PID Power System Stabilizer Design based on Shuffled Frog Leaping Algorithm

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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 (PID-PSS) is considered. The parameters of this PID type PSS (PID-PSS) are tuned based on Shuffled Frog Leaping algorithm. The proposed PID-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.
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1. Introduction

Large electric power systems are complex nonlinear 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 nonlinear 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 nonlinear 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 (Linda and Nair 2010; Yassami et al. 2010; Sumathi et al. 2007; Jiang et al. 2008; Sudha et al. 2009) and Fuzzy logic method (Hwanga et al. 2008; Dubey 2007). 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-PSS which its parameters are tuned by Shuffled Frog Leaping algorithm Optimization method. To show effectiveness of the new optimal control method, this method is compared with the CPSS. Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions.

Apart from this introductory section, this paper is structured as follows. The system under study is presented in section 2. Section 3 describes about the system modeling and system analysis is presented in section 4. The power system stabilizers are briefly explained in section 5. Section 6 is devoted to explaining the proposed methods. The design methodology is developed in section 7 and eventually the simulation results are presented in section 8.

2. System under Study

Figure 1 shows a single machine infinite bus power system (Kundur 1993). The static excitation system has been considered as model type *IEEE – ST1A*.

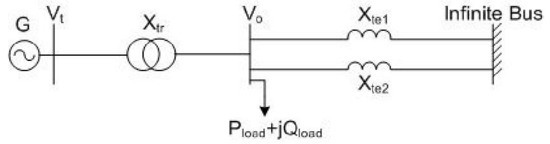


Figure 1. A single machine infinite bus power system

3. Dynamic Model of the System

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). 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 (1) (Kundur 1993).

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

Figure 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.

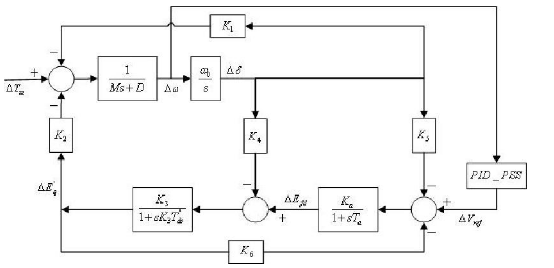


Figure 2. Heffron-Phillips model of the power system

3.1. Dynamic model of the system in the state-space form

The dynamic model of the system in the state-space form is obtained as (2) (Kundur 1993).

4. Analysis

In the nominal operating condition, the eigen values of the system are obtained using analysis of the state-space model of the system presented in (2) and these eigen values are shown 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 the Power System Stabilizer (PSS) for stability.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{M} & 0 \\ 0 & 0 \\ 0 & \frac{K_A}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta T_m \\ \Delta V_{ref} \end{bmatrix} \qquad (2)$$

Table 1. The eigen values of the closed loop system

-4.2797
-46.366
+0.1009 + j4.758
+0.1009 - j4.758

5. 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 ($\Delta\omega$) 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 SFL algorithm is considered to tuning parameters of the PID-PSS. In the next section, the proposed method is briefly introduced and then designing the PID-PSS, based on the proposed methods, is done.

6. The proposed method

In this paper the SFL algorithm optimization method is considered to adjustment PID-PSS. For more introductions, the proposed methods are briefly introduced in the following subsections.

6.1. SFLA Overview

Over the last decades there has been a growing concern in algorithms inspired by the observation of natural phenomenon. It has been shown by many researches that these algorithms are good alternative tools to solve complex computational problems.

The SFLA is a meta-heuristic optimization method inspired from the memetic evolution of a group of frogs when searching for food (Huynh

2008). SFLA, originally developed in determining the optimal discrete pipe sizes for new pipe networks and for existing network expansions. Due to the advantages of the SFLA, it is being researched and utilized in different subjects by researchers around the world, since 2003 (Elbeltagi 2007; Ebrahimi et al. 2011).

The SFL algorithm is a memetic meta-heuristic method that is derived from a virtual population of frogs in which individual frogs represent a set of possible solutions. Each frog is distributed to a different subset of the whole population described as memeplexes. The different memeplexes are considered as different culture of frogs that are located at different places in the solution space (i.e. global search). Each culture of frogs performs simultaneously an independent deep local search using a particle swarm optimization like method. To ensure global exploration, after a defined number of memeplex evolution steps (i.e. local search iterations), information is passed between memeplexes in a shuffling process. Shuffling improves frog ideas quality after being infected by the frogs from different memeplexes, ensure that the cultural evolution towards any particular interest is free from bias. In addition, to improved information, random virtual frogs are generated and substituted in the population if the local search cannot find better solutions. After this, local search and shuffling processes (global relocation) continue until defined convergence criteria are satisfied. The flowchart of the SFLA is illustrated in Figure 3.

The SFLA begins with an initial population of "*P*" frogs $F=\{X_1,X_2,...,X_n\}$ created randomly within the feasible space Ω. For S-dimensional problems (S variables), the position of the ith frog is represented as $X_i=[x_{i1},x_{i2},...,x_{is}]^T$. A fitness function is defined to evaluate the frog's position. Afterward the performance of each frog is computed based on its position. The frogs are sorted in a descending order according to their fitness. Then, the entire population is divided into *m* memeplexes, each of which consisting of *n* frogs (i.e. $P=n\times m$). The division is done with the first frog goes to the first memeplex, the second frog goes to the second memeplex, frog *m* goes to the m^{th} memeplex, and the $(m+1)^{th}$ frog back to the first memeplex, and so on. The local search block of Figure 3 is shown in Figure 4.

According to Figure 4, during memeplex evolution, the position of frog i^{th} (D_i) is adjusted according to the different between the frog with the worst fitness (X_w) and the frog with the best fitness (X_b) as shown in (3). Then, the worst frog X_w leaps toward the best frog X_b and the position of the worst frog is updated based on the leaping rule, as shown in (4).

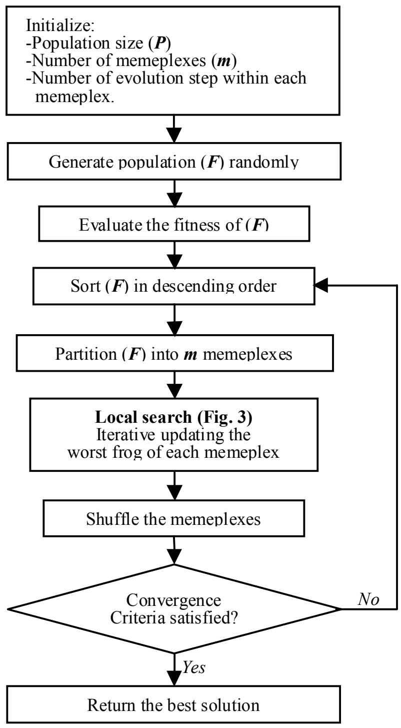


Figure 3.General principle of SFLA (Ebrahimi et al., 2011)

$$\text{Position change } (D_i) = rand() \times (X_b - X_w) \quad (3)$$

$$X_w(new) = X_w + D, (\|D\| < D_{\max}) \quad (4)$$

where *rand ()* is a random number in the rang [0,1] and D_{max} is the maximum allowed change of frog's position in one jump. If this repositioning process produces a frog with better fitness, it replaces the worst frog, otherwise, the calculation in (3) and (4) are repeated with respect to the global best frog (X_g), (i.e. X_g replaces X_b). If no improvement becomes possible in this case, then a new frog within the feasible space is randomly generated to replace the worst frog. Based on Figure 3, the evolution process is continued until the termination criterion is met. The termination criterion could be the number of iterations or when a frog of optimum fitness is found (Huynh 2008).

To compute the fitness value for each frog, firstly, the values of the I_{pi} variables are extracted by decoding the frog information. In this study the fitness index is considered as (5). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

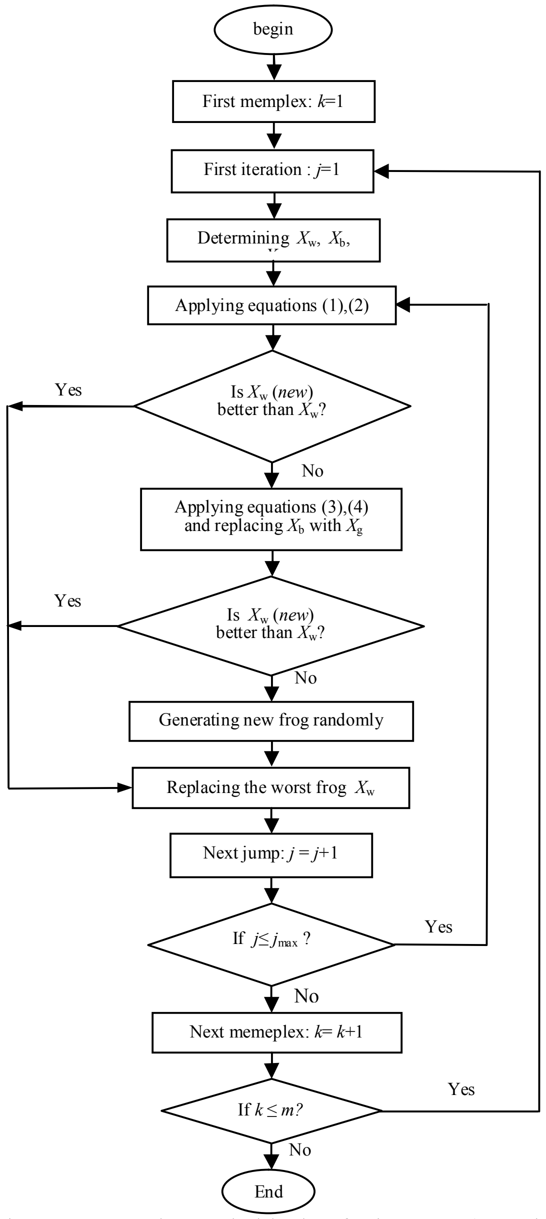


Figure 4. Local search block of Figure 3 (Huynh, 2008).

$$ITAE = \int_0^t t|\Delta\omega|dt \qquad (5)$$

Based on Figure 3 the local search and shuffling processes (global relocation) continue until the last iteration is met. In this paper, the number of iteration is set to be 50.

7. Design methodology

In this section the PID-PSS parameters tuning based on the Shuffled Frog Leaping algorithm is presented. The PID-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 PID-PSS and speed deviation $\Delta\omega$ is considered as input to PID-PSS. The optimum values of K_P, K_I and K_D which minimize an array of different fitness indexes are computed using the SFLA. It is clear that the controller with lower fitness is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in reference mechanical torque (ΔTm) is assumed and the performance index is minimized using SFLA. The first step to implement the SFL is generating the initial population (*N* frogs) where *N* is considered to be 20. The number of memeplex is considered to be 3 and the number of evaluation for local search is set to 3. Also D_{max} is chosen as *inf.* To find the best value for the solution, the algorithms are run for 10 independent runs under different random seeds. The optimum values of the parameters K_P, K_I and K_D are obtained using SFLA and summarized in the Table 2.

Table 2. Obtained parameters of PID-PSS using Shuffled Frog Leaping algorithm

PID Parameters	KP	KI	KD
Obtained Value	54.860	9.248	16.237

8. Simulation results

In this section, the proposed optimal PID-PSS is applied to the under study system (single machine infinite bus power system). To show effectiveness of the proposed optimal PID-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 (7).

$$CPSS = \frac{35(0.3S+1)}{(0.1S+1)} \qquad (7)$$

In order to study the PSS performance under system uncertainties (controller robustness), three operating conditions are considered as follow:

i : Nominal operating condition

ii: Heavy operating condition (20% changing parameters from their typical values)

iii: Very heavy operating condition (50% changing parameters from their typical values)

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 and Very heavy) and results are shown at Table 3. Following step change at ΔT_m, the optimal PID-PSS has better performance than the CPSS at all operating conditions. Where, the optimal PID-PSS has lower *ITAE* index in comparison with CPSS, therefore the optimal PID-PSS can damp power system oscillations more successfully.

To demonstrate the robustness and safe performance of the proposed method, speed deviations of the machine following a 10% step change in the reference mechanical torque (ΔT_m) at all operating conditions (Nominal, heavy and Very heavy) is shown in figure 5.

Table 3. The calculated ITAE

	Optimal PID-PSS	CPSS
Nominal operating condition	4.3231×10^{-4}	5.5686×10^{-4}
Heavy operating condition	3.4428×10^{-4}	7.2451×10^{-4}
Very heavy operating condition	2.9189×10^{-4}	8.9021×10^{-4}

9. Conclusions

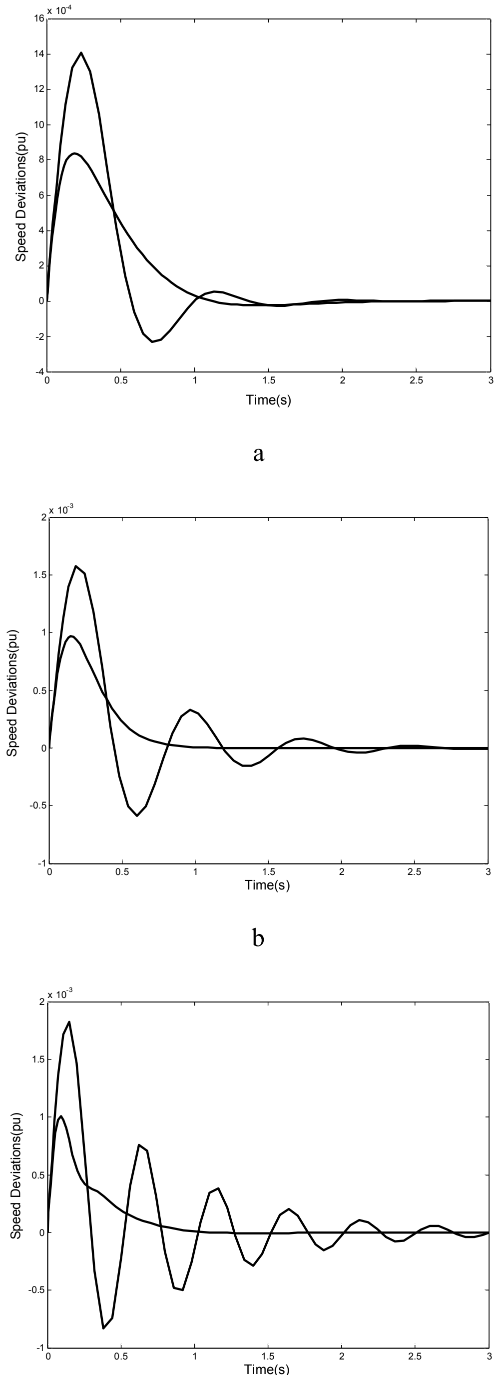
In this paper a new optimal PID-PSS based on SFLA has been successfully proposed. The design strategy includes enough flexibility to set the desired level of stability and performance, and to consider the practical constraints by introducing appropriate uncertainties. Also the final designed optimal PID-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 optimal PID-PSS is capable of guaranteeing the robust stability and robust performance of the power system under a wide range of system uncertainties.

10. Appendix

The nominal parameters and operating conditions of the system are listed in Table 4.

Table 4. The nominal system parameters

Generator	M=10Mj/MVA Xq=1.6 p.u.	T′do= 7.5 s X′d=0.3 p.u.	Xd=1.68p.u. D = 0
Excitation system		Ka=50	Ta = 0.02 s
Transformer		Xtr=0.1p.u.	
Transmission lines	Xte1=0.5p.u.	Xte2=0.9p.u.	
Operating condition	Vt=1.05p.u.	P=1 p.u.	Q=0.2 p.u.



c

Figure 5. 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
solid line (HS-PSS), dashed line (CPSS)

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