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PSO Based State Feedback Controller Design for SVC to Enhance the Stability of Power System

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ABSTRACT

SVC is one of the most significant devices in FACTS technology, which is used in parallel compensation, enhancing the transient stability, limiting the low frequency oscillations and, etc. designing a proper controller is effective in operation of SVC. In this paper, a simplified analysis of the effect of a SVC on the stability of a Single Machine Infinite Bus (SMIB) system is presented. The SVC which is located at the terminal of the generator has the state feedback controller in which the coefficients of state feedback are optimized by the Particle Swarm Optimization (PSO) algorithm in order to damp the Low Frequency Oscillations (LFO). The equations that describe the proposed system have been linearized, and then the optimum state feedback controller has been designed for SVC which its optimal coefficients have been earned by PSO algorithm. The system with proposed controller has been simulated for a special disturbance in nominal loading condition. Thereafter, for three states viz light loading condition, normal loading condition and heavy loading condition, to show the robustness of the proposed controller, the previous disturbance has been applied again. Then the dynamic responses of the generator have been presented. The simulation results showed that the system composed with proposed controller has a suitable operation in fast damping of oscillations of the power system. to ensure stability and tracking. Simulations is carried out to verify the theoretical results.

Keywords: *PSO, Statefeedback controller, SVC, Power system Stability.*

I. INTRODUCTION

Recently, substantial changes have taken place in the electrical environment. The deregulation of the electric power market and the restrictions applied to the construction of new power transmission lines have caused new technical problems in the operation of power system. Due to this, it is necessary the electrical network improvement in order to meet these new network requirements [1]. In this new situation, it is necessary to utilize the existing power transmission system at its maximum capacity to meet increasing demand of electrical energy [2]. Flexible Alternating-Current Transmission Systems (FACTS) is a recent technological development in electrical power systems.[3] These devices have the ability to control, in an adaptive fashion, key network parameters that have a direct bearing on the operation of the power system[4] Some of the FACTS devices are Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Unified Power Flow Controller (UPFC), Inter-phase Power Flow Controller (IPFC), Static Synchronous Series Controller (SSSC), Convertible Series Compensator (CSC), Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Shifter (TCPS), Super Conducting Magnetic Energy Storage (SMES)[5].Typically, the devices are divided into three categories: shunt-connected, series-connected and a combination of both.[6]. FACTS devices are being presently employed for various applications, as follows:

- Increasing power transmission capacity of existing lines
- Improving the steady state and dynamic stability limits
- Improving damping of different types of power oscillations
- Improving voltage stability [7].

SVC is one of the key elements in the power system that provides the opportunity to improve power quality and reliability due to its fast response. SVC has the functional capability to handle dynamic conditions, such as transient stability and power oscillation damping in addition to providing voltage regulation [8]. Due to the characteristics of power transmission systems, the FACTS Compensator control algorithm must be designed resorting to control methods capable to deal with system non-linearities and unknown disturbances [9]. In this paper the SVC has the state feedback controller where its coefficients have been optimized by PSO algorithm when the input power of generator has been changed suddenly. The dynamic response of generator with and without controller has been represented for normal loading condition. Following, the dynamic responses of generator for three loading conditions have been shown as preceding one for the input power of generator.

II. MODEL OF PROPOSED SYSTEM

A synchronous machine with an IEEE type-ST_1 excitation System connected to an infinite bus through a transmission Line has been selected to demonstrate the derivation of simplified linear models of power system for dynamic stability analysis [10]. Fig. 1 shows the model consists of a generator supplying bulk power to an infinite bus through a transmission line, with an SVC located at its terminal.

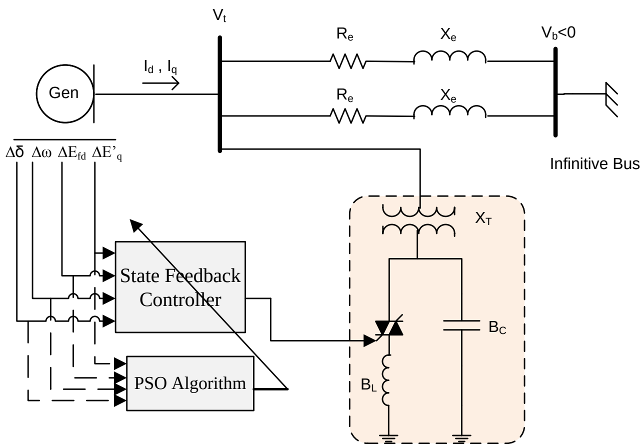


Fig. 1. Single machine-infinite bus system model with SVC.

The equations that describe the generator and excitation system have been represented in following equations:

$$\dot{\delta} = \omega_o(\omega - 1) \quad (1)$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1))/M \quad (2)$$

$$\dot{E}'_q = (E_{fd} - (X_d - X'_d)id - E'_q)/\tau'_{do} \quad (3)$$

$$\dot{E}_{fd} = (K_A(V_{ref} - V_t + U_{pss}) - E_{fd})/T_A \quad (4)$$

Where

$$P_e = V_{td}I_d + V_{tq}I_q \quad (5)$$

$$V_t = V_{td} + jV_{tq} \quad (6)$$

$$V_{td} = X_q I_q \quad (7)$$

$$V_{tq} = E'_q - X'_d I_d \quad (8)$$

$$B_{SVC} = B_C - B_L \quad (9)$$

$$C_1 I_d + C_2 I_q = V_b \sin(\delta) + C_3 E'_q \quad (10)$$

$$C_4 I_d + C_5 I_q = V_b \cos(\delta) - C_6 E'_q \quad (11)$$

Where in

$$C_1 = \left(\frac{R_e X'_d B_{svc}}{1 - X_T B_{svc}}\right) - R_e \quad (12)$$

$$C_2 = X_q + X_e - \left(\frac{X_e X_q B_{svc}}{1 - X_T B_{svc}}\right) \quad (13)$$

$$C_3 = \frac{R_e B_{svc}}{1 - X_T B_{svc}} \quad (14)$$

$$C_4 = \left(\frac{X_e X'_d B_{svc}}{1 - X_T B_{svc}}\right) - X'_d - X_e \quad (15)$$

$$C_5 = \left(\frac{R_e X_q B_{svc}}{1 - X_T B_{svc}}\right) - R_e \quad (16)$$

$$C_6 = 1 - \left(\frac{X_e B_{svc}}{1 - X_T B_{svc}}\right) \quad (17)$$

δ is the rotor angle, V_b the infinite bus voltage, ω the rotor speed, P_m the mechanical input power, P_e active power, E'_q the internal voltage, E_{fd} the excitation voltage, and V_{ref} is the reference voltage. The constant values of these equations have been represented in Table I.

Table I: System Parameters

Synchronous machine [p.u]	Excitation system δ transmission line [p.u]
X_d=1.7, X_q=1.64 X'_d=0.245 D=0, H=2.37, τ'_{do}=5.9	T_A=0.05, K_A=400 X_e=0.8, R_e=0 X_t=0.08

III. SVC BASED STABILIZER

A basic topology of SVC consists of a series capacitor bank *C* in parallel with a thyristor controlled reactor *L*. The SVC can be seen as an adjustable susceptance which is a function of thyristors firing angle .The susceptance of the SVC, *B*, can be described as:

$$B_{SVC} = B_C - B_L \quad (18)$$

The B_L is controlled by state feedback controller while B_C is constant.

IV. POWER SYSTEM LINEARIZED MODEL

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition (P_e=0.8, Q_e=0.13). The linearized model of power system as shown in Fig. 1 is given as follows [11]:

$$\Delta\dot{\delta} = \omega_o \Delta\omega \quad (19)$$

$$\Delta\dot{\omega} = (\Delta P_m - \Delta P_e)/M \quad (20)$$

$$\Delta\dot{E}'_q = (\Delta E_{fd} - (X_d - X'_d)\Delta i_d - \Delta E'_q)/\tau'_{do} \quad (21)$$

$$\Delta\dot{E}_{fd} = (K_A(\Delta V_{ref} - \Delta V_t + U_{pss}) - \Delta E_{fd})/T_A \quad (22)$$

$$\Delta I_q = c_7\Delta\delta + c_8\Delta B_{SVC} \quad (23)$$

$$\Delta I_d = c_9\Delta\delta + c_{10}\Delta E'_q + c_{11}\Delta B_{SVC} \quad (24)$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_3\Delta B_{svc} \quad (25)$$

$$\Delta V_t = K_4\Delta\delta + K_5\Delta E'_q + K_6\Delta B_{svc} \quad (26)$$

K_1, K_2, ..., K_6 and C_7, ..., C_{11} are linearization constants. The block diagram of the linearized power system model [12] is depicted as shown in Fig 2. K_7, K_8, and K_9 are constant defined as:

$$(X_d - X'_d)c_9 = K_7 \quad (27)$$

$$(X_d - X'_d)c_{10} + 1 = K_8 \quad (28)$$

$$(X_d - X'_d)c_{11} = K_9 \quad (29)$$

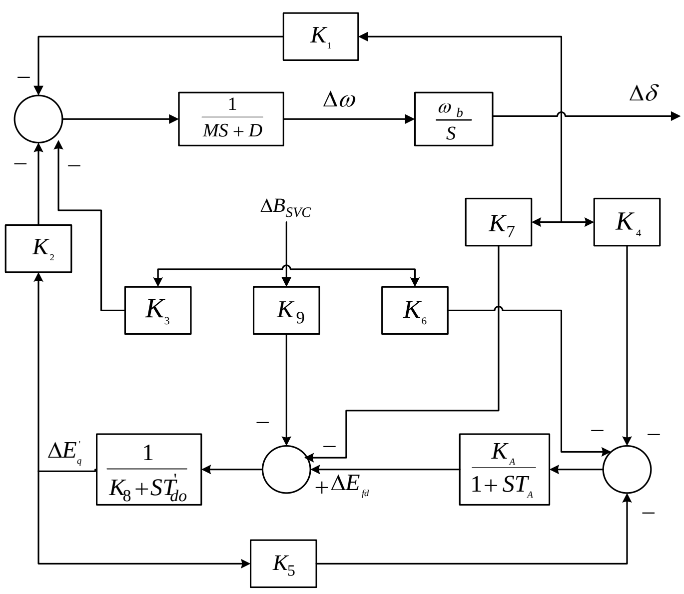


Fig. 2. Block diagram of the linearized model

V. PSO ALGORITHM

PSO algorithm was first proposed by Kennedy and Eberhart [13,14] where is a novel evolutionary algorithm paradigm which imitates the movement of birds flocking or fish schooling looking for food. Each particle has a position and a velocity, representing the solution to the optimization problem and the search direction in the search space The particle adjusts the velocity and position according to the best experiences which are called the p_{best} found by itself and g_{best} found by all its neighbours. In PSO algorithms each particle moves with an adaptable velocity within the regions of decision space and retains a memory of the best position it ever encountered. The best position ever attained by each particle of the swarm is communicated to all other particles. The updating equations of the velocity and position are given as follows [15]:

$$v_i(k+1) = wv_i(k) + r_1c_1[g_{besti} - x_i(k)] + r_2c_2[p_{besti} - x_i(k)] \quad (30)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (31)$$

Where v is the velocity and x is the position of each particle. c_1 and c_2 are positive constants referred to as acceleration constants and must be $c_1+c_2 \leq 4$, usually $c_1=c_2=2$. r_1 and r_2 are random numbers between 0 and 1, w is the inertia weight, p_{best} refers to the best position found by the particle and g_{best} refers to the best position found by its neighbours. Fig 3 shows the flowchart of PSO algorithm.

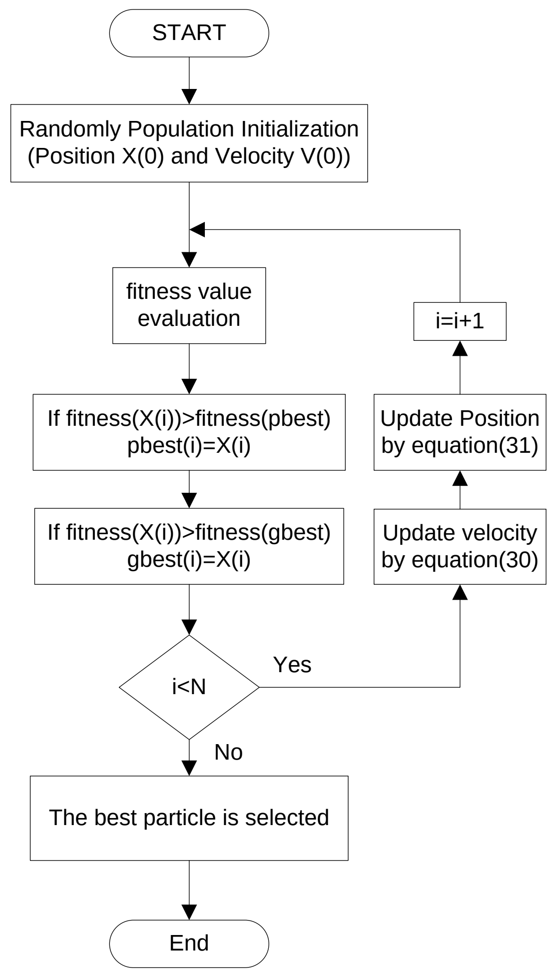


Fig. 3. Flowchart of the PSO Algorithm

VI. SIMULATION RESULT

A power system can be described by a linear time invariant (LTI) state-space model as follows:

$$\dot{X} = AX + BU \quad (32)$$

$$Y = CX \quad (33)$$

Where X, U and Y are state, input and output vectors, respectively. A, B and C are constant matrixes. The aim of designing of State feedback controller is to move the eigenvalues of power system to the left hand side of the complex plane. The structure of State feedback controller is as follow [11]:

$$U = -HX \qquad (34)$$

Where the gain vector H is [h_1 h_2 h_3 h_4] and the state vector X is $[\Delta\delta\ \Delta\omega\ \Delta E'_q\ \Delta E_{fd}]^T$. The fitness function used in this paper for PSO algorithm is represented in (35) that t_{sim} is the simulation time, dw is the deviation of rotor speed and $d\delta$ is the deviation of rotor angle of generator.

$$fitness = \int_0^{t_{sim}} t \times [10 \times |dw| + |d\delta|] dt \qquad (35)$$

Fig. 4 shows the overall PSO method and how it interplays with the simulation model during optimization. The convergence of fitness function is represented in Fig. 5. The PSO has been run 20 times and Table II shows the best parameters found in the 20 runs of PSO. Optimized parameters have been earned when the input power of generator has been changed 10% at t=1 (s) for six cycles, and the operating condition is P_e=0.8 and Q_e=0.13.

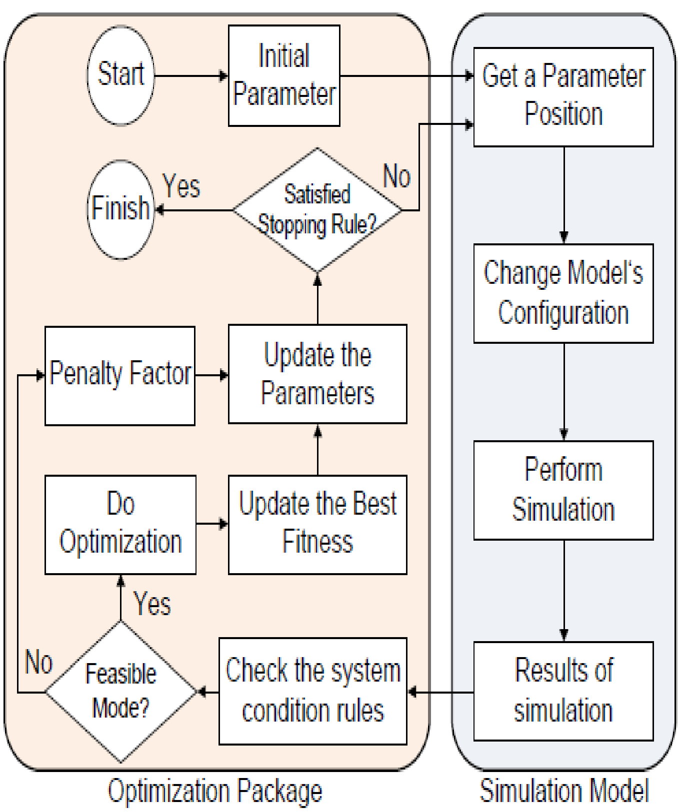


Fig. 4. Optimization method on stochastic simulation

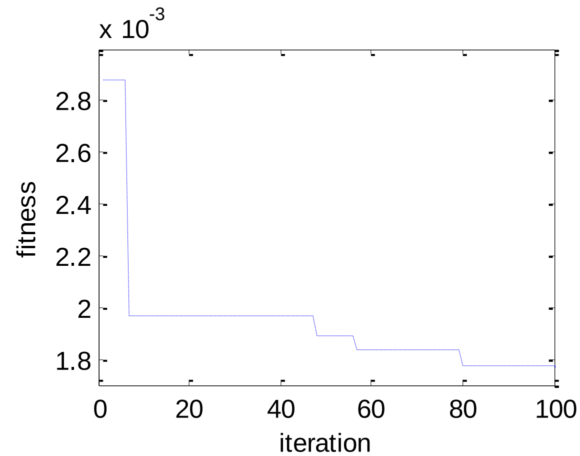


Fig. 5: Convergence of Fitness Function

Table II: Optimized Values

h_1	h_2	h_3	h_4
5.62	-27.87	15.005	0.0147

Fig. 6 and Fig. 7 show system dynamic responses for the nominal operating point following 10% disturbance on the mechanical generator power input for six cycles fault disturbance for internal voltage variation, terminal voltage variation, rotor speed variation and rotor angle variation respectively, for following two states:

-with State Feedback controller
-None controller

The robustness of the controller was tested by applying the proposed controller to a number of operating conditions. Fig. 8 and Fig. 9 show the system dynamic responses for six cycles fault disturbance for rotor speed variation, rotor angle variation, internal voltage variation and terminal voltage variation respectively, for the following 3 loading conditions when the SVC controller was optimized by PSO algorithm:

a) Nominal loading: P_e=*0.8 p.u.* and Q_e=*0.13 p.u.* ;
b) Heavy loading: P_e=*1p.u.* and Q_e=*0.20p.u.* ;
c) Light loading: P_e=*0.6 p.u.* and Q_e=*0.07 p.u.* ;

The eigenvalues of power system with and without proposed controller have been shown in Table III for 3 loading conditions. As considered in Table III, the system with incorporation of state feedback controller is more stable. Fig. 10 and Fig. 11 show the eigenvalue distribution of the system in case of normal loading, Heavy loading and Light loading.

(a)

(b)

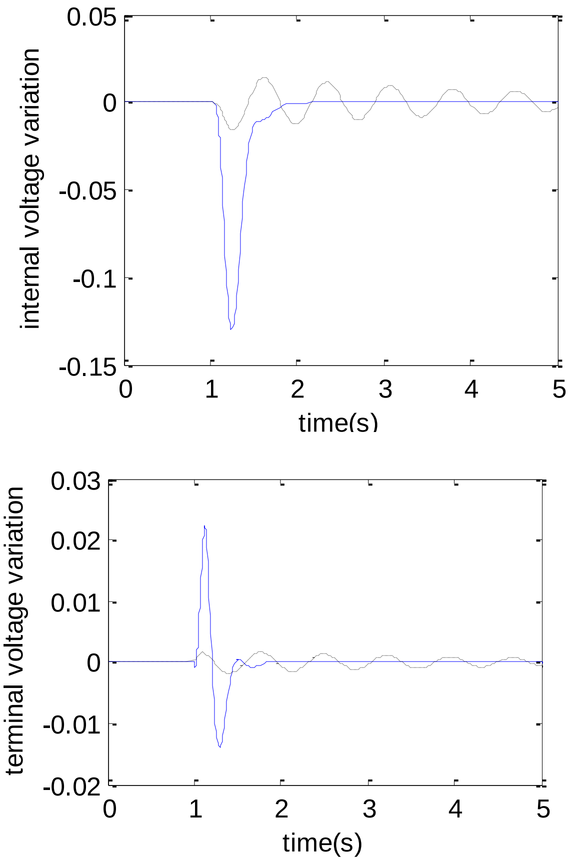
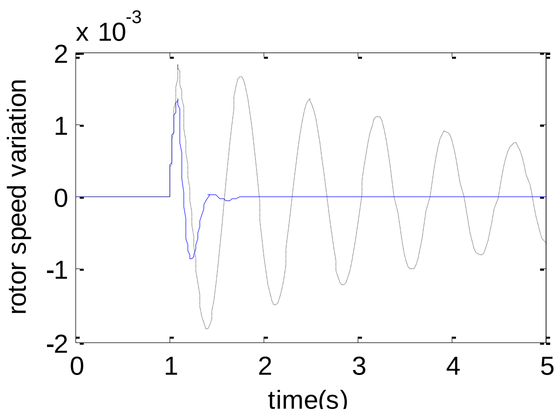
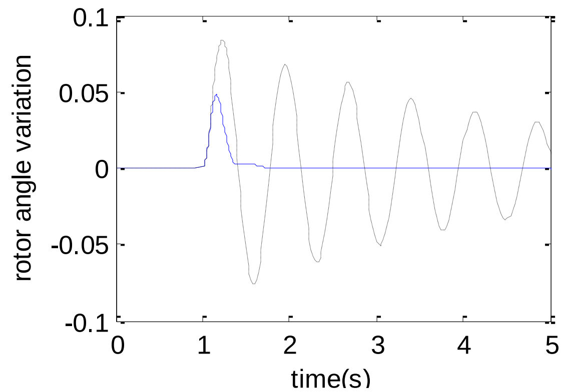


Fig. 6: System Dynamic Response for Six Cycles Fault Disturbance. (a) Internal Voltage Variation,(b) Terminal Voltage Variation, Solid (SVC based Controller), Dash (without Controller)

(a)





(B)

Fig. 7. System Dynamic Response For Six Cycles Fault Disturbance. (A) Rotor Speed Variation, (B) Rotor Angle Variation, Solid (SVC Based Controller), Dash (Without Controller)

(a)

(b)

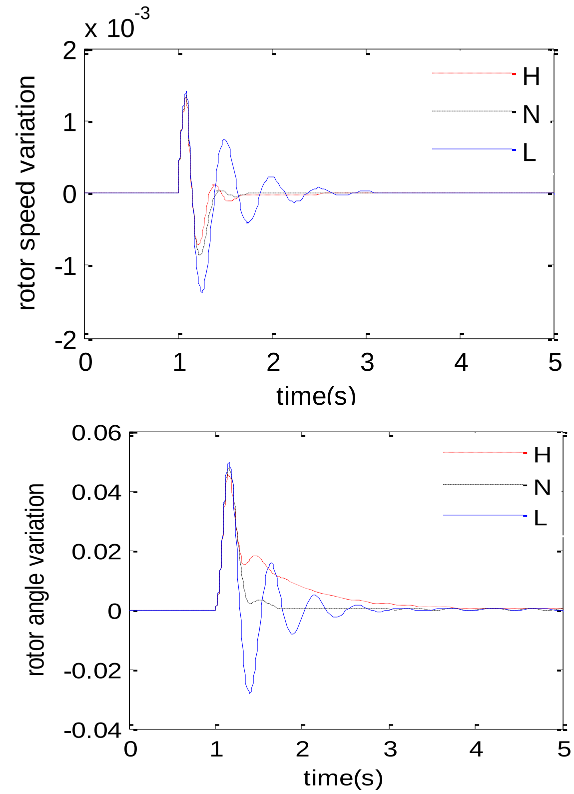


Fig. 8. System Dynamic Response for Six Cycles Fault Disturbance With Normal, Light and Heavy Loading. (A) Rotor Speed Variation, (B) Rotor Angle Variation.

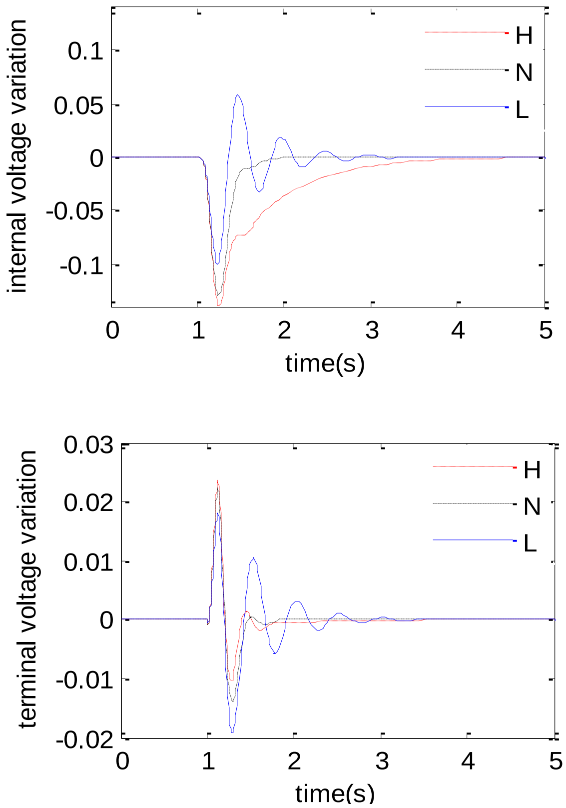


Fig. 9. System Dynamic Response for Six Cycles Fault Disturbance with Normal, Light and Heavy Loading. (A) Internal Voltage Variation, (B) Terminal Voltage Variation

Table III: Eigenvalues of the System

conditions	State feedback controller	Without controller
Nominal loading	-8.358±16.454i -6.7108,-22.003	-0.060±9.8500i -10.20±22.22i
Heavy loading	-7.312±18.702i -1.471,-34.087	0.396±10.872i -10.66±21.07i
Light loading	-2.431 ±12.734i -16.06 ±19.772i	-0.281 ± 8.677i -9.986 ±23.74i

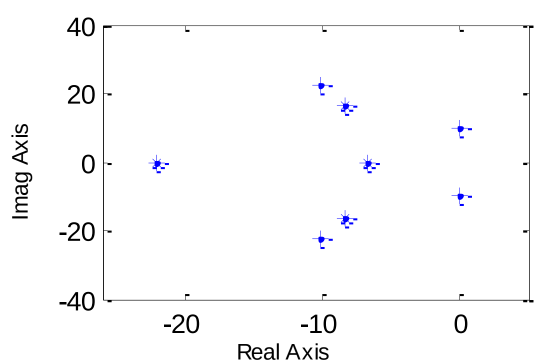


Fig. 10: Eigenvalue Distribution of the System in case of Normal Loading. (* with Controller, + without Controller)

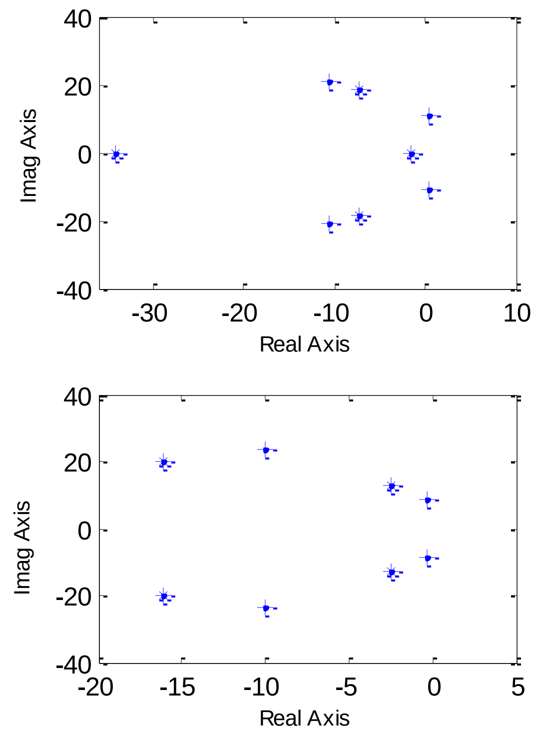


Fig. 11: Eigenvalue Distribution of the System. (a) Heavy Loading, (b) Light Loading. (* with Controller, + without Controller)

VII. CONCLUSION

In this paper, the SMIB system where SVC located at the terminal of the generator has been considered. The State Feedback controller has been designed for SVC to improve the stability of the power system. In order to show the excellent operation of the proposed controller, the input power of the generator has been changed 10% instantaneously and the system with proposed controller has been simulated for different loading conditions (light, normal, heavy), then the dynamic responses of the generator for rotor speed variation, rotor angle variation, internal voltage variation and terminal voltage variation have been represented. Eigenvalues analysis exposes exceptional performances of the proposed controllers. The simulation results showed that the system composed with proposed controller has a superior operation in fast damping of oscillations of the power system.

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