International Journal of Power Electronics and Drive System (IJPEDS)
Vol.2, No.1, March 2012, pp. 99~106
ISSN: 2088-8694

Design of Robust Power System Stabilizer Considering Less Control Energy

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Article Info

Article history:

Received Nov 2nd, 2011
Revised Feb 29th, 2012
Accepted Mar 15th, 2012

Keyword:

Control system design
Less control energy
Operation and control of power systems
Robust control application

ABSTRACT

This paper proposes design a robust power system stabilizer (PSS) considering less control energy using a genetic algorithm (GA). The structure of proposed PSS is a 1st-order lead-lag compensator, it is easy to implement in power system utility. In the design, system uncertainties are modeled by an inverse additive uncertainty. The performance, robust stability condition, and less control energy of the designed system are formulated as the objective function in the optimization problem. The GA is applied to solve an optimization problem and to achieve control parameters of proposed PSS. The performance and robustness against system uncertainties of the proposed PSS are investigated in the single-machine infinite bus system in comparison with a conventional PSS and a PSS designed by fixed-structure H_∞ loop shaping. Simulation results show that with less control energy, the robustness and damping effect of the proposed PSS can be guaranteed against various operating conditions.

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1. INTRODUCTION

Low frequency oscillation is one of the important issues in power system. It may appear when small disturbances are occurs in the system, such as changes in the load. The main cause of the problem is the lack of damping of the electromechanical oscillation modes, and power system stabilizer (PSS) has been selected as a cost effective device to provide the additional damping via the excitation system to damp the problem [1,2].

Several approaches based on modern control theories have been successfully applied to design PSSs, such as eigenvalue assignment [3], linear quadratic regulator [4] etc. Since these techniques do not take the presence of system uncertainties e.g. system nonlinear characteristics, variations of system configuration due to unpredictable disturbances, loading conditions etc. into consideration in the system modelling, the robustness of these PSSs against uncertainties can not be guaranteed.

Then H_∞ control has been applied to design of robust PSS [5,6] etc to overcome the problems above. In these works, the designed H_∞ PSS via mixed sensitivity approach have confirmed the significant performance and high robustness. In this approach, however, the controllers designed are complex, and weighting functions in H_∞ control design can not be selected easily. Moreover, the order of H_∞ controller is higher than, or at least similar to, that of plant. This leads to the complex structure PSS, high cost, difficult commissioning, poor reliability and potential problem in maintenance which is different from the conventional lead/lag PSS [7]. Despite the significant potential of control techniques mentioned above, power system utilities still prefer the conventional lead/lag PSS structure. This is due to the ease of implementation, the long-term reliability, etc.

On the other hand, much research on a conventional lead/lag PSS design has paid attentions to tuning of PSS parameters. The parameters of a lead/lag PSS are optimized under various operating conditions by heuristic methods such as tabu search [8], genetic algorithm [9], and simulated annealing [10]. In these studies, however, the uncertainty model is not embedded in the mathematical model of the power system. Furthermore, the robust stability against system uncertainties is not taken into consideration in the optimisation process. Therefore, the robust stability margin of the system in these works may not be guaranteed in the face of several uncertainties. Then the robust PSS design by the H_∞ loop shaping technique and GA has been proposed to tackle the problem [11]. The configuration of PSS is a fixed structure with a conventional 2nd-order lead/lag PSS. However, large control energy is needed by most of conventional robust controllers. It is mean the power system utility need install large controller.

To get balance of robustness and control energy, this paper proposes design of robust PSS with less control energy under consideration. The performance and robust stability conditions in inverse additive uncertainty technique as well as less control energy technique are formulated as the objective function. Then the GA is applied to solve the optimization problem. Simulation study in a single machine infinite bus system is carried out to evaluate the robustness and control energy output of the designed PSS in comparison with conventional robust PSS method.

This paper is organized as follows. First, system modelling is explained in section 2. Next, section 3 presents the proposed design procedure for optimization of PSS parameters by GA. Subsequently, section 4 shows the simulation results. Finally, the conclusion is given.

2. POWER SYSTEM MODELING

A single machine infinite bus system (SMIB) as shown in Fig. 1 is used in this study. The automatic voltage regulator (AVR), an excitation system, and the PSS are installed in the Generator G1. A detailed linearised model for an exciter, power system stabilizer, and overall power system model are explained as follows,

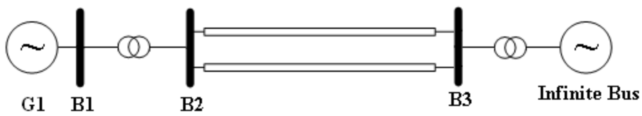


Figure. 1. Single machine infinite bus (SMIB)

2.1 SMIB System

Figure 2 depicts a linearised power system model in Fig. 1. It is represented by the Heffron-Phillips model [1]. This system is represented by a forth-order model with the small deviation of the power angle $\Delta\delta$, the rotor speed $\Delta\omega$, the internal voltage of generator $\Delta e_q'$ and the field voltage ΔE_{fd}, as the state variables.

The initial condition used as the design condition of the proposed PSS is P_e = 0.8 p.u., x_e = 0.2 p.u. from [12].

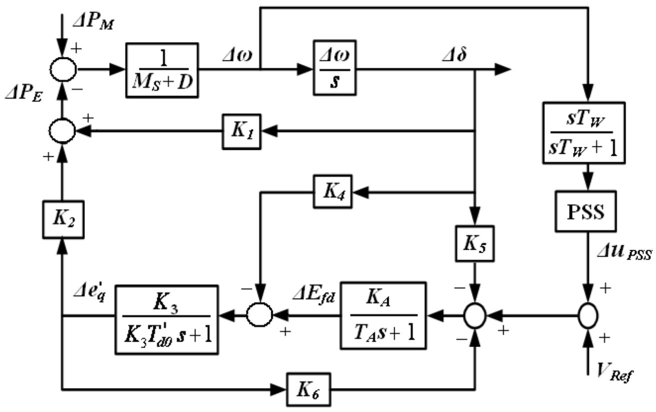


Figure. 2 . Linearised model of SMIB system

2.2. Exciter

The linearised excitation system model that be used in this study is shown in figure 3 below,

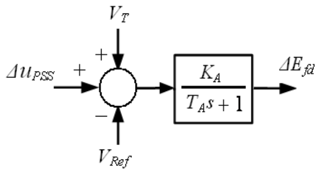


Figure. 3. Exciter model

The exciter is modelled by the first-order transfer function with gain K_A = 50, and time constant T_A =0.05 s.

2.3 Power System Stabiliser (PSS)

The block diagram of PSS is shown in Fig. 4. In this study, the PSS is modelled by two block diagram. The first block is wash out with time constant T_W = 2 s, the second block is controller which represented by the 1st order lead/lag controller [12].

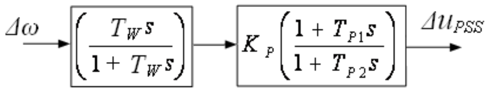


Figure.4. PSS model

Where $\Delta\omega$ is angular velocity deviation as input signal of PSS, Δu_{PSS} is the control output signals of the PSS controller. K_P , T_{P1} and T_{P2} are gain and time constants of PSS.

2.4 State Space Equation

The state equation of the overall power system model in Fig. 2 can be expressed as

$$\Delta\dot{X} = A\Delta X + B\Delta u_{pss} \quad (1)$$

$$\Delta Y = C\Delta X + D\Delta u_{pss} \quad (2)$$

$$\Delta u_{pss} = K(s)\Delta\omega \quad (3)$$

Where the state vector $\Delta X = [\Delta\delta \;\; \Delta\omega \;\; \Delta e_q' \;\; \Delta E_{fd}]^T$, the output vector $\Delta Y = [\Delta\omega]$, Δu_{pss} is the control output signal of the PSS ($K(s)$), which uses only the angular velocity deviation ($\Delta\omega$) as a feedback input signal. Note that the system (1) is a single-input single-output (SISO) system. The proposed method is applied to design a robust PSS.

3. PROPOSED METHOD

In this section, the design procedure of the proposed method is explained as follows,

3.1 System Uncertainties

To enhance the robustness of power system damping controller against system uncertainties, the inverse additive perturbation [7] is applied to represent all possible unstructured system uncertainties. The concept of enhancement of robust stability margin is used to formulate the optimization problem of controller parameters.

The feedback control system with inverse additive perturbation is shown in Fig. 5. Where G is the nominal plant and K is the controller to be designed. v, r, u and y are output of additive uncertainty, reference input, control signal and output, respectively. For unstructured system uncertainties, they are represented by Δ_A which is the additive uncertainty model.

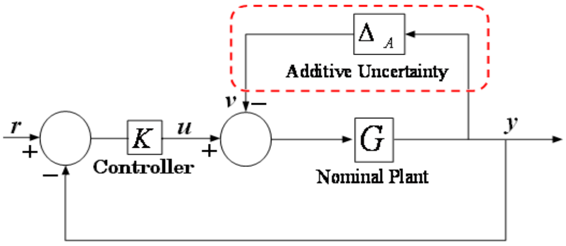


Figure. 5. Feedback system with inverse additive perturbation.

Based on the small gain theorem, for a stable additive uncertainty Δ_A, the closed loop system will be robustly stable if

$$\left\| \Delta_A(s) \frac{G(s)}{1 - G(s)K(s)} \right\|_\infty < 1 \tag{4}$$

The equation (5) can be modified as follows,

$$\left\| \Delta_A(s) \right\|_\infty < \frac{1}{\left\| G(s)\left(1 - G(s)K(s)\right) \right\|_\infty} \tag{5}$$

The equation (6) becomes,

$$\left\| \Delta_A(s) \right\|_\infty < \frac{1}{\left\| G(s)/(1 - G(s)K(s)) \right\|_\infty} \tag{6}$$

The right hand side of equation (6) implies the size of system uncertainties or the robust stability margin against system uncertainties. Then, the robust stability margin of the closed loop system can be guaranteed in terms of the additive stability margin (ASM) as,

$$ASM < \frac{1}{\left\| G(s)/(1 - G(s)K(s)) \right\|_\infty} \tag{7}$$

By minimizing $\left\| G/(1 - GK) \right\|_\infty$, the robust stability margin of the closed-loop system is a near optimum.

3.2 Less Control Energy

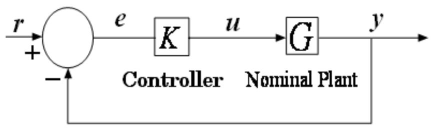


Figure. 6. Feedback system with controller

Based on small gain theorem, the less control output signal can be achieved by minimizing the ∞ norm of relationship between control signal (*u*) and reference input (*r*) [7]. The relationship between *u* and *r* as follow,

$$u = K(I + GK)^{-1} r \tag{8}$$

Where K is controller and G is nominal plant. As a result the less control energy can be reduces by minimising the following norm,

$$\left\| K(I + GK)^{-1} \right\|_\infty \tag{9}$$

3.3 Optimization Problem

In this study, the problem constraints are the controller parameters bounds. In addition to enhance the robust stability, another objective is to increase the damping ratio and place the closed-loop eigenvalues of hybrid wind-diesel power system in a D-shape region [9]. The conditions will place the system closed-loop eigenvalues in the D-shape region characterized by $\zeta \geq \zeta_{spec}$ and $\sigma \leq \sigma_{spec}$ as shown in Fig. 7.

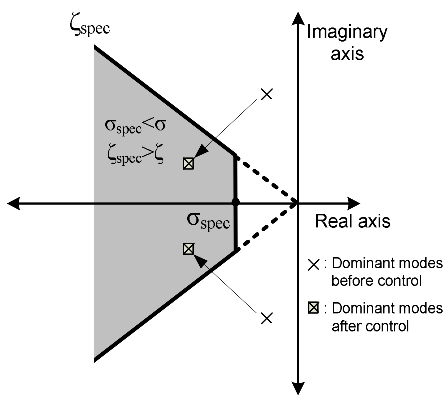


Figure. 7. D-shape region in the s-plane

Therefore, the design problem can be formulated as the following optimization problem.

Minimize $$\alpha\left\| G(1-GK)^{-1}\right\|_{\infty}+\beta\left\| K(1-GK)^{-1}\right\|_{\infty} \tag{10}$$

Subject to

$$\zeta \geq \zeta_{spec}\,,\ \sigma \leq \sigma_{spec} \tag{11}$$
$$K_{P,min} \leq K_P \leq K_{P,max}$$
$$T_{P,min} \leq T_P \leq T_{P,max}$$

where ζ and ζ_{spec} are the actual and desired damping ratio of the dominant mode, respectively; σ and σ_{spec} are the actual and desired real part, respectively; $K_{P,max}$ and $K_{P,min}$ are the maximum and minimum controller gains, respectively; $T_{P,max}$ and $T_{P,min}$ are the maximum and minimum time constants, respectively. Moreover, α and β are chosen appropriately to get balance between robust and less control energy. Then, the optimization problem is solved by GA [13] to search the controller parameters.

3.4 Parameters Optimization by GA

In this section, GA is applied to search the controller parameters with off line tuning. Each step of proposed method is explained as follows.

Step 1 Generate the objective function for GA optimization.

In this study, the performance and robust stability conditions in inverse additive perturbation design approach is adopted to design a robust controller as mention in equation (10) and (11).

Step 2 Initialize the search parameters for GA. Define genetic parameters such as population size, crossover, mutation rate, and maximum generation.

Step 3 Randomly generate the initial solution.

Step 4 Evaluate objective function of each individual in equation (10) and (11).

Step 5 Select the best individual in the current generation. Check the maximum generation.

Step 6 Increase the generation.

Step 7 While the current generation is less than the maximum generation, create new population using genetic operators and go to step 4. If the current generation is the maximum generation, then stop.

4. RESULTS AND ANALYSIS

In this study, simulation studies in SMIB system are carried out using MATLAB/Simulink software. In the optimization, the ranges of search parameters and GA parameters are set as follows: $K_P \in [1 \quad 50]$, T_1 and $T_2 \in [0.001\ 1]$, $\zeta_{spec}=0.4$, $\delta_{spec}=-0.5$, arithmetic crossover, uniform mutation, population size is 200, and maximum generation is 100. Consequently, the designed PSS is given as follow,

$$K(s)=18.27\left(\frac{0.3243\,s+1}{0.0658\,s+1}\right) \tag{12}$$

Table 1. Comparison of oscillation mode

	Without PSS	Proposed PSS
Eigenvalue	-0.1281±j9.134	-2.502±j 0.859
Damping ratio	0.014	0.94

The eigenvalues corresponding to the electromechanical mode without PSS and the proposed PSS are listed in Table 1. Clearly, the desired damping ratio and the desired real part of the oscillation mode are achieved by the proposed PSS. In simulation studies, the performance and robustness of the proposed controllers are compared with those of the PSS designed by fixed structured H_∞ loop shaping method (FH PSS) obtained from [11], that is

$$K(s)=48.02\left(\frac{0.7010\,s+1}{0.2761\,s+1}\right)\left(\frac{0.0808\,s+1}{0.0003\,s+1}\right) \tag{13}$$

and the conventional lead-lag controller (CPSS) obtained from [12], that is

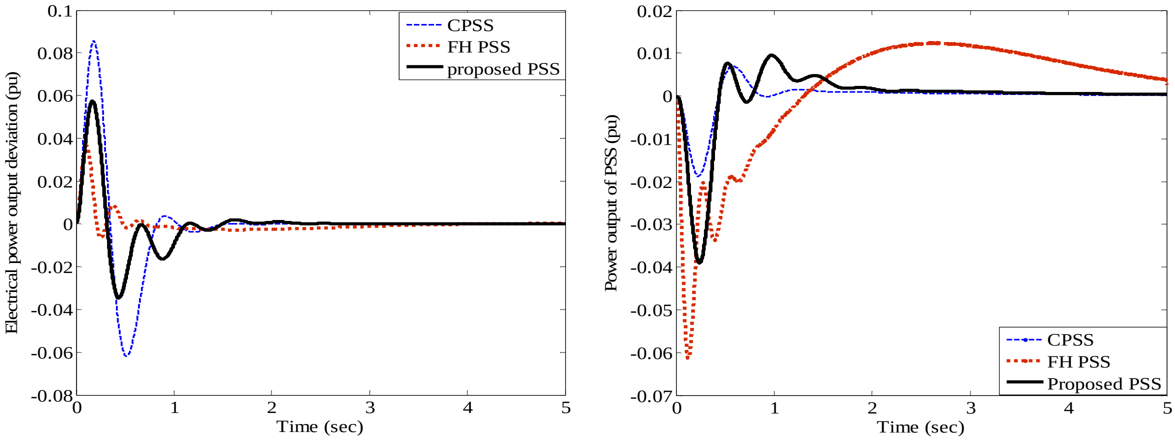
$$(CPSS)K(s)=5.5\frac{(1+0.1732s)^2}{(1+0.0577s)^2} \tag{14}$$

Table 2. Operating Condition

System Parameters	(1) Normal Condition	(2) Weak Line	(3) Heavy Load &Weak line
P(p.u)	0.8	0.8	0.95
Q(p.u)	0.4	0.4	0.4
x_e (p.u)	0.2	0.8	0.8

In simulation studies, the system responses with PSSs are examined under three case studies as in Table 2, while a small disturbance of 5 % (0.05 p.u.) step response of ΔV_{ref} is applied to the system at $t = 0$ s.

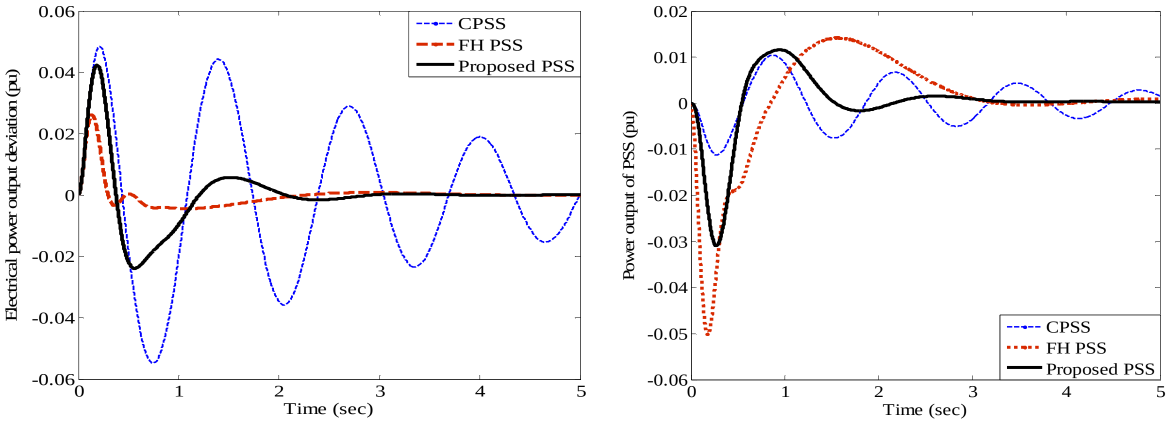
Fig. 8 shows the responses of electrical power output deviation and power output of PSS in case 1. CPSS, FH PSS and the proposed PSS are able to damp power oscillations. Nevertheless, the overshoot of power oscillations in cases of FH PSS and the proposed PSS are much lower than that of CPSS. Moreover, the proposed PSS uses less control energy than FH PSS. By less control output of controller, the proposed controller can quarantee the performance and robustness of controller. It is one of the advantages of the proposed controller.



(a) Electrical power output of case 1 (b) Power output of PSS in case 1

Figure. 8. Simulation results of case 1

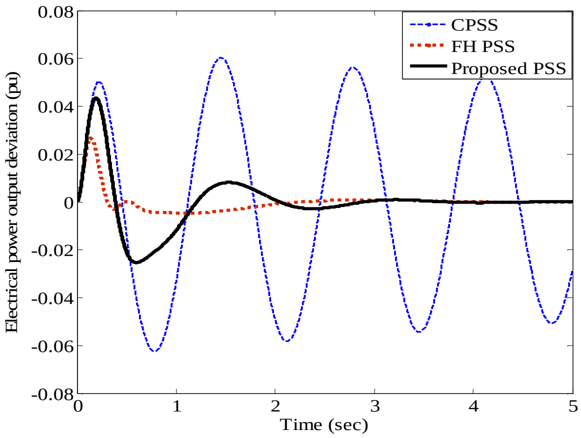
Simulation results in case 2 are shown in Fig. 9. The damping effect of CPSS is deteriorated by the increase in transmission line reactance. On the other hand, using less control energy, the proposed PSS still can stabilize the power oscillations effectively. Both FH PSS and the proposed PSS are rarely sensitive to the weak line condition.



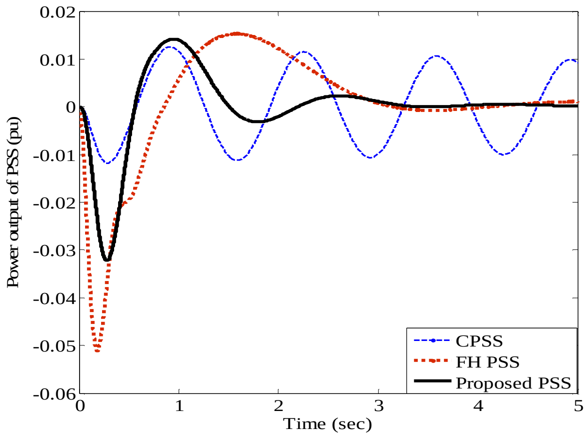
(a) Electrical power output of case 2 (b) Power output of PSS in case 2

Figure. 9. Simulation results of case 2

Finally, the electrical power output is increased in case 3 to get heavy load and weak line condition. The simulation results are shown in Fig. 10. The results shows that the CPSS fails to damp power system. The power oscillation gradually increases and diverges. In contrast, the FH PSS and the proposed PSS can tolerate this situation. The power oscillations are significantly damped. In addition, the output of control energy in case of proposed PSS is smaller than that of FH PSS. As a result, the power system utility can install smaller capacity of PSS by the proposed method in comparison with FH PSS, and it can reduce cost of investment significantly without compromising the effectiveness, performance and robustness of PSS controller.



(a) Electrical power output of case 3



(b) Power output of PSS in case 3

Figure. 10. Simulation results of case 3

5. CONCLUSION

The design of robust PSS considering less control energy into account has been proposed in this work. The performance of controller is guaranteed by an enhancement of system damping, and system uncertainties system uncertainties are modelled by an inverse additive uncertainty as well as less control energy is achieved by minimizing the ∞ norm of relationship between control signal and reference input of closed loop system. All of the techniques have been formulated as the optimization problem. The GA has been employed to tune the control parameters of PSS. The designed PSS is based on the conventional 1^{st}-order lead-lag compensator. Accordingly, it is easy to implement in real systems. The performance and robustness of the proposed PSS have been evaluated in the SMIB system. Simulation results confirm that the proposed PSS is very robust against various operating condition. With less control energy, the stabilizing effect and robustness of the proposed PSS are almost the same as that of the FH PSS with higher control energy. For future development, the proposed method will be applied to design PSSs in a multi-machine power system.

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