Optimal PID power system stabilizer tuning based on particle swarm optimization

Sayed Mojtaba Shirvani Boroujeni, Reza Hemmati, Hamideh Delafkar and Amin Safarnezhad Boroujeni

Islamic Azad University, Boroujen Branch, Department of Electrical Engineering, Boroujen, Iran
Mo_shirvani@yahoo.com, reza.hematti@gmail.com, delafkar@aut.ac.ir, safarnezhad@gmail.com

Abstract

Power system stabilizers (PSS) are used to generate supplementary damping control signals for the excitation system in order to damp the low frequency oscillations (LFO) of the electric power system. The PSS is usually designed based on classical control approaches but this conventional PSS (CPSS) has some problems. To overcome the drawbacks of CPSS, numerous techniques have been proposed in literatures. In this paper a PID type PSS is considered for damping electric power system oscillations. The parameters of this PID type PSS are tuned based on particle swarm optimization method. The proposed PSS (PSO-PSS) is evaluated against the conventional power system stabilizer (CPSS) at a single machine infinite bus power system considering system parametric uncertainties. The simulation results clearly indicate the effectiveness and validity of the proposed method.

Introduction

Large electric power systems are complex non-linear systems and often exhibit low frequency electromechanical oscillations due to insufficient damping caused by adverse operating. These oscillations with small magnitude and low frequency often persist for long periods of time and in some cases they even present limitations on power transfer capability (Liu *et al.,* 2005). In analyzing and controlling the power system's stability, two distinct types of system oscillations are recognized. One is associated with generators at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as "intra-area mode" oscillations. The second type is associated with swinging of many machines in an area of the system against machines in other areas. This is referred to as "inter-area mode" oscillations. Power system stabilizers (PSS) are used to generate supplementary control signals for the excitation system in order to damp both types of oscillations (Liu *et al.,* 2005). The widely used conventional power system stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead-lag compensator. The parameters of CPSS are determined based on the linearized model of the power system. Providing good damping over a wide operating range, the CPSS parameters should be fine tuned in response to both types of oscillations. Since power systems are highly non-linear systems, with configurations and parameters which alter through time, the CPSS design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. Therefore, an adaptive PSS which considers the non-linear nature of the plant and adapts to the changes in the environment is required for the power system (Liu *et al.,* 2005). In order to improve the performance of CPSSs, numerous techniques have been proposed for designing them, such as intelligent optimization methods (Sumathi *et al.,* 2007; Jiang *et al.,* 2008; Sudha *et al.,* 2009; Linda & Nair, 2010; Yassami *et al.,* 2010) and fuzzy logic method (Dubey, 2007; Hwanga *et al.,* 2008). Also many other different techniques have been reported by Chatterjee *et al.* (2009) and Nambu and Ohsawa (1996) and the application of robust control methods for designing PSS has been presented by Gupta *et al.* (2005), Mocwane and Folly (2007), Sil *et al.* (2009) and Bouhamida *et al.* (2005). This paper deals with a design method for the stability enhancement of a single machine infinite bus power system using PID type PSS which its parameters are tuned using particle swarm optimization method (PSO-PSS). To show effectiveness of the new PID type PSO-PSS, this method is compared with the CPSS. Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions.

System under study

Fig. 1 shows a single machine infinite bus power system (Kundur, 1993). The static excitation system has

Fig. 1. A single machine infinite bus power system.
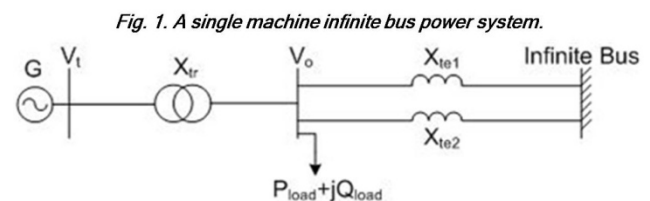
been considered as model type *IEEE - ST1A*.

Dynamic model of the system

Non-linear dynamic model

A non-linear dynamic model of the system is derived by disregarding the resistances and the transients of generator, transformers and transmission lines (Kundur, 1993). The non-linear dynamic model of the system is given as (1).

Linear dynamic model

A linear dynamic model of the system is obtained by linearizing the non-linear dynamic model around the nominal operating condition. The linearized model of the system is obtained as (2) (Kundur, 1993).

$$\begin{cases} \dot{\omega} = \dfrac{(P_m - P_e - D\Delta\omega)}{M} \\[2mm] \dot{\delta} = \omega_0(\omega - 1) \\[2mm] \dot{E}'_q = \dfrac{(-E_q + E_{fd})}{T'_{do}} \\[2mm] \dot{E}_{fd} = \dfrac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \end{cases} \quad (1)$$

$$\begin{cases} \Delta\dot{\delta} = \omega_0 \Delta\omega \\[2mm] \Delta\dot{\omega} = \dfrac{-\Delta P_e - D\Delta\omega}{M} \\[2mm] \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\[2mm] \Delta\dot{E}_{fd} = -\left(\dfrac{1}{T_A}\right)\Delta E_{fd} - \left(\dfrac{K_A}{T_A}\right)\Delta V \end{cases} \quad (2)$$

Fig. 2 shows the block diagram model of the system. This model is known as Heffron-Phillips model (Kundur, 1993). The model has some constants denoted by K_i. These constants are functions of the system parameters and the nominal operating condition. The nominal operating condition is given in the appendix.

Dynamic model in the state-space form

The dynamic model of the system in the state-space form is obtained as (3) (Kundur, 1993).

Fig. 2. *Heffron-Phillips model of the electric power system.*
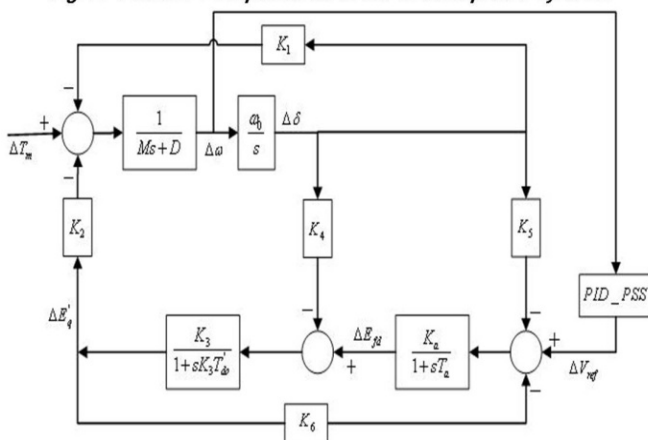
Analysis

In the nominal operating condition, the Eigen values of the system are obtained using analysis the state-space model of the system presented in (3) and these Eigen values are listed in Table 1. It is clearly seen that the system has two unstable poles at the right half plane and therefore the system is unstable and needs to power system stabilizer (PSS) for stability.

Table 1.The Eigen Values of the closed loop system.

-4.2797
-46.3666
0.1009 + j4.758
0.1009 - j4.758

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\dfrac{K_1}{M} & 0 & -\dfrac{K_2}{M} & 0 \\ -\dfrac{K_4}{T'_{do}} & 0 & -\dfrac{K_3}{T'_{do}} & \dfrac{1}{T'_{do}} \\ -\dfrac{K_A K_5}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \dfrac{1}{M} & 0 \\ 0 & 0 \\ 0 & \dfrac{K_A}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta T_m \\ \Delta V_{ref} \end{bmatrix}$$

$$(3)$$

Power system stabilizer

A Power system stabilizer (PSS) is provided to improve the damping of power system oscillations. Power system stabilizer provides an electrical damping torque *(ΔT_m)* in phase with the speed deviation *(Δω)* in order to improve damping of power system oscillations (Kundur, 1993). As referred before, many different methods have been applied to design power system stabilizers so far. In this paper a new optimal method based on the PSO is considered to tuning parameters of the PID type PSS. In the next section, the proposed method is briefly introduced and then designing the PID-PSS, based on the proposed methods, is done.

The proposed method

In this paper PSO method is considered for tuning PID type PSS. For more introductions, the PSO method is briefly introduced in the following subsection.

Particle swarm optimization

PSO was formulated by Edward and Kennedy in 1995. The thought process behind the algorithm was inspired by the social behavior of animals, such as bird flocking or fish schooling. PSO is similar to the continuous GA in that it begins with a random population matrix. Unlike the GA, PSO has no evolution operators such as crossover and mutation. The rows in the matrix are called particles (same as the GA chromosome). They contain the variable values and are not binary encoded. Each particle moves about the cost surface with a velocity. The particles update their velocities and positions based on the local and global best solutions as shown in (4) and (5) (Randy & Sue, 2004):

$$V_{m,n}{}^{new}= w \times V_{m,n}{}^{old}+ \Gamma_1 \times r_1 \times (P_{m,n}{}^{local\ best}-P_{m,n}{}^{old})+$$
$$\Gamma_2 \times r_2 \times (P_{m,n}{}^{global\ best}-P_{m,n}{}^{old}) \qquad (4)$$

$$P_{m,n}{}^{new}= P_{m,n}{}^{old}+ \Gamma\ V_{m,n}{}^{new} \qquad (5)$$

Where: $V_{m,n}$ = particle velocity; $P_{m,n}$ = particle variables; W= inertia weight; r_1, r_2 = independent uniform random numbers
$\Gamma_1 = \Gamma_2$ = learning factors; $P_{m,n}{}^{local\ best}$ = best local solution; $P_{m,n}{}^{global\ best}$ = best global solution.

The PSO algorithm updates the velocity vector for each particle then adds that velocity to the particle position or values. Velocity updates are influenced by both the best global solution associated with the lowest cost ever found by a particle and the best local solution associated with the lowest cost in the present population. If the best local solution has a cost less than the cost of the current global solution, then the best local solution replaces the best global solution. The particle velocity is reminiscent of local minimizes that use derivative information, because velocity is the derivative of position. The advantages of PSO are that it is easy to implement and there are few parameters to adjust. The PSO is able to tackle tough cost functions with many local minima (Randy & Sue, 2004).

Design methodology

In this section the PID type PSS parameters tuning based on the PSO is presented. The PID type PSS configuration is as (6).

$$PID-\ PSS = K_P+\frac{K_I}{S}+K_D S \qquad (6)$$

The parameter ΔE_{ref} is modulated to output of PSS and speed deviation $\Delta\omega$ is considered as input to PSS. The optimum values of K_P, K_I and K_D which minimize an array of different performance indexes are accurately computed using PSO. In this study the performance index is considered as (7). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error *(ITAE).*

$$ITAE = \int_0^t t|\Delta\omega|dt \qquad (7)$$

The parameter "t" in performance index is the simulation time and is considered equal to 30 sec for simulation. It is clear to understand that the controller with lower performance index is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in the reference mechanical torque (ΔTm) is assumed and the performance index is minimized using PSO. In order to acquire better performance, number of particle, particle size, number of iteration, Γ_1, Γ_2, and Γ are chosen as 12, 3, 50, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. It should be noted that PSO algorithm is run several times and then optimal set of PSS parameters is selected. The optimum values of the parameters K_P, K_I and K_D are obtained using PSO and summarized in the

Table 2. The boundaries of K_P, K_I and K_D are presented in the appendix.

Table 2. Obtained parameters of PID-PSS using PSO.

PID parameters	K_P	K_I	K_D
Obtained value	74.0115	49.558	13.1215

Simulation results

In this section, the proposed PSO-PSS is applied to the under study system (single machine infinite bus power system). To show effectiveness of the proposed optimal PSO-PSS, A classical lead-lag PSS based on phase compensation technique (CPSS) is considered for comparing purposes. The detailed step-by-step procedure for computing the parameters of the classical lead-lag PSS (CPSS) using phase compensation technique is presented in (Kundur, 1993). Here, the CPSS has been designed and obtained as (8).

$$CPSS = \frac{35\ (0.3S\ + 1)}{(0.1S\ + 1)} \qquad (8)$$

In order to study the PSS performance under system uncertainties (controller robustness), three operating conditions are considered: 1) Nominal operating condition. 2) Heavy operating condition (20 % changing parameters from their typical values) and 3) Very heavy operating condition (50 % changing parameters from their typical values).

In the nominal operating condition, the Eigen values of the system with CPSS and PSO-PSS are obtained and listed in Table 3. It is clear to see that the Eigen values of

*Table 3. The Eigen values of system with different PSSs.*

PSO-PSS	CPSS	Without PSS
-0.7652	-3.4256	-4.2797
-4.1015	-4.0503	-46.366
-4.9711	-46.3704	+0.1009 + j4.758
-46.3735	-3.2991 + j57.32	+0.1009 - j4.758
-406.2483	-3.2991 - j57.32	

the system with PSO-PSS are farther than the imaginary axis and the system stability margin is more than CPSS method. Also to demonstrate the robustness performance of the proposed method, The *ITAE* is calculated following a 10% step change in the reference mechanical torque *(ΔT_m)* at all operating conditions (Nominal, heavy &Very heavy) and results are shown at Table 4. Following step change at *ΔT_m*, the PSO-PSS has better performance than the CPSS at all operating conditions. Where, the PSO-PSS has lower *ITAE* index in comparison with CPSS, therefore the PSO-PSS can damp power system oscillations more successfully. Also the control effort signal is one of the most important factors to compare responses. The parameter *ΔV_{ref}* which is shown in Fig. 2 is the output of controller and is considered as the control effort signal. The control effort signal is computed as (9).

Table 4. The calculated ITAE.

Condition	PSO-PSS	CPSS
Nominal operating condition	3.2547×10^{-4}	5.5686×10^{-4}
Heavy operating condition	3.0095×10^{-4}	7.2451×10^{-4}
Very heavy operating condition	2.4291×10^{-4}	8.9021×10^{-4}

Fig. 3. Dynamic responses Δω following 0.1 step in the
reference mechanical torque (ΔTm)
a: Nominal operating condition   b: Heavy operating
condition   c: Very heavy operating condition.
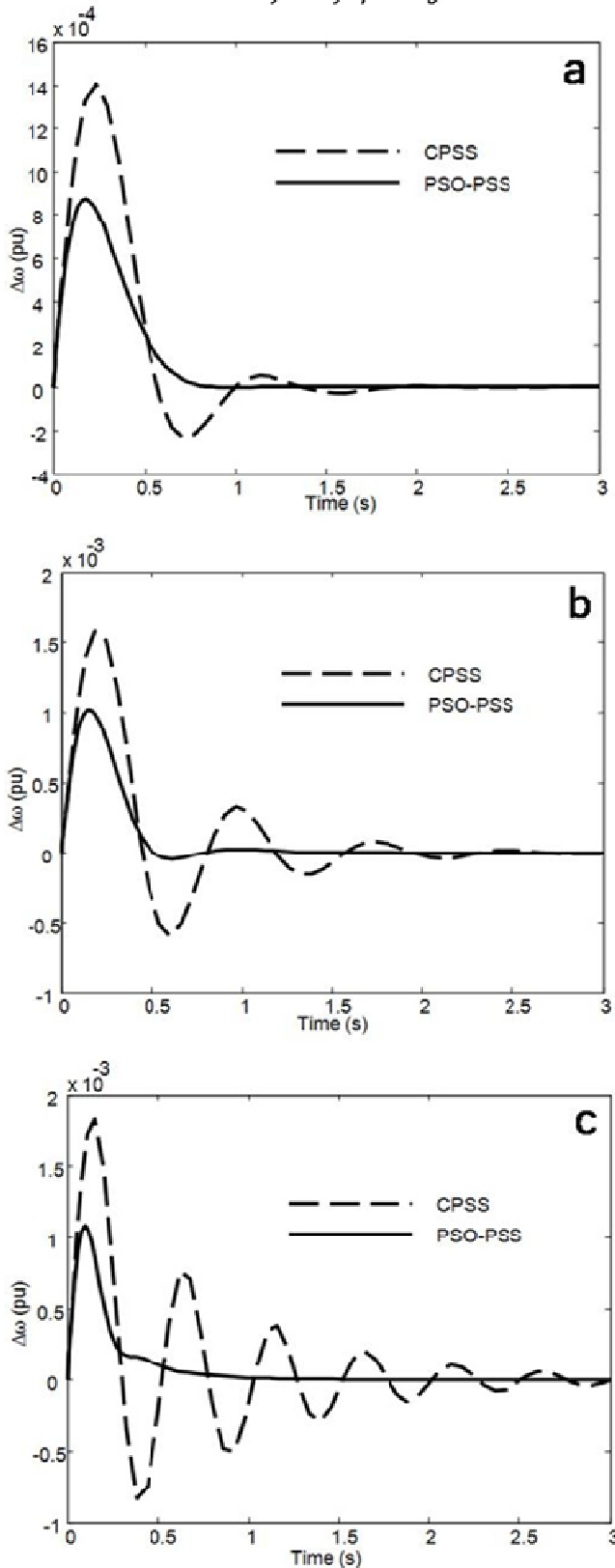
$$Control\_Effort = \int_0^t t|\Delta Vref|dt \quad (9)$$

The control effort has been calculated following a 10% step change in the reference mechanical torque (ΔT_m) at all operating conditions (Nominal, Heavy and Very heavy) and results are shown at Table 5. It is clear to see that following step change at ΔT_m, the PSO-PSS has lower control effort than the other methods at all operating conditions. This means that the PSO-PSS damps power system oscillations by injecting lower control signal. Lower control effort signal of the PSO-PSS can lead to a simple and also lower cost implementation of the controller. Although the control effort and performance index results are enough to compare the methods, but it can be more useful to show responses in figures. Fig. 3 shows $\Delta \omega$ at nominal, heavy and very heavy operating conditions following 10% step change in the reference mechanical torque (ΔT_m). It is clear to see that between all operating conditions, the PSO-PSS has better performance than the other method in mitigating oscillations. PSO-PSS characteristics in the damping power system oscillations are in the range of acceptable. Eventually between two methods, the PSO-PSS has a very significant better performance than CPSS. The CPSS ability in damping power system oscillations goes to unstable and large oscillations with changing system operating conditions and under heavy loads.

Table 5. The calculated control effort signal.

Condition	PSO-PSS	CPSS
Nominal operating condition	0.0689	0.0327
Heavy operating condition	0.0654	0.0490
Very heavy operating condition	0.0610	0.0721

Conclusion

In this paper a new optimal PID type PSS based on PSO (PSO-PSS) method has been successfully proposed. The design strategy includes enough flexibility to set the desired level of stability and performance, and to consider the practical constraints by introducing appropriate uncertainties. Also the final designed PSO-PSS is low order and its implementation is easy and cheap. The proposed method was applied to a typical single machine infinite bus power system containing system parametric uncertainties and various loads conditions. The simulation results demonstrated that the designed PSO-PSS is capable of guaranteeing the robust stability and robust performance of the power system under a wide range of system uncertainties.

Appendix

The nominal parameters and operating conditions of the system are listed in Table 6. The boundaries of K_P, K_I and K_D for optimal search are listed in Table 7.

Table 6. The nominal system parameters.

Generator	M = 10 Mj/MVA	T'_{do} = 7.5 s	X_d = 1.68 p.u.
	X_q = 1.6 p.u.	$X'd$ = 0.3 p.u.	D = 0
Excitation system		K_a = 50	T_a = 0.02 s
Transformer		X_{tr} = 0.1 p.u.	
Transmission lines	X_{te1} = 0.5 p.u.	X_{te2} = 0.9 p.u.	
Operating condition	V_t =1.05 p.u.	P=1 p.u.	Q=0.2 p.u.

Table 7. The boundaries of K_P, K_I & K_D.

Parameters	1≤ K_P≤100	1≤ K_I≤100	1≤ K_D≤100

Acknowledgement

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