Design of Output Feedback SSSC and PSS Controllers to Enhance the Stability of Power System Using PSO

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Abstract

The Static Synchronous Series Compensator (SSSC) is one of the most significant devices in FACTS technology, which is used in series compensation, enhancing the transient stability, limiting the low frequency oscillations and, etc. Designing a proper controller is effective in operation of SSSC. In this paper, focuses on designing of the output feedback controller based two control parameters of the SSSC (*m*-based and *ψ*-based) and PSS in Single Machine Infinite Bus (SMIB) in order to damp the Low Frequency Oscillations (LFOs). The equations of the proposed system are linearized, and the optimum output feedback controller is designed for SSSC and PSS. The SSSC optimal coefficients are obtained by the Particle Swarm Optimization (PSO) algorithm. The effectiveness of the proposed controllers is explained by the analysis of the eigenvalues. The simulation for a special disturbance is carried out and then performances of SSSC and PSS based output feedback controllers are compared.

1. Introduction

The building of new transmission lines and expansion of existing transmission systems are becoming more difficult because of economic reasons [1]. Power systems experience Low Frequency Oscillations (LFOs) during and after a large or small disturbance happened to a system, especially in heavy loading conditions [2]. These oscillations may sustain and grow to cause system separation if no adequate damping is available [3]. The most commonly used controller is the Power System Stabilizer (PSS), which is installed at the generator so that it can damp both local oscillations and inter-area oscillations [4]. The power electronics development allows the application of new devices to improve power system performance. Some of the devices may be used to damp electromechanical oscillation. The Flexible AC Transmission Systems (FACTS), for example, are such devices that may be used to damp the oscillations in power systems. The use of the FACTS devices is a cost-effective alternative to improve the flexibility and performance of power system operation compared to system expansion [5-7]. Using FACTS technology, such as Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controller (UPFC), etc, the bus voltages, line impedances and phase angles in the power system can be regulated rapidly and flexibly. Thus, FACTS can facilitate the power flow control, enhance the power transfer capability, decrease the generation cost, and improve the security and stability of the power system [8, 9]. SSSC uses a voltage source converter to inject a controllable voltage in quadrature with the line current of a power network belongs to the family of series FACTS devices. Such a device is rapidly able to provide both capacitive and inductive impedance compensation independent of the line current. Moreover, SSSC with a properly designed external damping controller can also be used to damp the low frequency power oscillations in power systems [10].

In this paper, the designing of the output feedback controller for PSS and SSSC (*m*-based and *ψ*-based), in order to damp the low frequency oscillations, when the input power of the generator is changed suddenly, is carried out. To select the best parameters of the PSS and SSSC output feedback controllers a flexible optimization problem is provided. The problem is solved using PSO method. Then the dynamic responses of the generator are compared.

The remainder paper is organized as follows; Section 2 describes the proposed system; Section 3 presents the Power system linearized model; the PSO algorithm is discussed in Section 4; the output feedback controller and PSO based Output feedback controller are described in section 5; the computer simulation results are presented and discussed in Section 6; Finally, in Section 7, a conclusion is provided.

2. Description of Case Study

2.1. Generator and Exciter

A synchronous machine with an IEEE type-ST1 excitation System connected to an infinite bus through a transmission line is selected to demonstrate the derivation of simplified linear models of power system for dynamic stability analysis. The network of Fig. 1 shows a single-machine infinite-bus power system. In this Figure the SSSC is installed on the transmission line [11]. The equations that describe the generator and excitation system are represented in following equations [12]:

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

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

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

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

Where

$$P_e = V_{td} I_{tsd} + V_{tq} I_{tsq} \quad (5)$$

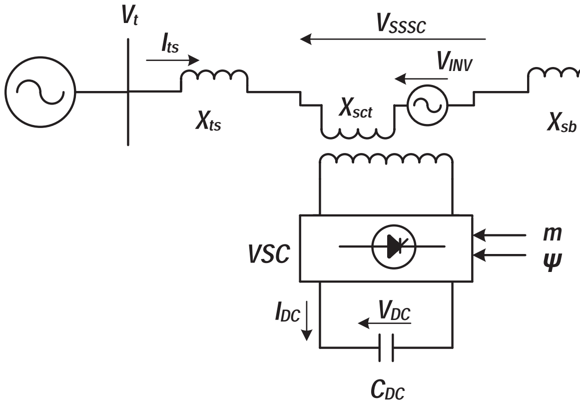

Fig. 1. Single machine-infinite bus system model with SSSC

V_b is the infinite bus voltage, ω_o is the synchronous speed. δ and ω are the rotor angle and speed, respectively. P_m and P_e are the input and output powers of the generator, respectively M and D are the inertia constant and damping coefficient, respectively E'_q is the internal voltage, E_{fd} is the excitation voltage, and V_{ref} is the reference voltage. X_d and X'_d are the d-axis reactance and the d-axis transient reactance of the generator, respectively. K_A and T_A are the gain and time constant of the excitation system, respectively. τ'_{do} is the open circuit field time constant. V_t is the terminal voltage. Also V_t can be expressed as:

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

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

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

Where Xq is the q-axis reactance of the generator.

2.2. Static Synchronous Series Compensator

The SSSC consists of a three-phase voltage source converter (V_{INV}), a boosting series coupling transformer with a leakage reactance of X_{SCT} and a DC capacitor (C_{DC}). The two input control signals to the SSSC are m and ψ. Where signal ψ is the phase of the injected voltage and is kept in quadrature with the line current (loss of the inverter is ignored), and signal m is the amplitude modulation ratio of the Pulse Width Modulation (PWM) based VSC, that determines the magnitude of the inserted voltage [13-15]. The dynamic model of SSSC to study power system stability is as follows [14]:

$$\overline{I_{ts}} = I_{tsd} + jI_{tsq} = I_{TS} \angle \phi \quad (9)$$

$$\overline{V}_{INV} = mkV_{DC} (\cos\psi + j\sin\psi) = mkV_{DC} \angle \psi \quad (10)$$

$$\psi = \phi \pm 90 \quad (11)$$

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}} (I_{tsd} \cos\psi + I_{tsq} \sin\psi) \quad (12)$$

Where k is the fixed ratio between AC and DC voltage of SSSC voltage source inverter. The constant values of equations of Generator, excitation system and SSSC have been represented in Table 1.

Table 1. System parameters

Generator	$M = 9.26 MJ/MVA$; $T'_{do} = 5.04\ s$; $D = 0$ $w_o = 120\pi\ rad/s$; $X_d = 0.97$; $X_q = 0.5$; $X'_d = 0.19$;
Excitation System	$K_A = 50$; $T_A = 0.05$;
SSSC Parameters and network	X_{total}=0.997, $V_{dc} = 1$; $C_{dc} = 1$; $V_t = 1$; $V_b = 1$;

3. Power System Linearized Model

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system as shown in Fig. 1 is given as follows:

$$\Delta\dot{\delta} = \omega_o \Delta\omega \quad (13)$$

$$\Delta\dot{\omega} = (\Delta P_m - \Delta P_e - D\Delta\omega) / M \quad (14)$$

$$\Delta\dot{E}'_q = (\Delta E_{fd} - (X_d - X'_d)\Delta i_{tsd} - \Delta E'_q) / \tau'_{do} \quad (15)$$

$$\Delta\dot{E}_{fd} = (K_A(\Delta V_{ref} - \Delta V_t + U_{pss}) - \Delta E_{fd}) / T_A \quad (16)$$

$$\Delta\dot{V}_{DC} = K_1\Delta\delta + K_2\Delta E'_q + K_3\Delta V_{DC} + K_4\Delta m + K_5\Delta\psi \quad (17)$$

$$\Delta I_{tsd} = K_6\Delta\delta + K_7\Delta E'_q + K_8\Delta V_{DC} + K_9\Delta m + K_{10}\Delta\psi \quad (18)$$

$$\Delta P_e = K_{11}\Delta\delta + K_{12}\Delta E'_q + K_{13}\Delta V_{DC} + K_{14}\Delta m + K_{15}\Delta\psi \quad (19)$$

$$\Delta V_t = K_{16}\Delta\delta + K_{17}\Delta E'_q + K_{18}\Delta V_{DC} + K_{19}\Delta m + K_{20}\Delta\psi \quad (20)$$

K_1, K_2, ..., K_{20} are linearization constants.

4. PSO algorithm

PSO algorithm was first proposed by Kennedy and Eberhart [16, 17] 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 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 [18]:

$$v_i(k+1) = wv_i(k) + r_1c_1\left[g_{besti} - x_i(k)\right] + r_2c_2\left[p_{besti} - x_i(k)\right] \quad (21)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (22)$$

Where v and x are the velocity and the position of each particle, respectively. 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 neighbors. Fig. 2 shows the flowchart of PSO algorithm.

5. PSO-based Output Feedback Controller Design

A power system can be described by a Linear Time Invariant (LTI) state-space model as follows:

$$\dot{X} = AX + BU \quad (23)$$

$$Y = CX \quad (24)$$

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

$$U = -HY \quad (25)$$

Where the gain vector H is $[h_1\ h_2]$ and the state vector Y is $[\Delta\omega\ \Delta V_t]^T$. The controller objective is to increase the damping of the critical modes to the desired level. In this paper, two control parameters of the SSSC (m-based and ψ-based) are modulated in order to damping controller design and are compared with the PSS [19].

The fitness function used in this paper for PSO algorithm is represented in (26). t_{sim} is the simulation time, $d\omega$ is the deviation of speed and dv_t is the deviation of the generator terminal voltage.

$$fitness = \int_0^{t_{sim}} t \times [|d\omega| + |dv_t|]dt \quad (26)$$

Table 2 shows the best parameters found in the PSO algorithm. Optimized parameters have been obtained when the input power of the generator has been changed10% at t=1 (sec) for six cycles. Fig. 3 shows the overall PSO method and how it interplays with the simulation model during the optimization.

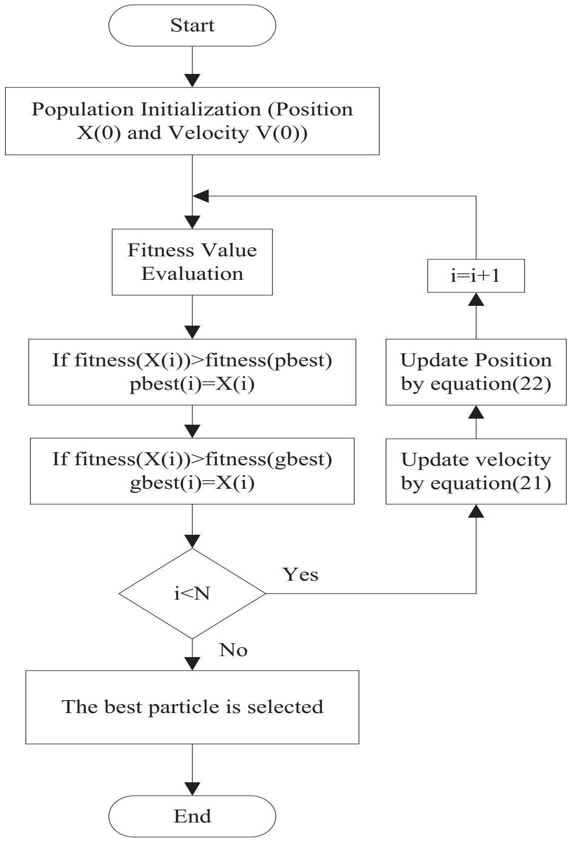

Fig. 2. Flowchart of the PSO algorithm

Table 2. Optimized values

Conditions	h_1	h_2
ψ-based controller	301.2	-82.5
m-based controller	-335.66	1.58
PSS based controller	-589.978	26.0214

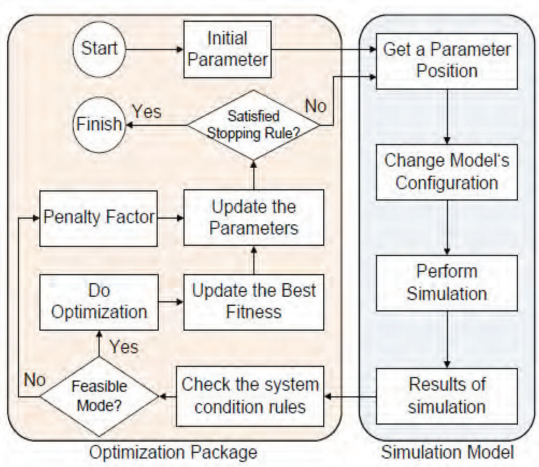

Fig. 3. Optimization method on stochastic simulation

6. Simulation Results

The simulation studies and the optimization of the output feedback controller parameters are performed in MATLAB. The aims of designing process of the output feedback controllers for PSS and SSSC are as follows:

a) Fast damping ratio of electromechanical modes,
b) Reduces the system responses overshoots, undershoots, settling times,
c) Improves the system damping characteristics.

Fig. 4 and Fig. 5 show system dynamic responses for 10% disturbance on the mechanical generator power input. The figures show terminal voltage variation, internal voltage variation, rotor angle variation and rotor speed variation, respectively. The following four modes are compared in each of the figures; With output feedback ψ- based controller, With output feedback m- based controller, With output feedback PSS based controller and Without controller.

The eigenvalues of power system with and without the proposed controllers are shown in Table 3 for 4 modes. As considered in Table 3, the system with output feedback ψ-based controller is more stable.

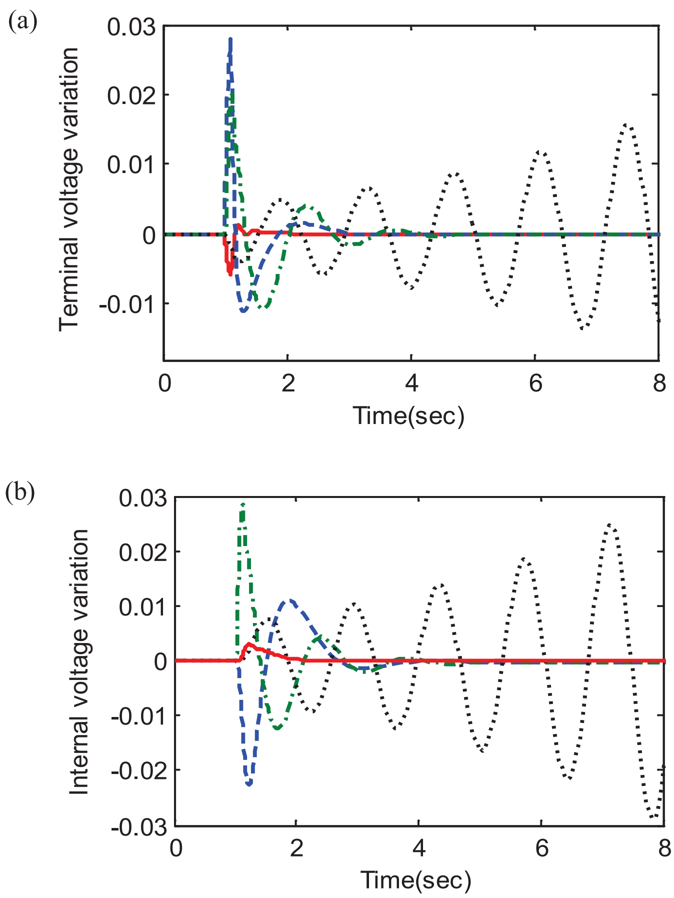

Fig. 4. system dynamic response for six cycles fault disturbance. (a) Terminal voltage variation, (b) Internal voltage variation, solid (ψ-based controller), dashed *(m- based* controller), dash-dotted (PSS based controller), dotted (none controller)

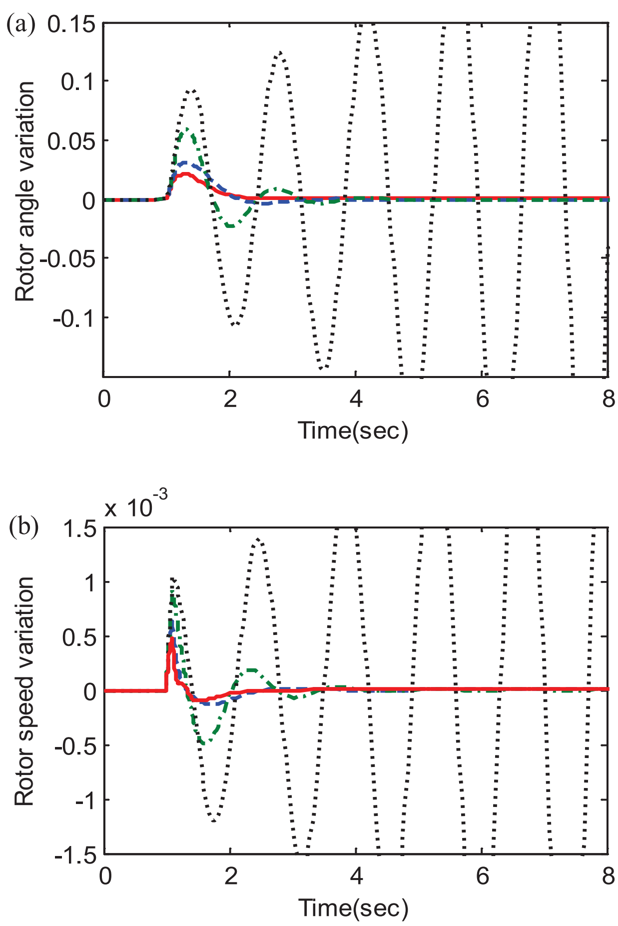

Fig. 5. System dynamic response for six cycles fault disturbance. , (a) Rotor angle variation, (b) Rotor speed variation, solid (ψ- based controller), dashed (m-based controller), dash-dotted (PSS based controller),dotted(none controller)

Table 3. Eigenvalues of the system

Controller mode	Eigenvalues
ψ-based controller	-9.7219 ± 9.8558i -3.2803 ± 3.2551i -0.0375
m-based controller	-14.1310 ± 8.1840i -1.9014 ± 2.5945i -0.0368
PSS based controller	-8.7545 ±63.9336i -1.3811 ± 4.4570i -0.0329
Without controller	-10.3418 ± 7.7583i 0.2068 ±4.4915i -0.0343

7. Conclusion

In this paper, the SMIB system with SSSC has been considered. The output Feedback controller has been designed for SSSC and PSS 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 four states; ψ-based controller, *m*-based controller, PSS controller and without controller. Then the dynamic responses of the generator for terminal voltage variation, internal voltage variation, rotor angle variation and rotor speed variation have been represented. Eigenvalues analysis exposes exceptional performances of the proposed controllers. The simulation results have been shown that the system composed with the proposed controller has a superior operation in fast damping of the oscillations of the power system. Moreover, the output feedback ψ-based damping controller is superior than both output feedback m-based controller and PSS based controller.

7. References

[1] M.R.S. Tirtashi, K. Mazlumi, M. Sadeghi, "TCPS Controller Design Using PSO and Chaos Algorithm to Damping the Power System Oscillations", *IEEE International Conference on Electrical Engineering Telecommunications and Information Technology,* pp.1191-1195, 2010.

[2] S. Sheetekela, K. Folly, O. Malik, "Design and Implementation of Power System Stabilizers based on Evolutionary Algorithms", *IEEE International Conference on Electrical Engineering*, pp. 1-6, 2009.

[3] S. Panda, "Multi-objective evolutionary algorithm for SSSC-based controller design", *International journal of Electric Power Systems Research*, 79, pp.937–944, 2009.

[4] Q. Liu, V. Vittal, N. Eli, "LPV Supplementary Damping Controller Design system for a Thyristor Controlled Series Capacitor (TCSC) Device", *IEEE Transactions on power systems*, vol. 21, no. 3, pp.1242-1249, 2006.

[5] R. Kuiava, R.V.de Oliveira, R.A. Ramos, N.G. Bretas, "Simultaneous Coordinated Design of PSS and TCSC Damping Controller control for Power Systems", *IEEE conference*, pp.1-8, 2006.

[6] M. M. Farsangi, Y. H. Song, K. Y. Lee, "Choice of FACTS device control inputs for damping inter area oscillations", *IEEE Transactions on Power Systems*, vol. 19, no.2, pp. 1135 – 1143, 2004.

[7] J.J. Paserba, "How FACTS controllers benefit AC transmission systems", *IEEE Power Engineering Society General Meeting*, vol. 2, pp. 1257 – 1262, 2004.

[8] N. Li, Y. Xu, H. Chen, "FACTS-based power flow control in interconnected power systems", *IEEE Transactions on Power Systems*, vol. 15, no.3, pp. 257 – 262, 2000.

[9] A. El-Zonkoly, "Optimal sizing of SSSC controllers to minimize transmission loss and a novel model of SSSC to study transient response", *International journal of Electric Power Systems Research*, 78, pp.1856–1864, 2008.

[10] W. Qiao, R.G. Harley, G.K. Venayagamoorthy, "Fault-Tolerant Optimal Neurocontrol for a Static Synchronous Series Compensator Connected to a power network", *IEEE Transactions on industry applications,* vol. 44, no. 1, pp.74-84, 2008.

[11] J.y.P. Wang, D.R. Hur, H.H. Chung, N.R. Watson, J. Arrillaga, S.S. Matair, "A Genetic Algorithms Approach to Design an Optimal PI Controller for Static Var Compensator", *IEEE International Conference on Electrical Engineering,* pp.1557-1562, 2000.

[12] A. Ajami, M. Armaghan, "Application of Multi-Objective PSO Algorithm for Power System Stability Enhancement by Means of SSSC", *International Journal of Computer and Electrical Engineering*, vol. 2, no. 5, pp. 838 – 845, 2010.

[13] H.F. Wang, "Design of SSSC Damping Controller to Improve Power System Oscillation Stability", *IEEE International Conference on Electrical Engineering*, pp.495-500, 1999.

[14] S. Khani, M. Sadeghi, S.H. Hosseini, "Optimal Design of SSSC Damping Controller to Improve Power System Dynamic Stability Using Modified Intelligent Algorithms", *IEEE International Conference on Power Electronic and Drive Systems and Technologies*, pp.393-397, 2010.

[15] A.Kazemi, M. ladjevardi, M.A.S. Masoum, "Optimal selection of SSSC Based Damping controller parameters for improving power system dynamic stability using genetic algorithm", *Iranian Journal of Science & Technology, Transaction B, Engineering*, vol. 29, no. B1.2005.

[16] Sh. Miyuan, W. Juan, P. Danni, "Particle Swarm and Ant Colony Algorithms Hybridized for Multi-mode Resource-constrained Project Scheduling Problem with Minimum Time Lag", *IEEE International conference*, pp5898-5902, 2007.

[17] J. Kennedy, R.C. Eberhart, "Particle swarm optimization", *Proc. IEEE International Conference on neural networks,* vol. 4, pp. 1942-1948, 1995.

[18] L. Zhao, Y. Yang, "PSO-based single multiplicative neuron model for time series prediction", *International journal of Expert Systems with Applications*, pp. 2805–2812, 2009.

[19] H. Shayeghi, H.A. Shayanfar, S. Jalilzadeh, A. Safari, "Design of output feedback UPFC controller for damping of electromechanical oscillations using PSO", *International journal of Energy Conversion and Management*, 50, pp.2554–2561, 2009.