Coordinated Design of SVC and PSS Controllers Using PSO Algorithm for Damping Power System Oscillations

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Abstract— In this paper, the coordinated Static VAR Compensator SVC and Power System Stabilizers PSS devices using for damping of oscillation in the multi-machine power system. Particle Swarm Optimization PSO is used for searching optimized parameters of proposed coordinated controllers. The objective function in this study is based on the minimization of integral of time speed deviation.

In PSO, individuals in a new generation are created by update position and velocity of each particle. The effectiveness of this algorithm and the proposed coordinated controllers are examined for the multimachine power system, subjected to a disturbance. The results proposed technique are compared with the same power system without a controller, with the PSS controller, and with coordinated controllers without PSO.

Keywords—Particle swarm optimization PSO, power system stabilized static var compensator, FACTS, multi-machine, oscillation.

I. Introduction

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and system oscillations are increased. The conventional PSS is widely utilized to enhance the system damping. In some cases, if the utilization of PSS cannot provide sufficient damping for system oscillations, Flexible AC transmission systems FACTS devices are substitute effectual solutions. The principle of these FACTS devices is to regulate the reactance and voltage. SVC is the most popular FACTs device utilized to improve the reliability of power systems [01] [02], due to its low cost and good performance [03].

In this paper, the coordinated of PSS and SVC controllers using for damping of oscillation in the multi-machine power system, because a single controller is not sufficient for improving the global or near global power system stability.

Recent years, intelligent optimization algorithms have been broadly used to design power system stabilizers [04]. In this paper, PSO is applied for optimized parameters of coordinated PSS and SVC controllers by minimization the objective function.

The Multi-machine Power System model involving three machines has been considered for examined the effectiveness of the proposed coordinated controllers optimized by PSO. The results proposed technique are compared with the same power system without a controller, with the PSS controller, and with coordinated controllers without PSO.

The paper sets out as follows: section two presents the problem formulation. The proposed solution for damping of oscillation in a multi-machine power system is presented in section three. Particle Swarm Optimization PSO is presented in section four. Finally, section five is presented simulation and concludes the paper.

II. PROBLEM FORMULATION

A. *Generator Equations*

The dynamic behavior of generators within a power system is of fundamental importance to the overall quality of the power supply. The mechanical equations of a rotating machine are very well established and they are based on the swing equations of the rotating inertia.

Generator dynamics is described by [05]:

$$M\frac{dw}{dt} = P_m - P_e - D\frac{d\delta}{dt} \tag{1}$$

Where $\boldsymbol{M}$ is the inertia coefficient, $\boldsymbol{D}$ is the damping coefficient, $\boldsymbol{P_m}$ is the mechanical power, $\boldsymbol{P_e}$ is the electrical real power, $\boldsymbol{\delta}$ is the rotor angle and $\boldsymbol{\Delta w = d\delta/dt}$ is the rotor speed deviation.

The swing equation relates the machine's rotor torque angle to the accelerating torque, which is the difference between the shaft torque and electromechanical torque. When there is an equilibrium between the mechanical shaft and breaking electrical torques, the shaft speed will be constant. Any imbalances between the torques will cause the acceleration or deceleration of the machine according to the lows of motion of a rotating body [05].

$$T_{acc} = J \cdot \frac{d^2 \delta_m}{dt^2} = T_m - T_e \qquad (2)$$

Where T_{acc} the accelerating torque, J is the combined moment of inertia of the generator and turbine, δ_m is the mechanical torque angle of the rotor, t is the time, T_m is the mechanical torque and T_e is the electrical torque.

B. Excitation System

The IEEE type-ST1 excitation system shown in Fig 1 is considered. It can be described as:

$$\rho E_{fd} = \frac{K_A\left(V_{ref} - v\right) - E_{fd}}{T_A} \qquad (3)$$

Where, K_A and T_A are the gain and time constant of the excitation system, respectively; and V_{ref} is the reference voltage [06] [07] [08].

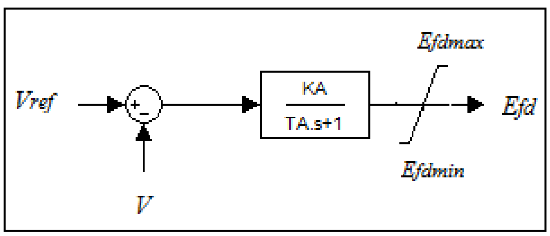

Fig. 1. Excitation system

C. Power System Model

The power system can be modeled by a set of nonlinear differential equations as:

$$\dot{X} = f(X, U) \qquad (4)$$

Where X the vector of state variables, U is the vector of input variables.

In this study $X = [\delta_i \; w_i \; E'_{qi} \; E_{fdi}]$ and $U = [U_{PSS} \; U_{SVC}]$ is the PSS output signals. Here, δ_i w_i E'_{qi} and E_{fdi} are the rotor angle, rotor speed, internal voltage, and field voltage respectively. Also, U_{PSS} and are the PSS and SVC output stabilizing signals, respectively [09].

The linearized incremental models around an equilibrium point are usually employed. The linearized model of the power system is given by [10].

$$\dot{X} = AX + BU \qquad (5)$$

III. CONTROLLERS STRUCTURES

The electromechanical oscillation can be damped with controllers. In this study, the structure and design of PSS and SVC controllers are as discussed below [08].

A. Structure of Power System Stabilizer PSS

Power System Stabilizer PSS is shown in Fig 2.

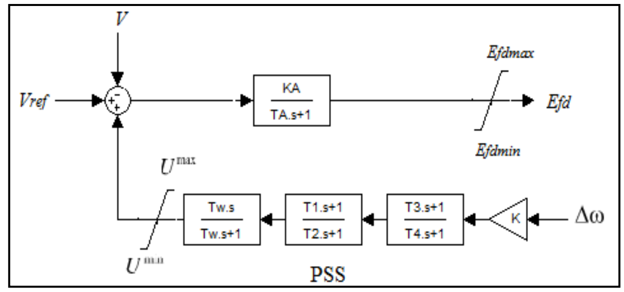

Fig. 2. Basic Structure of PSS

PSS is the equipment that generates control signals for excitation and turbine system and works to increase the limit of stability with a set of generator excitation to provide damping to the rotor of the synchronous oscillations. To improve the damping, the PSS must produce an electrical torque component on a machine that has the same phase. This method can improve the performance of power system stability [11] [12]. The transfer function of the PSS is given by :

$$U = K\left(\frac{sT_W}{1 + sT_W}\right)\left[\frac{(1 + sT_1)(1 + sT_3)}{(1 + sT_2)(1 + sT_4)}\right] \qquad (6)$$

B. Static Var Compensator SVC

The static VAR compensator (SVC) is a shunt compensating Flexible Alternating Current Transmission System (FACTS) device. SVCs based on Thyristor Controlled Reactors (TCR) are commonly used and installed in the modern power systems to improve system transient stability, voltage support, and to damp power oscillations [13]. The SVC regulates the voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power. When system voltage is high, it absorbs reactive power. The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches TSC. Reactors are either switched on-off TSR or TCR [05].

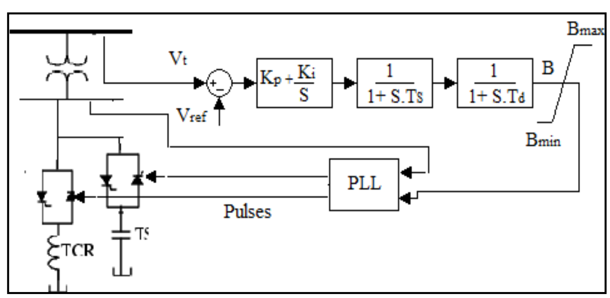

Fig. 3. Single-line Diagram of SVC

Fig 3 shows a single-line diagram of a static var compensator and a simplified block diagram of its control system.

The output voltage and current are described by the following three equations:

$$V_t = V_{ref} + X_s I \qquad -B_{c\max} \le B \le B_{l\max} \tag{7}$$

$$V_t = \frac{I}{B_{c\max}} \qquad B = B_{c\max} \tag{8}$$

$$V_t = \frac{I}{B_{l\max}} \qquad B = B_{l\max} \tag{9}$$

IV. PARTICLES SWARM OPTIMIZATION

Particle swarm optimization is a population based stochastic optimization technique. It was developed by James Kennedy and Russel C. Eberhart in 1995. PSO has a pliant and finely adjusted mechanism to raise the global and local exploration abilities [04]. the position of *(j,k)* particle represented as a vector $X_{j,k}$ and the velocity of *(j,k)* particle represented as vector $V_{j,k}$ in the N-dimensional space. The best position of the particle *(j,k)* is stored and represented as vector $X_{pbest\,j,k}$ The best position among all particles is represented as X_{gbest} . The operators of PSO are given below in Fig.4.

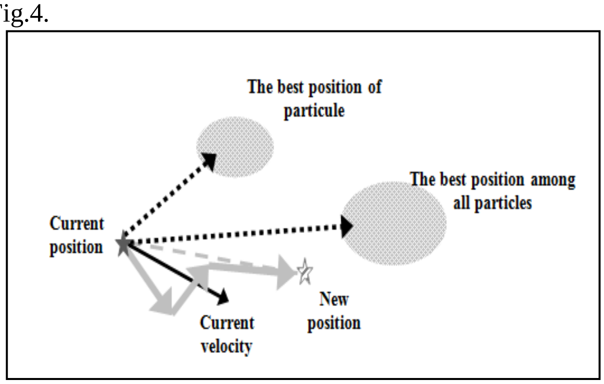

Fig. 4. The concept of a searching point by PSO

This modification can be represented by the concept of velocity. The velocity of each agent can be modified by the following equation:

$$V_{j,k} = w(t) * V_{j,k}(t-1) + C_1 * r_1 * \left(X_{pbest\,j,k}(t-1) - X_{j,k}(t-1)\right) + C_2 * r_2 \left(X_{gbest\,j,k}(t-1) - X_{j,k}(t-1)\right)$$

Sing the above equation, a certain velocity, which gradually gets close to $X_{pbest\,j,k}$ and X_{gbest} can be calculated.

The current position (searching point in the solution space) can be modified by the following equation:

$$X_{j,k}(t) = \left(V_{j,k}(t) + X_{j,k}(t-1)\right) \tag{11}$$

$X_{j,k}(t-1)$ is current searching point , $X_{j,k}(t)$ is modified searching point , $V_{j,k}(t-1)$ is current velocity, $V_{j,k}(t)$ is modified velocity of agent $X_{pbest\,j,k}(t-1)$ previous best position of particle *(j,k)* at iteration $(t-1)$. $X_{gbest}(t-1)$ is the best position among all individuals in the population at, ***w*** is weight function for velocity of agent (*t*), C_i is weight coefficients for each term. C_1 and C_2 are two positive constants.

- r_1 and r_2 are two randomly generated numbers with a range of [0,1].
- ***w*** is the inertia weight and it is defined as a function of iteration index (t) as follows:

$$w(t) = w_{max} - \frac{w_{max} - w_{min}}{MAXiter} * t \tag{12}$$

Where MAXiter, is a maximum number of iterations and the current number of iterations respectively.

The main steps of the PSO approach are as below:

1. First step: randomly generated initial population.
2. Second step: For each particle, the construction operators are applied
3. Third step: fitness function evaluation.
4. Fourth step: compare particles fitness function and determine X_{pbest} and X_{gbest} .
5. Fifth step: change of particles velocity and position according to (10) and (11) respectively.
6. Sixth step: If the iteration number reaches the maximum limit.
7. Seventh step: Otherwise, set iteration index K = K +1, and go back to Step 2.

V. OPTIMIZATION STRATEGY

In this paper, for damping of oscillation in the multi-machine power system, the integral of time speed deviation *J* is considered as objective function [14] [15] [16] [17]:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta w_i|\, dt \qquad i = 1, 2, \ldots ng \tag{13}$$

Where $|\Delta w|$ is the speed deviation, t_{sim} is the time range of the simulation and ***ng*** number of generators.

The problem constraints are the parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J (14)

Subject to

$$\begin{cases} Value_{min} \le K_{(PSS)}, K_{i(SVC)} \le Value_{max} \\ Value_{min} \le T_{1(PSS)}, T_{3(PSS)}, T_{d(SVC)} \le Value_{max} \end{cases} \tag{15}$$

Where $K_{(PSS)}$ represents the gain of damping stabilizer block, $T_{1(PSS)}$, $T_{3(PSS)}$ are the time constants of lead-lag blocks in the damping controllers, $K_{i(SVC)}$ represents a proportional gain of the voltage regulator of SVC and $T_{d(SVC)}$ time delay due to thyristor valves firing.

The Schematic of the proposed algorithm PSO is given below:

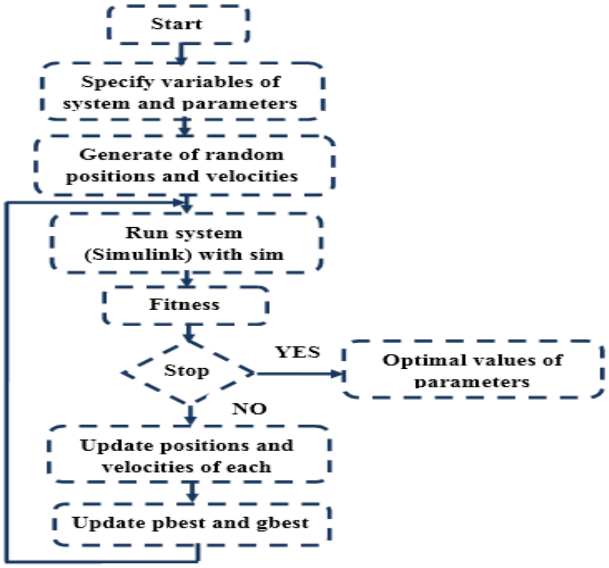

Fig. 5. Schematic representation of the PSO

The parameter settings to execute PSO are presented in Table I.

TABLE I. PARAMETER VALUES FOR PSO

No	Parameters	Values
1	Number of generations	60
2	Population size	20
3	Coefficient C1, C2	0.2
4	Inertia w	[0,4 0,9]

VI. SIMULATION AND RESULTS

The test system that has been considered here is the multi-Machine System as shown below in Fig.6.

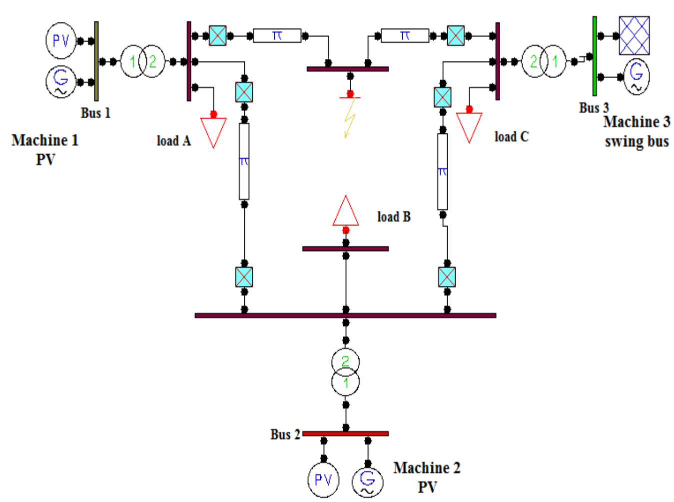

Fig. 6. Three generators power system.

This system containing three generators is equipped with PSS using the acceleration power and SVC is installed on a bus of generator tow. The details of this model are given in the appendix.

The PSO has been developed by the MATLAB environment version 7. And run on Pentium 4 having 3 GHZ 1GB RAM.

The performance of the proposed coordinated PSS with SVC controllers is examined by applying a 6 cycle three phase fault at **T = 1s** and cleared at **1.1s** at the middle of the transmission compared with the same power system without line **F** and controller, with PSS controller and with coordinated controllers without PSO.

The convergence of the objective function J with PSO is shown in Fig 7.

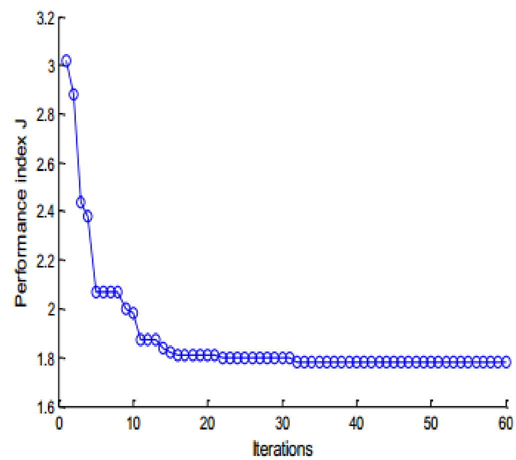

Fig. 7. Performance index J convergence.

The final settings of the optimized parameters for the proposed controllers are given in Table II.

TABLE II. OPTIMAL PARAMETER SETTINGS OF THE PROPOSED CONTROLLERS

	PSS1	PSS2	PSS3	SVC
K	20.3500	22.606	27.5503	-
T_1	0.0561	0.0491	0.0953	-
T_3	2.6958	3.4360	3.5796	-
K_i	-	-	-	235.1054
T_d	-	-	-	0.0091

Fig.8 shows the performance index J of different system configuration without a controller, with PSS, with coordinated PSS and SVC controllers and with coordinated controllers using the PSO algorithm. It is clear from the performance index J that the system stability is greatly enhanced with the proposed coordinated controllers using the optimized parameters of the PSO algorithm.

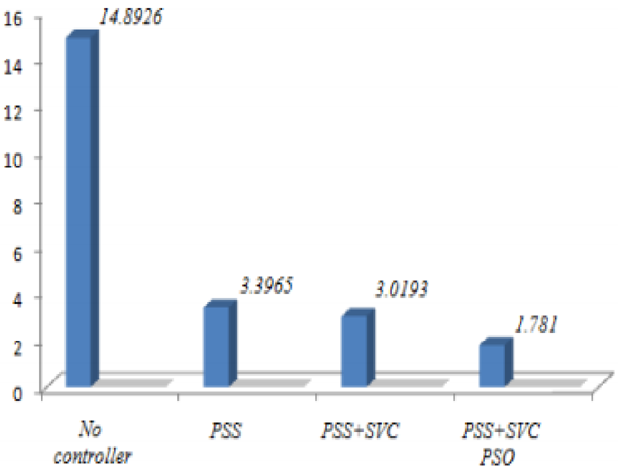

Fig. 8. Values performance index J

Figure 9 below showed the response angle deviations, speed deviations when the system subjected to a disturbance without and with different controllers.

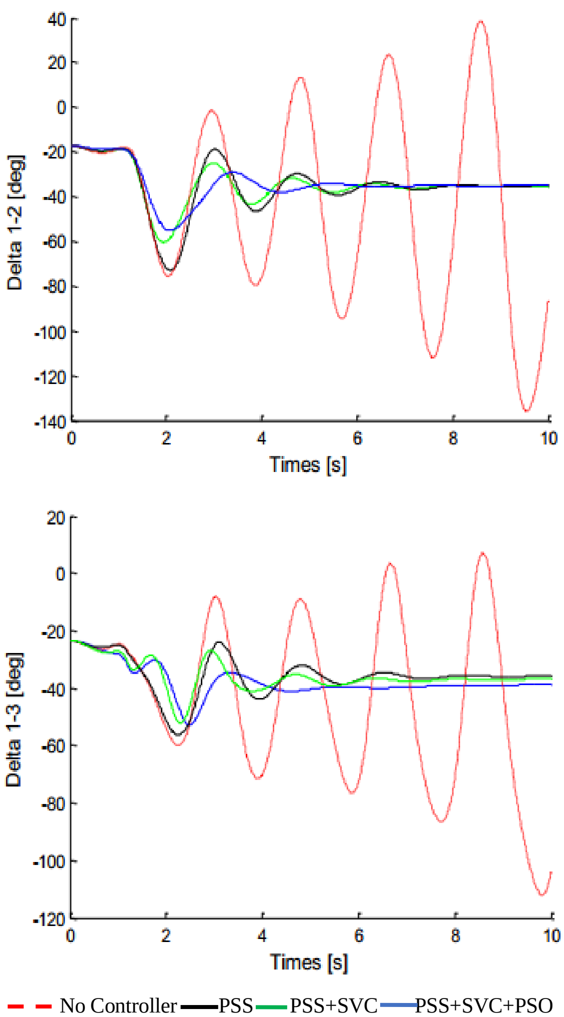

Fig. 9. Rotor angle deviation response to a 3-phase short circuit for a 6 cycle at F

Figure 10, 11, and 12 below showed the response speed deviations, power electrical and terminal voltage responses of generator 1, 2 and generator 3 when the system subjected to a disturbance without and with different controllers.

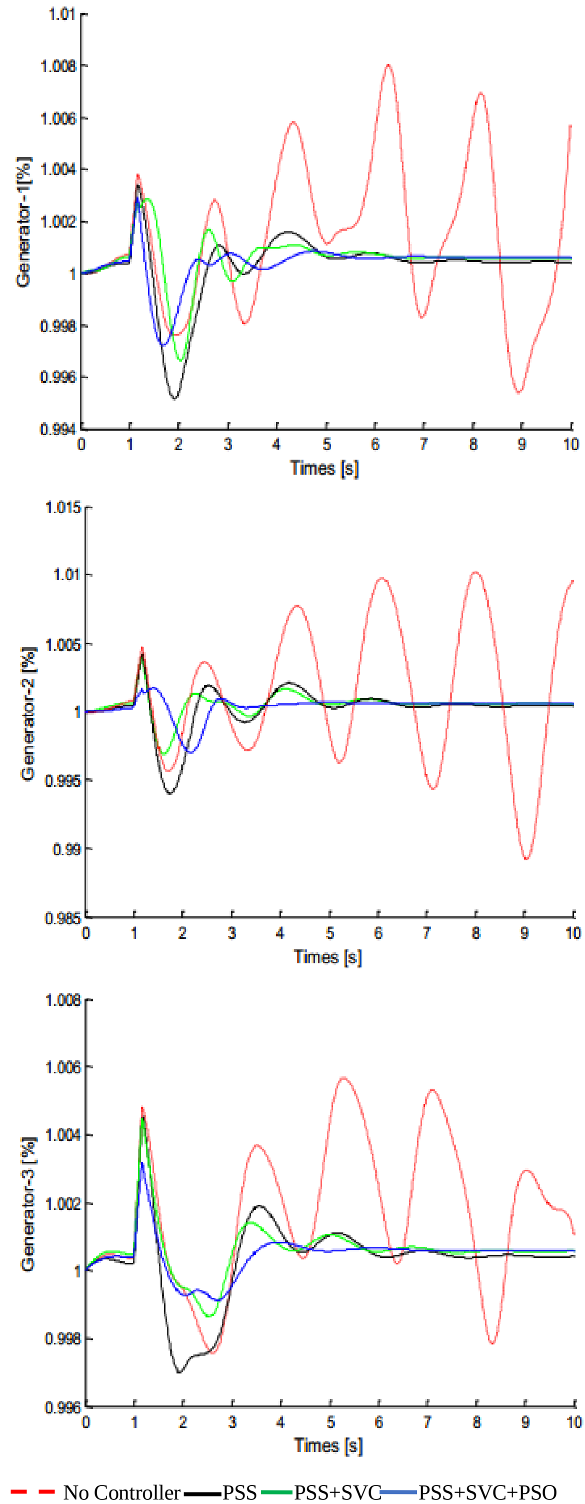

Fig. 10. Rotor Speed deviation response to a 3-phase short circuit for a 6 cycle at F

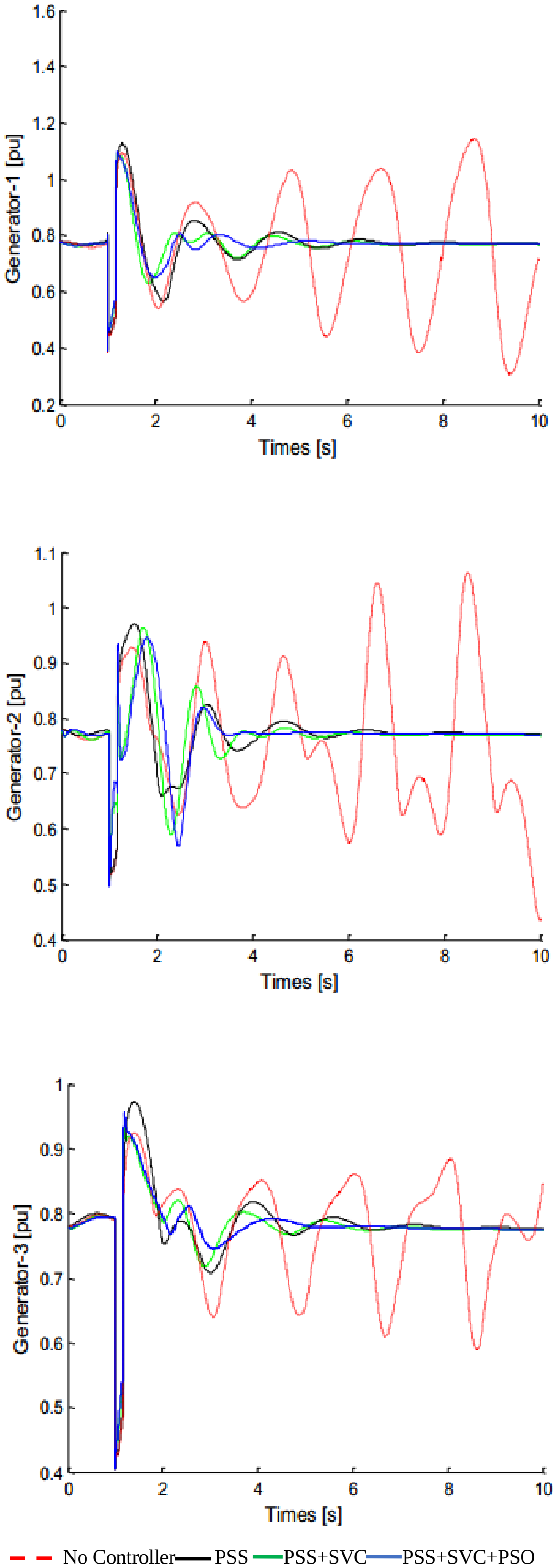

Fig. 11. Power electrical response to a 3-phase short circuit for a 6 cycle at F

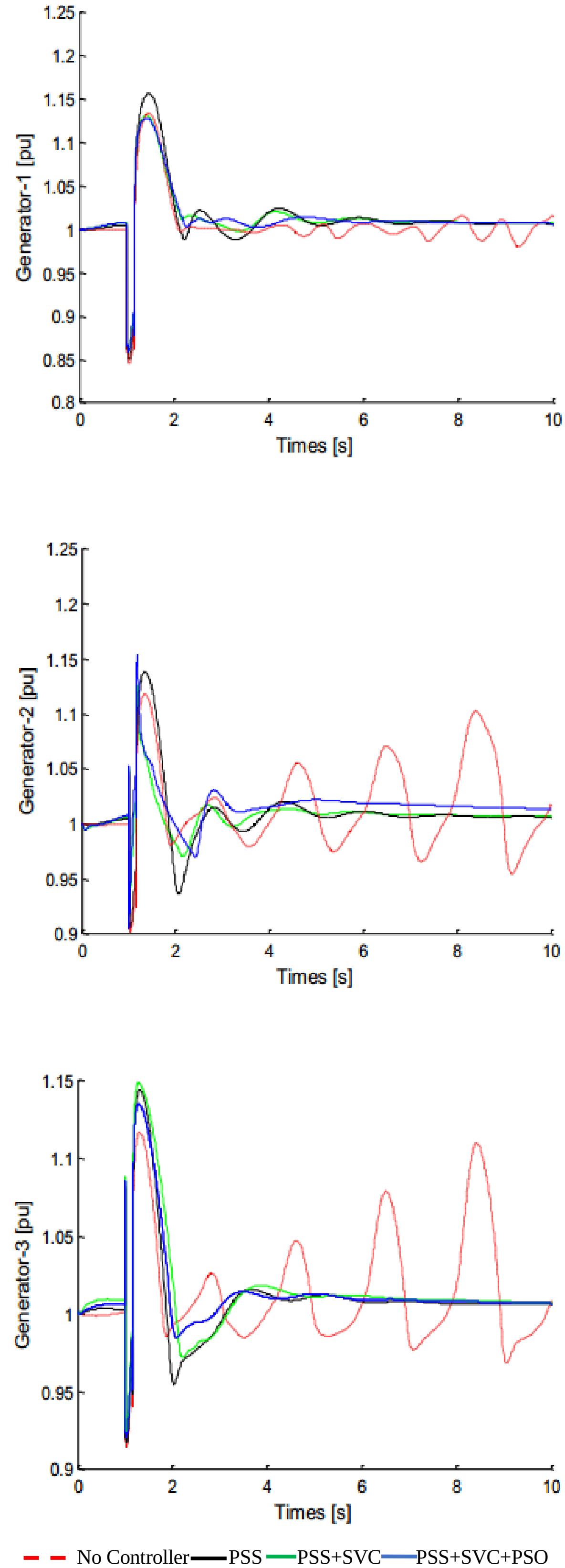

Fig. 12. Terminal voltage response to a 3-phase short circuit for a 6 cycle at F

VII. CONCLUSION

In this study, the particle swarm optimization technique PSO is applied for determining the optimal parameter setting of PSS and SVC devices based on the minimization of integral of time speed deviation. The proposed coordinated of PSS and SVC devices is applied a multi-machine power system when subjected to a disturbance. The simulation results show the effectiveness of the particle swarm optimization technique PSO for determining the optimal parameter setting of PSS and SVC controllers and gives the best response and good damping of the power system oscillations compared with PSS alone and the coordinate devices without optimal parameter setting.

APPENDIX

A. Synchronous machine parameters:

$S_n = 900MVA, V_T = 20KV, f = 60HZ, X_d = 1.8,$
$X'_d = 0.3,\ X''_d = 0.25,\ T'_d = 0.8,\ T''_d = 0.03, X_q = 1.7,$
$X'_q = 0.55, X''_q = 0.25, T'_q = 0.4, T''_q = 0.05,$
$X = 0.2 H(\delta) = 6.5\ Pole\ pairs = 4$

B. Excitation parameters:

$T_R = 0.002, K_A = 200, T_A = 0.001, E_{min} = 0,$
$E_{max} = 12.3$

C. Steam turbine and governor parameters:

$K_P = 1, T_1 = 0, T_2 = 10,\ T_2 = 3.3, T_4 = 0.5$
$T_{ST} = 0.001, T_{sm} = 0.15, v_{g\ min} = -0.1, v_{g\ max} = 0.1$

D. PSS parameters:

$K = 30, U_{PSS\ min} = -0.25, U_{PSS\ max} = 0.25$
$T_1 = 0.05, T_2 = 0.02, T_3 = 3, T_4 = 5.4$

E. SVC parameters:

$K_i = 300, K_P = 0, X_s = 0.03pu\ (200MVA),$
$X_n = 0.0667pu\ (200MVA), T_w = 0.0345, T_d = 0.004$

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