
20	-100.55 -1.57±j6.69	0.2285	6.8718
100	-317.38 -0.55±j3.83	0.1421	3.8693

Figures 10 and 11 show the phase portrait (the load angle and rotor speed) and STATCOM bus voltage variations with control only in the speed loop. The responses with no control, proportional-integral (PI) and proportional-derivative (PD) controllers are shown by curves a, b and c, respectively, which K_{WP}=100, K_{WD}=20 and K_{WI}=20.

Therefore, an increase in the gain K_{WD} decreases both the natural frequency (ω_n) and the damping ratio (η) of system oscillation mode. Conversely, increasing the gain K_{WI} poorly increase the ω_n and poorly decrease the η of the system oscillation mode. The effect of gains on system damping with controller in voltage loop for normal loading summarizes in Tables VII and VIII. Therefore, the voltage loop provides very little damping.

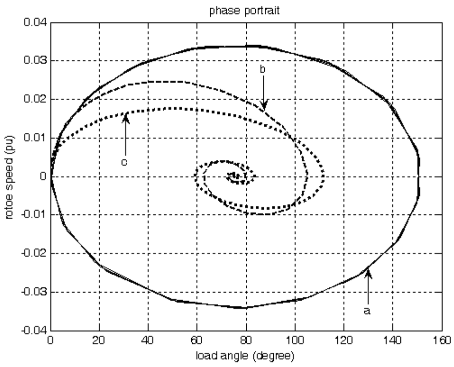

Fig. 10. The phase portrait of SMIB with STATCOM with control only in the speed loop

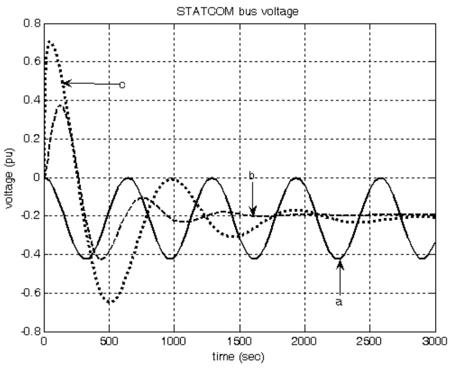

Fig. 11. The STATCOM bus voltage variation with control only in the speed loop

TABLE VII. THE EFFECT OF K_{VI} ON SYSTEM PERFORMANCE WITH K_{VP}=100 AND K_{VD}=0

K_{VI}	Eigenvalues	Damping ratio	Natural frequency
0	-1104.1 ±j0.01	0	0.0105
20	-1103.9 0.01±j10.48 -0.19	-0.0007	10.4755
100	-103.1 -0.01±j10.48 -0.96	-0.0009	10.4763

TABLE VIII. THE EFFECT OF K_{VD} ON SYSTEM PERFORMANCE WITH K_{VP}=100 AND K_{VI}=0

K_{VD}	Eigenvalues	Damping ratio	Natural frequency
20	-5.19 -0.02±j10.50	0.0011	10.4995
100	-1.04 -0.31±j10.51	0.0003	10.5078

The effect of derivative gain on system damping with proportional controller in voltage loop for normal loading summarizes in Table IX.

TABLE IX. THE EFFECT OF K_{WD} ON SYSTEM PERFORMANCE WITH K_{WP}=100 AND K_{VP}=100

K_{WD}	Eigenvalues	Damping ratio	Natural frequency
0	-259.83 -0.49±j10.37	0.0474	10.3864
20	-313.63 -0.44±j9.44	0.0462	9.4536
100	-528.70 -0.29±j7.28	0.0403	7.2812

Figures 12 and 13 shows the variation of the load angle and rotor speed for the various load conditions with controls in both speed and voltage loops. The responses with normal, heavy and light load are shown by curves a, b and c, respectively, which K_{WP}=100, K_{WD}=20 and K_{VP}=20.

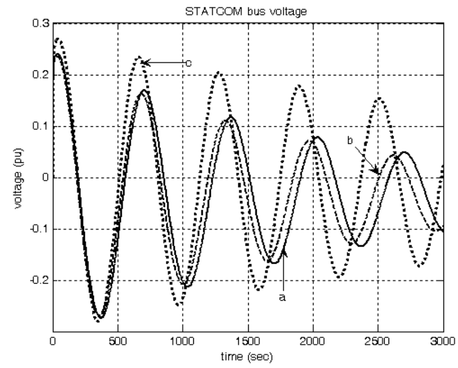

Fig. 12. The STATCOM bus voltage variation with control both in the speed loop and voltage loop

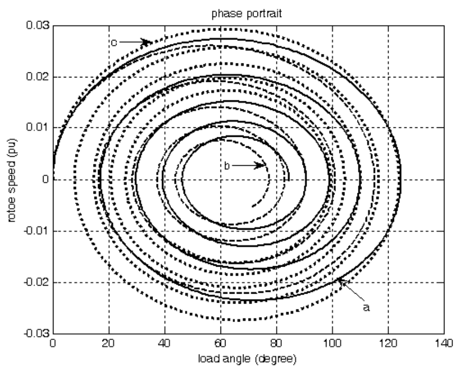

Fig. 13. The phase portrait of SMIB with STATCOM with control both in the speed loop and voltage loop

The gain matrix of controller is determined by pole placement in order to obtain the desired system properties. The tracking control law is obtained with a pole placement technique. We determine the PID gains via the pole placement method. The gains of controller for deferent damping ratio in normal loading summarizes in Tale X. The results simulation is shown in Figures 14, 15 and 16. We can see that percent overshoot is reduced with an increase in the real pole distance of imaginary axis, and the speed of response is increased with an increase in the complex pole distance of real axis.

TABLE X. THE EFFECT OF K_{WD} ON SYSTEM PERFORMANCE WITH K_{WP}=100 AND K_{WI}=0

Case	Poles	K_{WP}	K_{WD}	K_{VP}
A	-350, -1±j8	249.6	41.9	18.0
B	-350, -1±j6	239.1	80.3	8.2
c	-150, -3±j8	327.0	15.2	6.2
d	-250, -2±j8	362.4	27.9	12.2

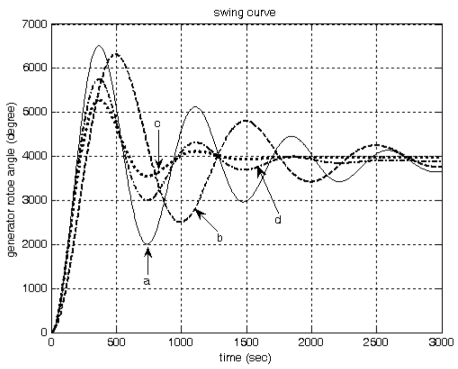

Fig. 14. Swing curve of the generator for various values of K_{WP}

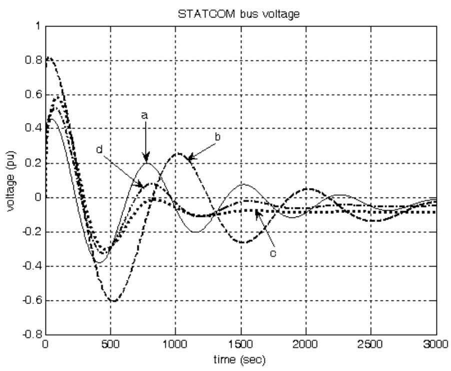

Fig. 15. The STATCOM bus voltage variation with control only in the speed loop (Table X)

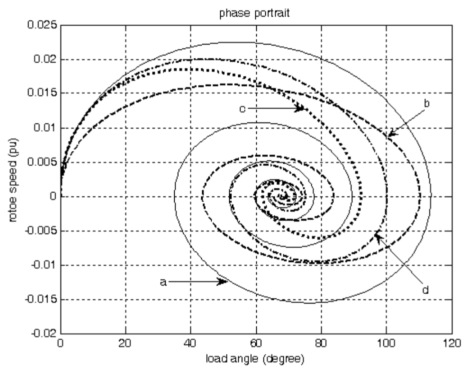

Fig. 16. The phase portrait of SMIB with STATCOM with control only in the speed loop (Table X)

V. CONCLUSION

This paper investigated the control ability of STATCOM, one in the speed loop and the other in the voltage loop, to increase power system stability by damping power oscillations. The various simulation results on a single area system under change of parameters validate the proposed approach. A controller in the speed loop has effective control over the electrical and electromechanical transient.

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