Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Optimal Coordination of Multiple ESS-based Stabilizers and PSS in Multi-machine Power System for Damping Improvement

Linjun Shi,* Jiajia Zhou,* Lei Zhang, Kwang Y. Lee*****

**College of Energy and Electrical Engineering, HoHai University, Nanjing, 210098 China (Tel: 086-015301590009; e-mail:shilj_hhu@ 163.com).*
*** Jiangsu Electric Power Company, Nanjing 210024 China (e-mail:jslszl@163.com)*
**** Department of Electrical & Computer Engineering, Baylor University, Waco, TX, USA, (Tel: (254) 710-4188; e-mail: Kwang_Y_Lee@baylor.edu)*

Abstract: This paper proposes to optimally coordinate multiple Energy Storage System (ESS) based stabilizers and Power System Stabilizers (PSS) to increase damping in a multi-machine power system using an improved particle swarm optimization (IPSO). The IPSO has the strong and global searching ability and high efficiency by applying chaos initialization and simulated annealing (SA) algorithm in iteration. All eigenvalues, including both electromechanical and non-electromechanical modes, that meet the stability requirements in a wide range of operating conditions have been included in the objective function. In the 4-machine power system, the power system oscillations are effectively suppressed at different operating conditions by multiple ESS-based stabilizers and PSSs coordinated by IPSO, where the damping effect is better with the stabilizers designed by the IPSO than with the stabilizers tuned individually by the conventional compensation method. The results show the validity, robustness and superiority of the IPSO design.

Keywords: Power system oscillation stability; Energy Storage System (ESS); Power System Stabilizer (PSS); Particle Swarm Optimization (PSO); Chaos algorithm; Simulated Annealing (SA) algorithm

1. INTRODUCTION

With the development of power electronics technology and material, Energy Storage System (ESS) applied to power system has attracted much attention in recent years, especially the application of ESS in the field of power system oscillation stability (Du et al., 2009; Li et al., 2006; Shi et al. 2010). In addition to the Power System Stabilizer (PSS) and FACTS-based stabilizer, ESS-based stabilizer is an alternative way to suppress power system oscillations. While using both ESS-based stabilizer and PSS, coordination should be established between them in order not to interfere with the performance and nor to cause system instability, which is similar to the coordination of FACTS-based stabilizer and PSS (Zhao et al., 2004).

Many intelligent optimization algorithms for coordination among stabilizers have been presented in the literature. Abido used genetic algorithm, particle swarm optimization (PSO), simulated annealing (SA) and tabu search algorithm to coordinate and optimize stabilizers (Abido, 2000a, 2000b, 2002, 2006). A PSS parameter optimization method based on evolutionary strategy is proposed in multi-machine power system (Niu et al., 2004). The chaos optimization algorithm is applied to coordination control between the HVDC modulations and PSS in the literature (Zheng et al., 2010). These intelligent optimization algorithms can be used to reach the global extreme point in solving complex optimization with multiple extremes. As an intelligent optimization algorithm, the PSO algorithm can be used to optimally coordinate multiple ESS-based stabilizers and PSS for damping control.

The PSO has many advantages, such as few parameters, simple coding and easy implementation. But the PSO also has some disadvantages, such as low efficiency, slow speed of constringency and easy trap in local optima. In order to overcome these shortcomings, the improved PSO algorithm (IPSO) is proposed in this paper which takes chaos algorithm and SA algorithm into consideration, and the IPSO is applied to coordinate the parameters of ESS-based stabilizers and PSS. All eigenvalues, including both electromechanical and non-electromechanical modes, that meet the stability requirements in a wide range of operating conditions have been included in the objective function. In the 4-machine power system, the power system oscillations are effectively suppressed at different operating conditions by the ESS-based stabilizers and PSS tuned by IPSO. The damping effect is better with the stabilizers designed by IPSO than with the stabilizers designed individually. The results show the validity, robustness and superiority of the IPSO design.

2. PROBLEM DESCRIPTION

2.1 Linear Model of Power System with ESS

For description purpose, ESS is represented by Flywheel Energy Storage System (FESS) (See Fig. 1). The energy of the FESS is stored in the rotation of the rotor. Regulating the speed of the flywheel, energy exchange between FESS and systems can be realized through the generator/motor (Zhang et al., 2003). FESS with doubly-fed induction machine has been represented by a third-order model (Akagi et al., 2002; Shi, et al., 2010). And additional stabilizers can be added in the FESS's active and reactive power control loops to suppress power system oscillations.

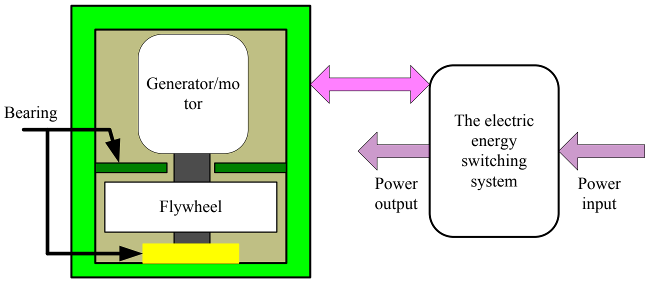

Fig. 1. A configuration of FESS.

From FESS model, generator model and other power system model, the full system linear model with FESS can be obtained as follows (Wang et al., 2003):

$$\begin{aligned} \Delta\dot{X} &= A\Delta X + \sum_{l=1}^{L} B_l \Delta u_l \\ \Delta y_l &= C_l \Delta X \end{aligned} \tag{1}$$

where L is the number of stabilizers, including FESS-based stabilizers and PSSs, ΔX is the state vector, A is the state matrix, B_l and C_l are the coefficient vectors, Δy_l is the deviation of the l-th output, and Δu_l is the deviation of the l-th stabilizer's output.

The transfer function of stabilizer (PSS or FESS-based stabilizer) can be expressed as (Kundur, 1994):

$$\Delta u_l = G_l(s)\Delta y_l$$

$$G_l(s) = K_l \frac{sT_{5l}}{1+sT_{5l}} \frac{1+sT_{1l}}{1+sT_{2l}} \frac{1+sT_{3l}}{1+sT_{4l}} \tag{2}$$

where K_l is gain, and T_{il}, i =1, 2, …, 5, are time constants.

Referring to (1) and (2), the whole power system linear stabilizer model can be obtained.

2.2 Objective Function

Generally, the objective functions only consider the damping ratios of electromechanical oscillation modes. In fact, the system stability is not depending only on electromechanical oscillation modes. It is observed that non-electromechanical oscillation modes and other eigenvalues are also affecting system stability. Thus, all eigenvalues, including both electromechanical and non-electromechanical modes, that meet the stability requirements in a wide range of operating conditions have been selected as the objective function. This leads to the objective function defined as follows:

$$\boldsymbol{J} = \sum_{p=1}^{N_p} \begin{pmatrix} a_p \sum\limits_{\forall \sigma_{q,p} > \sigma_0} (\sigma_{q,p} - \sigma_0) + \\ b_p \sum\limits_{\forall \xi_{q,p} < \xi_0} (\xi_0 - \xi_{q,p}) + \\ c_p \sum\limits_{\forall \xi_{nq,p} < \xi_{n0}} (\xi_{n0} - \xi_{nq,p}) \end{pmatrix} \tag{3}$$

Where:

N_p The number of operating conditions.

$\sigma_{q,p}$ The real part of the q electromechanical mode under the p operating condition.

$\xi_{q,p}$ The damping ratio of the q electromechanical mode under the p operating condition.

$\xi_{nq,p}$ The damping ratio of the nq non-electromechanical oscillation mode under the p operating condition.

$\sigma_0, \xi_0, \xi_{n0}$ Objective values.

a_p, b_p, c_p Weights.

The constraint is to ensure that the real part of all eigenvalues is negative, as well as the range of the parameters to be optimized:

$$\begin{aligned} &\boldsymbol{Min} \quad \boldsymbol{J} \\ &s.t. \begin{cases} Re(\boldsymbol{\lambda}) < 0 \\ K_{\min} \le K_l \le K_{\max} \\ T_{1\min} \le T_{1l} \le T_{1\max} \\ T_{2\min} \le T_{2l} \le T_{2\max} \end{cases} \end{aligned} \tag{4}$$

where $\boldsymbol{\lambda}$ is a vector of all eigenvalues. Generally, the time constants can be set as T_{1l}=T_{3l} and T_{2l}=T_{4l}. Thus, there are three parameters to be optimized in each stabilizer, namely gain K_l, and time constants T_{1l} and T_{2l}. According to (3) and (4), the coordination problem of the ESS-based stabilizers and PSS parameters can be transformed into a constrained optimization problem.

3. THE IMPROVED PSO

3.1 PSO Algorithm

PSO algorithm was first proposed by Kennedy and Eberhart in 1995 (Kennedy et al., 1995). The algorithm began as a simulation of the predatory behaviour of birds flocking, where each agent, according to its own flying experience and that of its neighbours, constantly modifies its flight direction and velocity, and ultimately approaches to the global best position through the whole searching space. In the PSO algorithm, the particle i can be expressed by a d-dimensional position vector $\boldsymbol{x}_i$, and the velocity vector $\boldsymbol{v}_i$. The position corresponding to the best fitness is called as p_{best} and the overall best out of all the particles in the population is called g_{best}. At each iteration the velocities of the individual particles are updated according to the best position of the particle itself and the neighbourhood best position. The particle swarm optimizer adjusts velocities and positions by the following equations:

$$\boldsymbol{v}_i(k+1)=\omega\boldsymbol{v}_i(k)+c_1r(\boldsymbol{p}_{\text{best},i}(k)-\boldsymbol{x}_i(k))+ c_2r(\boldsymbol{g}_{\text{best}}-\boldsymbol{x}_i(k)) \quad (5)$$

$$\boldsymbol{x}_i(k+1)=\boldsymbol{x}_i(k)+\boldsymbol{v}_i(k+1) \quad (6)$$

where k is the iteration number, ω is the inertia weight, c_1 and c_2 are the acceleration constants, r is the random number uniformly generated from [0,1], i=1,2,…, M, and M is the number of particles.

3.2 The Improved PSO Algorithm

1) Initialized by chaos algorithms

In order to improve the quality of the initial particles, the chaos algorithm is applied to the PSO algorithm. Chaos is a typical phenomenon in the non-linear system. It seems messy, but it contains interesting rules. As a matter of fact, due to its randomness and ergodicity, it can travel though all states without repetition in a certain range in accordance with its own laws. Thus, using these chaotic characteristics in the optimization is undoubtedly superior to other random searches (Zheng et al., 2010). The simplest chaotic system is Logistic chaotic system (Caponetto et al., 2003), with the iterative equation:

$$u(k+1)=\mu u(k)(1-u(k)) \quad (7)$$

Here μ is a control parameter in the range of $(2,4]$. When μ =4 and $0 \le u(0) \le 1$, the Logistic is completely in a chaotic state and the resulting sequence $\{u(k)\}$ is called chaotic variable. The chaotic system shown in (7) is applied for particle initialization to improve the quality of initial particles.

2) Limit position update by SA

SA algorithm (Abido, 2000a) is from a physical annealing process, which is introduced into the PSO to limit the position update in (6) so as to enhance the global search capability. Its basic idea is to start from a given solution, and then randomly generate another solution in the field. The acceptance criterion aims to allow the objective function J deteriorate in a limited range, and accept the new solution in a certain probability. The steps in detail are as follows:

a) Initialize the SA algorithm's starting temperature T, annealing temperature T_0 and termination rate α.

b) When particles' new position is updated by (6) , it is confined by the SA algorithm. ΔE is the difference in the objective function J after and before the position update by (6). If $\Delta E < 0$, the new position is accepted. If $\Delta E \ge 0$ and $\exp(\Delta E/T) > rand(0,1)$ ($rand(0,1)$ represents a random value between 0 and 1), the new location is accepted, otherwise the new position is not accepted.

c) If the new position is accepted and $T > T_0$, T should be cooled as $T = \alpha T$. If $T = T_0$, the procedure stops.

In this way, not only it can accomplish the limit in position, but also improve global search ability as a result of allowing deterioration with a certain probability and the possibility to escape from a local extreme at the same time.

3) The flow chart of IPSO

Fig. 2 shows the flow chart of the IPSO algorithm for coordination and tuning of the ESS-based stabilizers and PSSs.

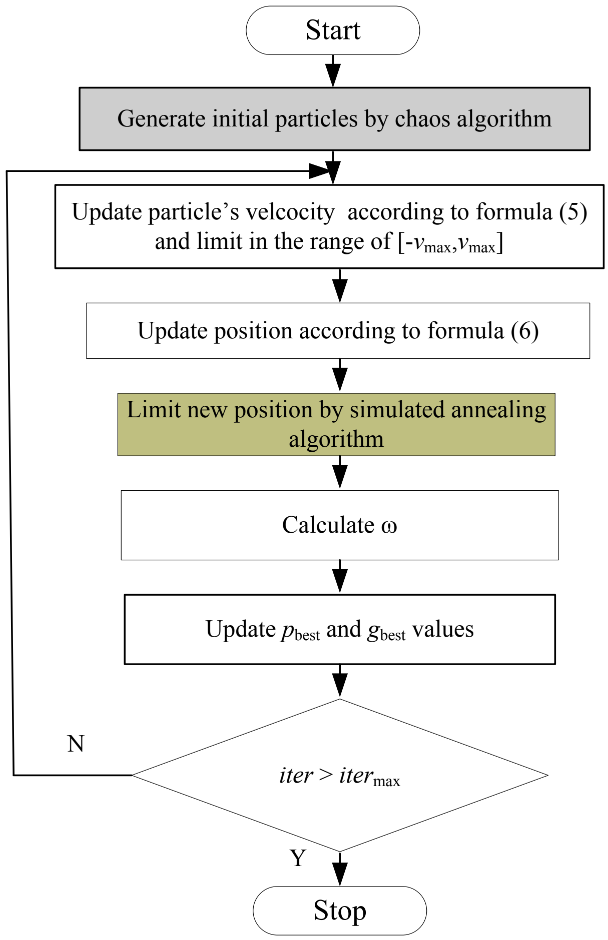

Fig. 2. Flow chart of the IPSO algorithm.

4. SIMULATION RESULTS

Fig. 3 shows the 4-machine power system (see for example Kundur, 1994). The 2 FESSs are respectively installed at nodes 7 and 9 and the capacities are both 10MVA.

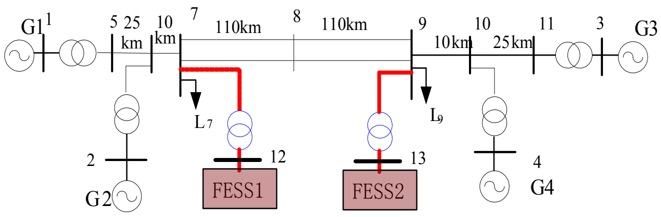

Fig. 3. Four-machine power system with 2 FESSs.

According to the different power flow between buses 7 and 8, the system is divided into four kinds of operating conditions, which is $\Phi(\mu)=\{\mu_1(P_{78} = 419\text{MW}), \mu_2(P_{78} = 200\text{MW}), \mu_3(P_{78} = -200\text{MW}), \mu_4(P_{78} = -400\text{MW})\}$. Without any PSS and ESS-based stabilizers, the system enters into instability by small-disturbance (Shi et al., 2010).

The stabilizers are equipped both with active and reactive power control loops. So there are 4 ESS-based stabilizers. The PSSs are installed in generators G2 and G4. For comparison, the coordination method with the IPSO and the tuning method with phase compensation (Yu, 1985) are both applied to tune the parameters of ESS-based stabilizers and PSSs.

There are 6 stabilizers and 18 parameters in total to be optimized by IPSO. The results of the optimized parameters are shown in Table 1. The results of eigenvalue after optimization in 4-machine power system are shown in Table 2.

Table 1. The optimized parameters

Stabilizer location	K_l	T_{l1}	T_{l2}
G2	11.884 3	0.472 1	0.174 8
G4	26.457 4	0.648 3	0.425 1
$\text{FESS1}_{\text{active}}$	0.644 2	0.687 6	0.112 1
$\text{FESS1}_{\text{reactive}}$	4.833 2	0.238 4	0.465 2
$\text{FESS2}_{\text{active}}$	7.608 7	0.134 2	0.532 2
$\text{FESS2}_{\text{reactive}}$	6.043 9	0.065 3	0.584 0

Table 2. Eigenvalues and damping ratios with coordinated stabilizers

$\Phi(\mu)$	Item	Electromechanical modes		
μ_1	eigenvalue	-1.106 5± j3.780 6	-1.562 6± j6.288 3	-1.577 1± j6.505 6
	damping ratio	0.241	0.236	0.281
μ_2	eigenvalue	-0.873 2± j4.009 6	-1.300 3± j5.982 3	-1.437 8± j6.320 6
	damping ratio	0.213	0.212	0.222
μ_3	eigenvalue	-1.002 1± j4.003 3	-1.286 2± j6.083 2	-1.436 3± j6.121 1
	damping ratio	0.243	0.207	0.228
μ_4	eigenvalue	-0.976 1± j3.844 2	-1.213 2± j6.100 3	-1.478 6± j6.208 2
	damping ratio	0.246	0.195	0.232

In order to validate the efficiency of IPSO algorithm, the comparison between the IPSO and the adaptive particle swarm optimization (APSO) algorithm (Sridhar et al., 2009) is shown in Fig. 4. The figure shows that the IPSO is better than the APSO in the quality of initial particles and convergence speed.

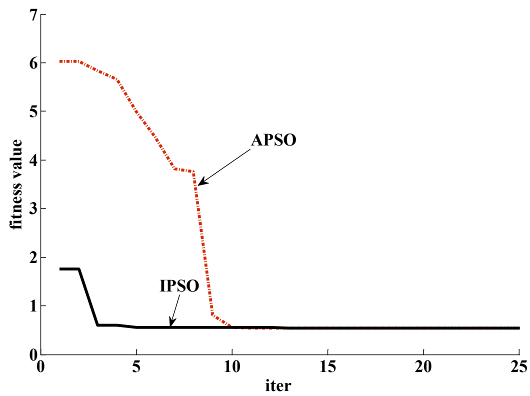

Fig. 4. Comparison of IPSO and APSO.

The 6 stabilizers also can be tuned by the compensation method individually under the operating condition μ_1. For comparison, the design damping ratio is the maximum of Table 2. The results of the parameters tuned by the compensation method individually are shown in Table 3. In Table 3, T_{l2} is preset. The results of eigenvalues and damping ratios after tuned by the compensation method individually are shown in Table 4.

Table 3. The parameters tuned by the compensation method individually

Stabilizer location	K_l	T_{l1}	T_{l2}
G2	20.078 2	0.053 2	0.02
G4	19.652 1	0.054 7	0.02
$\text{FESS1}_{\text{active}}$	1.215 6	0.373 2	0.05
$\text{FESS1}_{\text{reactive}}$	7.785 4	0.212 4	0.30
$\text{FESS2}_{\text{active}}$	10.521 3	0.250 2	0.50
$\text{FESS2}_{\text{reactive}}$	16.120 8	0.053 0	0.50

Table 4. Eigenvalues and damping ratios with stabilizers tuned by the compensation method

Φ(μ)	Item	Electromechanical modes		
μ_1	eigenvalue	-0.467 1± j3.950 1	-0.998 2± j6.206 1	-1.049 0± j6.349 7
	damping ratio	0.117	0.1588	0.163
μ_2	eigenvalue	-0.497 2± j3.943 6	-1.194 1± j5.809 7	-1.258 1± j6.303 1
	damping ratio	0.125	0.201	0.196
μ_3	eigenvalue	-0.496 2± j3.944 2	-1.028 2± j6.197 8	-1.296 7± j6.320 2
	damping ratio	0.125	0.201	0.164
μ_4	eigenvalue	-0.416 6± j3.783 7	-0.948 7± j6.166 6	-1.075 0± j6.440 0
	damping ratio	0.109	0.152	0.164

From Table 2 and Table 4, both methods can effectively suppress the power system oscillations. However, the compensation method is much worse than the coordination method because the compensation method used individually is lacking the interaction aspects among parameters. Therefore, the coordination method with the IPSO has advantage over the compensation method.

To validate the performance of the stabilizers a three-phase short circuit fault is applied at node 8 in 0.2s, and cleared after 0.1s. The nonlinear simulation results are shown in Figs. 5-7.

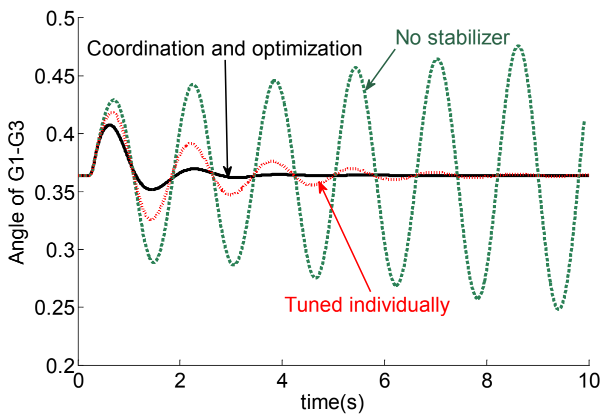

Fig. 5. Angle swing curves between generators G1 and G3.

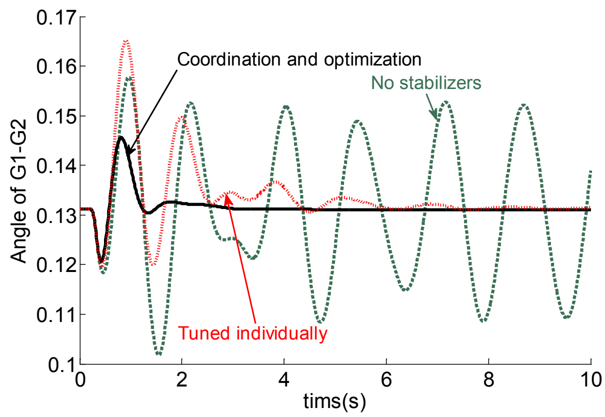

Fig. 6. Angle swing curves between generators G1 and G2.

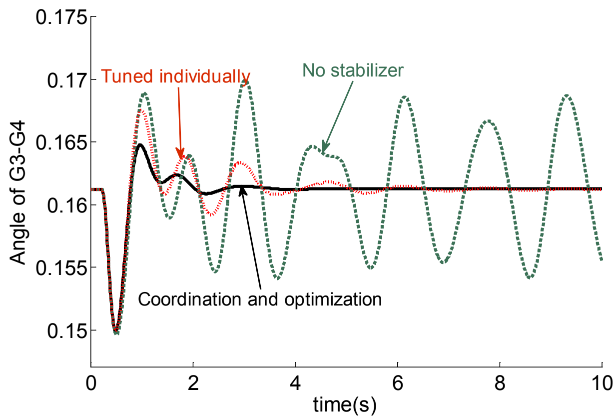

Fig. 7. Angle swing curves between generators G3 and G4.

As shown in Figs. 5-7, the coordination method by IPSO has better damping effect than the compensation method, which shows the advantage of the coordination method optimized by the IPSO. Thus, the 4-machine power system example illustrates the validity, robustness and superiority of the IPSO design, which can coordinate and optimize the ESS-based stabilizers and PSS parameters to suppress power system oscillations.

5. CONCLUSIONS

The paper has presented the IPSO algorithm to coordinate and optimize the parameters of ESS-based stabilizers and PSS, and draw the following conclusions:

a) The efficiency and global search capability of IPSO algorithm have been improved by the application of chaos algorithm in initialization and the SA algorithm in iteration.

b) The effectiveness and robustness of the algorithm have been demonstrated since various operating conditions and all eigenvalues are considered in the objective function.

c) Comparing with designing stabilizers individually with compensation method, the stabilizers coordinated and optimized by the IPSO algorithm are superior.

REFERENCES

Abido, M. A. (2000a). Pole placement technique for PSS and TCSC-based stabilizer design using simulated annealing. *Electrical Power and Energy Systems*, 22:543-554.

Abido, M. A., Abdel-Magid, Y. L. (2000b). Robust design of multi-machine power system stabilisers using tabu search algorithm. *IEE Proceedings Generation Transmission and Distribution*, 147(6): 387-394.

Abido, M. A. (2002). Optimal design of power system stabilizers using particle swarm optimization. *IEEE Transmission on energy conversion*, 17 (3):406-413.

Abido, M..A. (2006). Design of PSS and STATCOM-based damping stabilizers using genetic algorithms. *IEEE Power Engineering Society General Meeting*, Montreal, Que, pp:1-8.

Akagi, H. S., (2002), Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system. *IEEE Trans. Power Elect*., 17(1):109–116.

Caponetto, R., Fortuna, L., Fazzino, S., Xibilia, M.G. (2003). Chaotic sequences to improve the performance of evolutionary algorithms. *IEEE Transactions on Evolutionary Computation*, 7(3):289-304.

Du, W., Wang, H. F., Xiao, L., Dunn, R. (2009). The capability of energy storage systems to damp power system oscillations. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 223(4): 759-772.

Kundur, P. (1994). *Power System Stability and Control.* McGraw-Hill Professional, New York.

Kennedy, J., Eberhart, R. C. (1995). Particle swarm optimization. *Proceedings of the IEEE International Conference on Neural Networks*, Perth，Australia，pp: 1942-1948.

Li, G., Cheng, S., Wen, J., Pan, Y. (2006). Power system stability enhancement by the flexible power conditioner. Proceedings of the CSEE, 26(23):1-6.

Sridhar, M., Vaisakh, K., Murthy, K.S.L. (2009). Adaptive PSO based tuning of PID-fuzzy and SVC-PI Controllers for dynamic stability enhancement: a comparative analysis. *Second International Conference on Emerging Trends in Engineering and Technology*, *ICETET-09*, pp:985-990.

Niu, Z., Du, Z., Fang, W., Xia, D. (2004). Parameter optimization of multi-machine power system stabilizers using evolutionary strategy. *Proceedings of the CSEE,* 24(2):22-27.

Shi, L., Chen, Z., Wang, H., Tang G. (2010). Damping of power system low-frequency oscillations with FESS. *Automation of Electric power systems*, 34(8): 29-33.

Wang, X., Fang, W. (2003). *Modern power system analysis*. Science Press, Beijing.

Yu, Y. N. (1985). *Electric Power System Dynamics*. Water Power Press, Beijing.

Zhang, J., Huang, L., Chen, Z. (2003). Research on flywheel energy storage system and its controlling technique. *Proceedings of the CSEE*, 23(3): 108-111.

Zhao, S., Chang, X., He, R., Ma, Y. (2004). Borrow damping phenomena and negative damping effect of PSS control. *Proceedings of the CSEE*, 24(5):7-11.

Zheng, X., Li, X., Wang, Y. (2010). Coordination and optimization of PSS and HVDC modu-lations using chaotic optimization algorithm. *Transactions of China Electrotechnical Society*, 25(5): 170-175.