Journal of Artificial Intelligence in Electrical Engineering, Vol. 1, No. 1, June 2012

A PSO-Based Static Synchronous Compensator Controller for Power System Stability Enhancement

Meisam Mahdavi [1], Ali Nazari [2], Vahid Hosseinnezhad [3], Amin Safari [2]
1. School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran
Email: me.mahdavi@ut.ac.ir (Corresponding author)
2. Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
3. Sama Technical and Vocational Training Colleage, Islamic Azad University, Khoy Branch, Khoy, Iran.

ABSTRACT
In this paper Power system stability enhancement through static synchronous compensator (STATCOM) based controller is investigated. The potential of the STATCOM supplementary controllers to enhance the dynamic stability is evaluated. The design problem of STATCOM based damping controller is formulated as an optimization problem according to the eigenvalue based objective function that is solved by a particle swarm optimization (PSO) algorithm. The controllers are tuned to simultaneously shift the lightly damped and un-damped electro-mechanical modes of machine to a prescribed zone in the s-plane. The results analysis reveals that the designed PSO based STATCOM damping controller has an excellent capability in damping the power system low frequency oscillations and enhance greatly the dynamic stability of the power system.

KEYWORDS: STATCOM, Particle swarm optimization, damping controller, Dynamic stability.

1. INTRODUCTION

Intensive progress in power electronics has enabled application of flexible AC transmission system (FACTS) devices in high voltage transmission networks. The main aim of FACTS devices is normally steady-state control of a power system but, due to their fast response, FACTS can also be used for power system stability enhancement through improved damping of power swings [1]. Static synchronous compensator (STATCOM) is a member of FACTS family that is connected in shunt with the system. It replaces the bulky reactive elements of conventional static var compensator (SVC) by a solid-state synchronous voltage source. The STATCOM is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. Several trials have been reported in the literature to dynamic models of STATCOM in order to design suitable controllers for power flow, voltage and damping controls [2, 3]. Wang [4] presents the establishment of the linearized Phillips–Heffron model of a power system installed with a STATCOM. Wang has not presented a systematic approach for designing the damping controllers. Further, it seems no effort have been made to identify the most suitable STATCOM control parameter, in order to arrive at a robust damping controller. Intelligent controllers have the potential to overcome the above-mentioned problems. Fuzzy-logic-based controllers have, for example, been used for controlling a STATCOM [5]. The performance of such controllers can further be improved by adaptively updating their parameters. Although using the robust control methods [6], the uncertainties are directly introduced to the synthesis, but due to the large model order of power systems the order resulting controller will be very large in general, which is not feasible because of the computational economical difficulties in implementing. The PSO algorithm can be used to solve many of the same kinds of problems as GA and does not suffer from of GA's difficulties. The PSO is a novel population based meta heuristic, which utilize the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as a useful tool for engineering optimization. Unlike the other heuristic techniques, it has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. This algorithm has also been found to be robust in solving problems featuring non-linearing, non-differentiability and high-dimensionality [7-11].

In this study, the problem of robust STATCOM based damping controller design is formulated as an optimization problem and PSO technique is used to solve it. The aim of the optimization is to search for the optimum controller parameter settings that improve the dynamic system performance. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis and nonlinear time-domain simulation studies to damp low frequency oscillations under different operating conditions. Results evaluation shows that the proposed damping controller achieves good robust performance for a wide range of operating conditions and disturbance.

2. OVERVIEW OF PARTICLE SWARM OPTIMIZATION

The PSO method is a population-based one and is described by its developers as an optimization paradigm, which models the social behavior of birds flocking or fish schooling for food. Therefore, PSO works with a population of potential solutions rather than with a single individual [7]. Its key concept is: potential solutions are flown through hyperspace and are accelerated towards better or optimum solutions. Its paradigm can be implemented in simple form of computer codes and is computationally inexpensive in terms of both memory requirements and speed. The higher dimensional space calculations of the PSO concept are performed over a series of time steps. The population is responding to the quality factors of the previous best individual values and the previous best group values. It has also been found to be robust in solving problem featuring non-linearing, non-differentiability and high-dimensionality [8-10].

The PSO starts with a population of random solutions "particles" in a D-dimension space.

The ith particle is represented by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle i (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$. The global version of the PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population. The PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to Eq. (1). The velocity of particle i is represented as $V_i = (v_{i1}, v_{i2} \ldots v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest. The position of the ith particle is then updated according to Eq. (2) [11]:

$$v_{id} = w \times v_{id} + c_1 \times rand() \times (P_{id} - x_{id}) + c_2 \times rand() \times (P_{gd} - x_{id}) \tag{1}$$

$$x_{id} = x_{id} + cv_{id} \tag{2}$$

Where, P_{id} and P_{gd} are *pbest* and *gbest*. The positive constants c_1 and c_2 are the cognitive and social components that are the acceleration constants responsible for varying the particle velocity towards *pbest* and *gbest*, respectively. Variables r_1 and r_2 are two random functions based on uniform probability distribution functions in the range [0, 1]. The use of variable w is responsible for dynamically adjusting the velocity of the particles, so it is responsible for balancing between local and global searches, hence requiring less iteration for the algorithm to converge [7]. The following weighting function w is used in Eq. (1):

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter\_\max} iteration \tag{3}$$

Where, *iter_max* is the maximum number of iterations and *iteration* is the current number of iteration. The Eq. (3) presents how the inertia weight is updated, considering w_{max} and w_{min} are the initial and final weights, respectively [10]. Figure 1 shows the flowchart of the PSO algorithm.

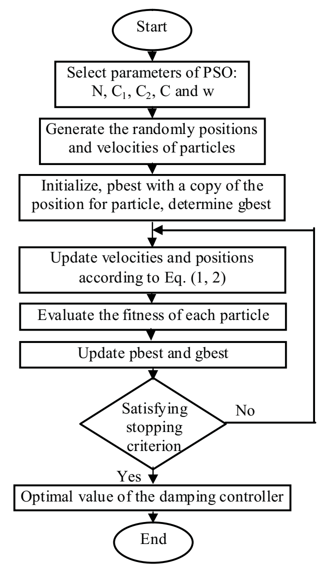

Fig.1. Flowchart of the proposed PSO technique

3. DESCRIPTION OF CASE STUDY NETWORK

Figure 2 is a single machine infinite bus power (SMIB) system installed with a STATCOM. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a STATCOM. The system data is given in the Appendix. The system consists of a step down transformer (SDT) with a leakage reactance XSDT, a three-phase GTO-based voltage source converter, and a dc capacitor [4].

The VSC generates a controllable AC voltage source $v_o(t) = V_0 \sin(wt - \varphi)$ behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage, $v_L(t)$

and $v_0(t)$ produces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude V_0 and the phase φ. The dynamic relation between the capacitor voltage and current in the STATCOM circuit are expressed as [4]:

$$\bar{I}_{Lo} = I_{Lod} + jI_{Loq} \tag{4}$$

$$V_o = cV_{dc}(\cos\varphi + j\sin\varphi) = cV_{dc}\angle\varphi \tag{5}$$

$$\dot{V}_{dc} = \frac{I_{dc}}{C_{dc}} = \frac{c}{C_{dc}}(I_{Lod}\cos\varphi + I_{Loq}\sin\varphi) \tag{6}$$

Where for the PWM inverter $c=mk$ and k is the ratio between AC and DC voltage depending on the inverter structure, m is the modulation ratio defined by the PWM and the phase c is also defined by the PWM. The C_{dc} is the dc capacitor value and I_{dc} is the capacitor current while i_{Lod} and i_{Loq} are the d- and q-components of the STATCOM current, respectively.

The dynamics of the generator and the excitation system are expressed through a third order model given as [10]:

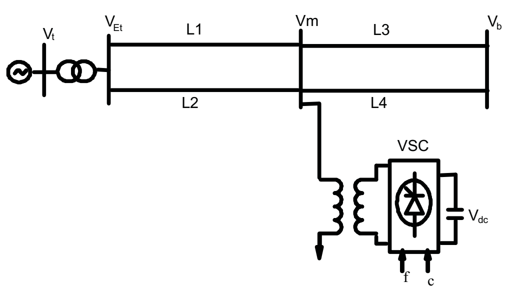

Fig.2. SMIB power system equipped with STATCOM.

$$\dot{\delta} = \omega_0(\omega - 1) \tag{7}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{8}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{9}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \tag{10}$$

The expressions for the power output, terminal voltage, and the d-q axes currents in the transmission line and STATCOM, respectively, are:

$$I_{tld} = \frac{(1+\frac{X_{LB}}{X_{SDT}})e'_q - \frac{X_{LB}}{X_{SDT}}mV_{dc}\sin\varphi - V_b\cos\varphi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1+\frac{X_{LB}}{X_{SDT}})x'_d} \tag{11}$$

$$I_{tlq} = \frac{\frac{X_{LB}}{X_{SDT}}mV_{dc}\cos\varphi + V_b\sin\varphi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1+\frac{X_{LB}}{X_{SDT}})x_q} \tag{12}$$

$$I_{Lod} = \frac{e'_q - (x'_d + X_{tL})I_{tLq} - mV_{dc}\sin\varphi}{X_{SDT}} \tag{13}$$

$$I_{Loq} = \frac{mV_{dc}\cos\varphi - (x'_d + X_{tL})I_{tLq}}{X_{SDT}} \tag{14}$$

Where, X_T, x'_d and x_q are the transmission line reactance, d-axis transient reactance, and q-axis reactance, respectively. 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:

$$\Delta\dot{\delta} = \omega_0\Delta\omega, \tag{15}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M, \tag{16}$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do}, \tag{17}$$

$$\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \tag{18}$$

$$\Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{dc}\Delta c + K_{d\varphi}\Delta\varphi, \tag{19}$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pdc}\Delta v_{dc} + K_{pc}\Delta c + K_{p\varphi}\Delta\varphi, \tag{20}$$

$$\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qdc}\Delta v_{dc} + K_{qc}\Delta c + K_{q\varphi}\Delta\varphi, \tag{21}$$

$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E_q^{/} + K_{vdc} \Delta v_{dc} + K_{vc} \Delta c + K_{v\varphi} \Delta\varphi, \quad (22)$$

K_1, K_2...K_9, K_{pu}, Kqu and K_{vu} are linearization constants. The block diagram of the linearized dynamic model of the SMIB power system with STATCOM is shown in Fig. 3.

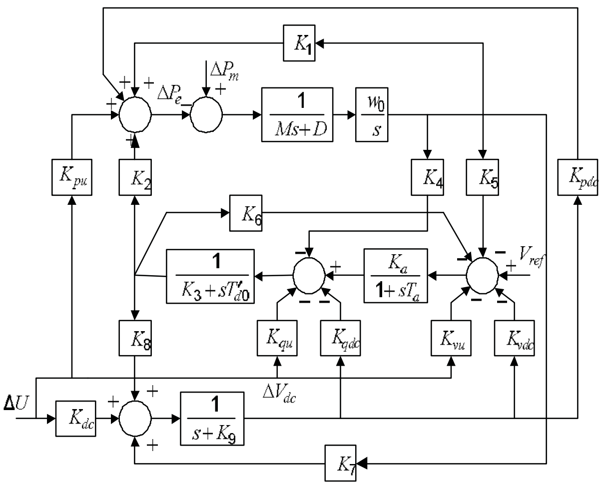

Fig.3. Modified Heffron–Phillips transfer function model.

4. STATCOM BASED DAMPING CONTROLLER DESIGN

The power oscillation damping (POD) controller is designed to produce an electrical torque in phase with the speed deviation according to phase compensation method. The structure of POD controller is given in Fig. 4. This controller may be considered as a lead-lag compensator. It comprises gain block, signal-washout block and lead-lag compensator. The block diagram of STATCOM dc voltage PI controller with power oscillation damping stabilizer is shown in Fig 5. The DC-voltage regulator controls the DC voltage across the DC capacitor of the STATCOM.

In the proposed method, we must tune the STATCOM controller parameters optimally to improve overall system dynamic stability. To increase the system damping to electromechanical modes, an eigenvalue-based objective function is considered as follows:

$$J = \sum_{j=1}^{NP} \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2 \quad (23)$$

Where, $\sigma_{i,j}$ is the real part of the ith eigenvalue of the jth operating point. The value of *NP* is the total number of operating points for which the optimization is carried out. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization. The proposed approach employs PSO to solve this optimization problem and searches for an optimal set of controller parameters. The optimization of controller parameters is carried out by evaluating the objective function as given in Eq. (23), which considers a multiple of operating conditions. The operating conditions are given in Table 1. Figure 6 illustrates the block diagram of STATCOM ac voltage PI controller with a power oscillation-damping stabilizer. In our implementation, the value of σ_0 is taken as −2.

In order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2, and c is chosen as 30, 7, 50, 2, 2 and 1, respectively. In addition, the inertia weight, *w*, is linearly decreasing from 0.9 to 0.4. The final values of the optimized parameters with objective function, *J,* are given in Table 2.

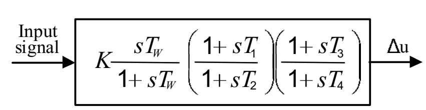

Fig.4. Power oscillation damping controller

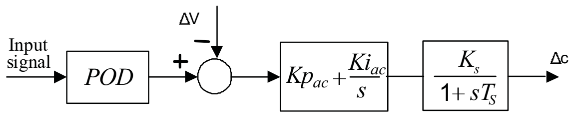

Fig. 5. STATCOM PI controller for dc voltage.

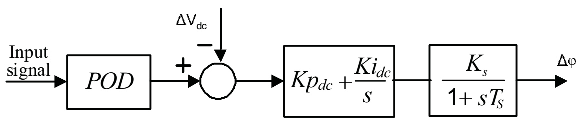

Fig. 6. STATCOM PI controller for dc voltage.

Table 1. Loading condition.

Lading condition	P_e(pu)	Q_e(pu)
Nominal	0.8	0.15
Light	0.2	0.01
Leavy	1.2	0.4

Table 2. Optimal parameters of the proposed controller.

Parameters	Type of controller	
	C	φ
K	98.54	181.44
T_1	0.375	0.13633
T_2	0.8765	0.16796
T_3	0.8889	0.043
T_4	0.4361	0.9368
Kp_{dc}	---	101.48
Ki_{dc}	---	0.4852
Kp_{ac}	2.276	---
Ki_{ac}	0.026	---

5. SIMULATION RESULTS

5.1. Eigenvalue analysis

The electromechanical modes and the damping ratios obtained for nominal and heavy operating conditions both with and without proposed controllers in the system are given in Table 3. When stabilizer is not installed, it can be seen that some of the modes are unstable (highlighted in Table 3). Moreover, it is also clear that the system damping with the proposed PSO based STATCOM damping controller is significantly improved.

Table 3. System eigenvalues with and without controller.

Type of controller	Nominal	Heavy
Without controller	**0.196 ± i3.389,-0.058** -97.87, -2.761, -0.066	**0.256 ± i4.49, -0.06** -3.3718, -96.643
C based controller	-3.68 ± i4.78, 0.609 -3.095, -1.404 -131.62, -0.1086	-30.91 ± i14.1, 0.90 -2.966, -1.316 -133.37, -0.1094
φ based controller	-5.712± i2.983, 0.886 -2.106 ± i3.964, 0.469 -2.62, -0.1013 -96.582	-5.908 ± i3.784, 0.84 -2.089 ± i3.73, 0.49 -2.623, -0.1012 -96.644

5.2. Nonlinear time domain simulation

In this section, the performance of the proposed controller under transient conditions is verified by applying a 6-cycle three-phase fault at t=1 sec, at the middle of the L_3 transmission line. Permanent tripping of the faulted line clears the fault. The system response to this disturbance is shown in Fig. 7. It can be seen that the proposed controller has good performance in damping low frequency oscillations and stabilizes the system quickly.

5. CONCLUSIONS

A method of designing a power oscillation-damping controller for a STATCOM has been proposed. The design problem of the controller is converted into an optimization problem, which is solved by a PSO technique. The robust design has been found to be very effective for a range of operating conditions of the power system. The eigenvalues analysis and nonlinear time domain simulation results show the robustness of the proposed controller and their ability to provide good damping of low frequency oscillations. Moreover, the φ-based stabilizer provides better damping characteristics and enhances greatly the first swing stability compared to the C-based stabilizer. Results demonstrate that the overshoot, undershoot, settling time and speed deviations of the machine are greatly reduced by applying the proposed methodology based tuned controller.

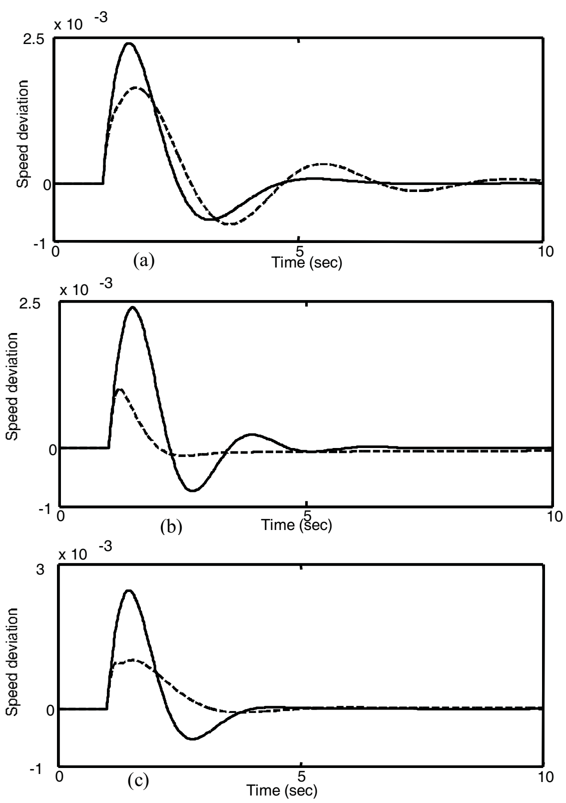

Fig.7. Speed deviation (Δω) at (a) Nominal (b) Light and (c) Heavy loading; Solid (φ based controller) and Dashed (C based controller).

APPENDIX

The nominal parameters are listed in Table 4.

Table4. System parameters

Generator	$M = 8$ MJ/MVA	$T'_{do} = 5.044$ s	$X_d = 1$pu
	$X_q = 0.6$p.u	$X'_d = 0.3$pu	$D = 0$
Excitation system	$K_a = 25$	$T_a = 0.05$s	
Transformers	$X_T = 0.1pu$	$X_{SDT} = 0.1\ pu$	
DC link parameter	$V_{DC} = 1pu$	$C_{DC} = 1pu$	
STATCOM parameter	$C = 0.25$	$\varphi = 52^{\circ}$	
	$K_s = 1$	$T_s = 0.05$	

REFERENCES

[1] J. Machowski and J. W. Bialek, "State variable control of shunt FACTS devices using phasor measurements," *Electric Power Systems Research*, Vol. 78, pp. 39-48, 2008.

[2] N.G Hingorani and L. Gyugyi, *Understanding FACTS: concepts and technology of flexible AC transmission systems*, Wiley-IEEE Press, 1999.

[3] M.A. Abido, "Analysis and assessment of STATCOM based damping stabilizers for power system stability enhancement," *Electric Power Systems Research*, Vol. 73, no. 3, pp. 177-185, 2005.

[4] H. F. Wang, "Phillips-Heffron model of power systems installed with STATCOM and applications," *IEE Proc. Generation Transmission and Distribution*, Vol. 146, pp. 521-527, 1999.

[5] S. Morris, P. K. Dash and K. P. Basu, "A fuzzy variable structure controller for STATCOM," *Electric Power Systems Research*, Vol. 65, pp. 23-34, 2003.

[6] A. H. M. A. Rahim and M. F. Kandlawala, "Robust STATCOM voltage controller design using loop shaping technique," *Electric Power Systems Research*, Vol. 68, pp. 61-74, 2004.

[7] J. Kennedy, "The particle swarm: social adaptation of knowledge," Proc. the International Conf. Evolutionary and Computation, Indianapolis, pp. 303-308, 1997.

[8] H. Shayeghi, A. Safari and H. Shayanfar, "Multimachine power system stabilizers design using PSO algorithm," *International Journal of Elect Power and Energy System Engineering*, Vol.

1, pp. 226-233, 2008.

[9] J. Kennedy, R. Eberhart and Y. Shi, *Swarm intelligence*, Morgan Kaufmann Publishers, San Francisco. 2001.

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

[11] A. T. Al-Awami, Y. L. Abdel-Magid and M. A. Abido, "A particle-swarm-based approach of power system stability enhancement with unified power flow controller," *Elect. Power and Energy Systems*, Vol. 29, pp. 251-259, 2007.