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Lead-lag PSS design satisfying H_∞ control performance using particle swarm optimization

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Abstract

The aim of this paper is to describe how to obtain robustness of a Power System Stabilizer (PSS) which has existing controller structure in a smart manner. In recent years, robust PSS designs that adopt an H_∞ controller have been investigated in order to guarantee the performance when the state of the system configuration and power flow change. However the H_∞ controller has not been widely adopted into practical use because of the intricate nature of its theory and structure. We consider the H_∞ control problem under the condition that PSS structure is fixed to be a lead-lag compensator. We optimize the parameters of the lead-lag PSS by a Particle Swarm Optimization (PSO) that has an evaluation function which takes into account a closed loop H_∞ norm and a desired response. In this way, we design a smart PSS which has a conventional controller structure and guarantees its H_∞ control performance.

Keywords: PSS, lead-lag compensation, H_∞ control theory, dimensional reduction, particle swarm optimization

1. Introduction

A conventional Power System Stabilizer (PSS) is generally designed to be effective for a linearized model at a particular operating point. However, the system configuration and the power flow condition are continually changing. Therefore, the performance and stability of conventional PSSs are not theoretically guaranteed. In recent years, design methods of smart PSSs that are robust for several operating points have been investigated. H_∞ control theory, which is one of these robust control theories, has been applied to PSS, and the validity of the PSS has been demonstrated [1]-[3].

However, the controllers that are generally used in industrial control systems are not H_∞ controllers but rather classical controllers, such as PID controllers. The H_∞ controller is not widely used in practice for several reasons. For example, the calculation costs of classical controllers are low because of the simplicity of their structure, and established experience and know-how can be used in controller tuning. On the other hand, the theory of H_∞ control is rather difficult to comprehend, and the structure is complex because the controller is high-dimensional. For these problems, methods for reducing the dimensions of the H_∞ controller to that of a classical controller have been proposed [4]-[7].

In this paper, we propose a design for a smart lead-lag PSS satisfying H_∞ control performance using the direct method for dimensional reduction. In our proposal, the parameters of the PSS are optimized by Particle Swarm Optimization (PSO) [8], and the H_∞ norm and desired response are used in the evaluation function of the PSO. We expect that the proposed PSS has H_∞ control performance and is highly robust. Moreover, the proposed PSS can be easily introduced and established know-how can be used because the structure is the same as that of existing PSSs. The validity of the proposed PSS is verified for a 3-machine 9-bus system by carrying out nonlinear simulations of three-phase to ground faults for system condition changes.

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2. H_∞ Control Theory

2.1. H_∞ control theory

For the closed loop system, the state equations of the generalized plant are expressed as follows.

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \tag{1}$$

where x represents the state variables; w, the disturbance; z, the controlled variable; u, the control input; and y, the observed variable $\left(x \in R^n, w \in R^{m1}, u \in R^{m2}, z \in R^{p1}, y \in R^{p1}\right)$.

The feedback control for a generalized plant $G(s)$ is given by using the controller $K(s)$:

$$u = Ky \tag{2}$$

The generalized plant $G(s)$ is expressed as:

$$G(s) = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \tag{3}$$

$$G_{ij}(s) = C_i \left(sI - A\right)^{-1} B_j + D_{ij}, \quad i, j = 1, 2 \tag{4}$$

As a result, the transfer function from w to z is:

$$T_{zw} = G_{11}(s) + \frac{G_{12}(s) G_{21}(s) K(s)}{1 - G_{22}(s) K(s)} \tag{5}$$

A controller that suppresses the value of the transfer function is required, because the aim is to suppress disturbances of the controlled value z. In H_∞ control theory, the H_∞ norm is used as an index of the size of the transfer function. The norm of a steady transfer function is defined by:

$$\|T_{zw}\|_\infty = \sup \frac{\|z\|_2}{\|w\|_2} \tag{6}$$

H_∞ control is defined as the problem of finding the controller $K(s)$ that internally stabilizes the closed-loop system in Fig. 1 and satisfies (7) for a given positive number γ. Here, the transfer function of the controller $K(s)$ is an $m^2 \times p^2$ matrix.

$$\|T_{zw}\|_\infty < \gamma \tag{7}$$

2.2. Dimensional reduction by direct method

The direct method [4] is one of the dimensional reduction methods that derive a low-dimension controller for a high-dimension controlled object. In the direct method, the parameters of the controller are determined by using some objective function under the condition that the controller structure is fixed. Direct dimensional reduction of the H_∞ controller adopts the H_∞ norm shown in the previous section as the objective function. The closed loop transfer function T_{wz} and the H_∞ norm $||T_{zw}||_\infty$ are derived from (5) which has the fixed-structure controller $K(s)$. The parameters of $K(s)$ are adjusted to satisfy the H_∞ norm constraint in (7). In this paper the structure of the controller $K(s)$ is identical to that of an existing PSS.

3. Particle Swarm Optimization

PSO [8] is a stochastic search technique which was proposed by J. Kennedy and R. Eberhart in 1995. PSO algorithm imitates the behavior of a flock of birds, and each bird, here *agent*, search for good solutions using information of position and velocity. The movement of the each *agent* from one point to the next is determined with a velocity vector defined as (8). Each *agent* knows the best position from its own experience (p_{best}) besides the best known position of whole flocks (g_{best}). The next velocity vector is determined by p_{best}, g_{best} and current velocity vector.

$$v_i^{k+1} = \omega \cdot v_i^k + c_1 \cdot rand_1 \cdot (p_{best\,i} - x_i^k) + c_2 \cdot rand_2 \cdot (g_{best\,i} - x_i^k) \tag{8}$$

where v_i^k is a velocity vector (*k*: iteration count , *i*: *agent* number); x_i^k , search point; ω, a weight of the current velocity vector; c_i, constant value; *rand*, a uniform random number between 0 and 1; p_{besti}, the position of the best solution of each *agent i*; g_{besti}, the position of the best solution among all *agents*.

ω (a weight of the first term) and c_i (weights of the second and third term) are defined as follows[9]:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \tag{9}$$

where ω_{max}= 0.9; ω_{min}= 0.4; *iter*, iteration count; $iter_{max}$, maximum iteration count.

$$c_1 = c_2 = 2 \tag{10}$$

Each *agent* updates its search point by (11) until it reaches the maximum iteration count.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{11}$$

4. Formulation of Proposed Evaluation Function for Dimensional Reduction

4.1. Elements of the evaluation function

We explain the elements of the evaluation function based on the aim of improving PSS performance.

A. H_∞ norm

If the value of the H_∞ norm is larger than 1, a penalty is added to the evaluation function in order to ensure H_∞ performance. Here, the value of the penalty is proportional to that of the H_∞ norm. By the procedure, solutions with high evaluation values are searched intensively. We can also find the controller with smallest H_∞ norm if no controller with an H_∞ norm smaller than 1 exists under the constraint of a fixed structure.

B. Control of power oscillation

When we design the reduced-dimension PSS controller, we need to take into account the reduction of the risk of the generator tripping and prompt suppression of the power oscillation [10]. These are evaluated based on the phase angle data obtained by transient stability calculations. We use an LMI-based H_∞ PSS for the evaluation [11]. In the proposed method, we make the oscillation within the desired value when the H_∞ PSS is installed. As the evaluation value, we adopt the sum of the absolute values of the difference between a phase angle with the proposed PSS and that of the H_∞ PSS.

C. Upper and lower bounds of the parameters

As we set an upper/lower bounds for the PSS parameters, we modify the parameters which over the limit. In addition, a penalty proportional to the excess amount of the bounds is imposed on the evaluation function in order to search adequately in the permission search space.

4.2. Proposed evaluation function

The proposed evaluation function is:

$$f = \sum_{time=0\sec}^{10\sec} \left| \delta_{H\infty} - \delta_{lead-lag} \right| + W_{f1} \cdot penalty1 + W_{f2} \cdot penalty2 \tag{12}$$

$$\|T_{zw}\|_\infty < 1 : penalty1 = 0, \quad \|T_{zw}\|_\infty > 1 : penalty1 = \|T_{zw}\|_\infty$$

where $\delta_{H\infty}$ is the value of the phase angle with the H∞ PSS, $\delta_{lead\text{-}lag}$ is the value of the phase angle with the proposed PSS, and $W_{f\,i}$ are weights of evaluation for the penalty terms of the function. We use the $W_{f1} = 10$, $W_{f2} = 50$ in this paper as an example. The *penalty*1 is added if the value of the H∞ norm is larger than 1. The *penalty*2 is added if the parameters excess the upper/lower bounds as a sum of the excess amount of the limit.

5. Design of the Proposed PSS

In this paper, we design a two-input ($\Delta P + \Delta\omega$ type) PSS that can control power swings of both long and short terms. The procedure for designing the proposed controller can be divided into five parts, as follows [12].

5.1. Definition of control target

A 3-machine 9-bus system model [13], [14] is used as a model for the proposed control design. In the system, generator 2 is the control target; therefore the designed PSS is installed at that generator. The system data and the generator models (AVR, GOV, etc.) are given in Ref. [14].

5.2. Definition of weight functions

We are designing a PSS for a distributed control system. Thus, we divide the 3-machine 9-bus system into 3 subsystems, and we make generator control system models for each subsystem. The generator control system model is shown in Fig. 1.

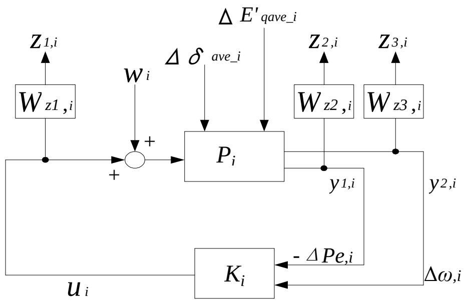

Fig. 1. Generator control system model of each subsystem.

In Fig. 1 $W_{z1,i}$ is the weight function for reducing the modeling error. $W_{z2,i}$ and $W_{z3,i}$ are the weight functions for reducing the control error. They are the sensitivity to active power deviations and angular velocity deviations, respectively. Generally, the frequency response of the modeling error is large in a high frequency band and that of the sensitivity for the control error is large in low frequency bands. Therefore, $W_{z1,i}$ is set to be large in high frequency bands, whereas $W_{z2,i}$ and $W_{z3,i}$ are set to be large in low frequency bands. The weight functions need to be adjusted by trial and error. In this paper, we select these weight functions when we design the H∞ PSS which is used to obtain the desired value, and we make use of them for the proposed reduced-dimension PSS. Each weight function is given by the following equation.

$$W(s) = K \cdot \frac{1+T_2 s}{1+T_1 s} \tag{13}$$

5.3. Definition of generalized plant

The equations of the generalized plant are

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \end{aligned} \tag{14}$$

where x represents the state variables; w, the disturbances; z, the controlled variables; y, the observed variables; and u, the control input.

The equations of the generalized plant in a ΔP + $\Delta\omega$ type H_∞ control system are given in (15)–(17). These equations apply to the subsystem of the i-th region.

$$\begin{bmatrix} \Delta\dot{\delta}_i \\ \Delta\dot{\omega}_i \\ \Delta\dot{E}'_{qi} \\ \Delta\dot{E}_{fdi} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{K_{1,ii}}{M_i} & -\frac{D_i}{M_i} & -\frac{K_{2,ii}}{M_i} & 0 \\ \frac{K_{4,ii}}{\tau'_{doi}} & 0 & -\frac{C_{3,ii}}{\tau'_{doi}} & \frac{1}{\tau'_{doi}} \\ -\frac{K_{Ai}}{T_{Ai}}K_{5,ii} & 0 & -\frac{K_{Ai}}{T_{Ai}}K_{6,ii} & -\frac{1}{T_{Ai}} \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \\ \Delta E_{fdi} \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_{Ai}}{T_{Ai}} \end{bmatrix} u_i + \begin{bmatrix} 0 & 0 & 0 \\ \sum_{j\neq i}\frac{K_{1,ij}}{M_i} & 0 & \sum_{j\neq i}\frac{K_{2,ij}}{M_i} \\ -\sum_{j\neq i}\frac{K_{4,ij}}{\tau'_{doi}} & 0 & \sum_{j\neq i}\frac{C_{3,ij}}{\tau'_{doi}} \\ \sum_{j\neq i}\frac{K_{Ai}}{T_{Ai}}K_{5,ij} & \frac{K_{Ai}}{T_{Ai}} & -\sum_{j\neq i}\frac{K_{Ai}}{T_{Ai}}K_{6,ij} \end{bmatrix} \begin{bmatrix} \Delta\delta_{ave\_i} \\ w_i \\ \Delta E'_{qave\_i} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} -\Delta Pe_i \\ \Delta\omega_i \\ u_i \end{bmatrix} = \begin{bmatrix} -K_{1,ii} & 0 & -K_{2,ii} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \\ \Delta E_{fdi} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_{ave\_i} \\ w_i \\ \Delta E'_{qave\_i} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_i \tag{16}$$

$$\begin{bmatrix} -\Delta Pe_i \\ \Delta\omega_i \end{bmatrix} = \begin{bmatrix} -K_{1,ii} & 0 & -K_{2,ii} & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{qi} \\ \Delta E_{fdi} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_{ave\_i} \\ w_i \\ \Delta E'_{qave\_i} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u_i \tag{17}$$

where Δ is the minimal change; δ, the rotor angle; ω, the angular velocity; E'_q, the q-axis component of the internal voltage; E_{fd}, the field voltage; ω_0, the nominal angular velocity ($2\pi f_0$); M, the inertia constant; K_1–K_6, the generator constants; K_A, the AVR gain; T_A, the AVR time constant; D, the damping coefficient; and τ'_{d0}, theopen circuit time constant. The averages are given by:

$$\Delta\delta_{ave\_i} = \frac{\sum_{j\neq i}\Delta\delta_j}{N-1}, \quad \Delta\omega_{ave\_i} = \frac{\sum_{j\neq i}\Delta\omega_j}{N-1}, \quad \Delta E'_{qave\_i} = \frac{\sum_{j\neq i}\Delta E'_{qj}}{N-1}, \quad \Delta E_{fdave\_i} = \frac{\sum_{j\neq i}\Delta E_{fdj}}{N-1}.$$

5.4. Definition of Parameters of the Controller

In our method, the structure of the controller is fixed as a 2-stage lead-lag compensator which is the existing PSS. The transfer functions of the PSS are

$$K_{PSS\_P} = K_P \cdot \frac{1+T_{P4}s}{1+T_{P3}s} \cdot \frac{1+T_{P2}s}{1+T_{P1}s} \tag{18}$$

$$K_{PSS\_\omega} = K_\omega \cdot \frac{1+T_{\omega 4}s}{1+T_{\omega 3}s} \cdot \frac{1+T_{\omega 2}s}{1+T_{\omega 1}s} \tag{19}$$

The parameters of K_P, K_ω, $T_{P1\text{–}4}$, and $T_{\omega 1\text{–}4}$ are selected using a PSO with upper and lower bounds

$$K_P,\ K_\omega \le 1.0, \quad 0.02 \le T_{P1-4}, T_{\omega 1-4} \le 1.0\,.$$

5.5. Evaluation of the Controller

The proposed PSS is evaluated using (12). We carried out 10 s simulations for 3-phase to ground faults using the 3-machine 9-bus system. The fault occurs at 0.01 s after the beginning of the simulation, one circuit of the double circuit lines is opened 0.07 s after the fault, and the re-closing is performed 0.6 s later.

6. Parameter Determination for Proposed PSS

We optimize the parameters of the PSS at nominal loading. We confirm that the value of the evaluation function decreases with the number of iteration by parameter optimization using PSO. In the simulation, the total number of solutions is 100 and the maximum number of iteration is 50.

The parameters of the PSS are show in Table 1. The value of the H_∞ norm is $||T_{zw}||_\infty$= 0.4347.

Table 1. Samples low-dimension PSS parameter

Input	K	T_1	T_2	T_3	T_4
ΔP	0.1903	0.0899	0.0193	0.0200	0.1457
$\Delta\omega$	0.6080	0.4809	0.9966	0.9870	0.0898

7. Simulations

7.1. Simulations of the proposed PSS

We compared the robustness of the proposed PSS and the conventional PSS by simulations of the 3-machine 9-bus system. Here, the parameters of the conventional PSS are shown in Table 2. They are tuned by trial and error to make the damping torque increase. We examined the robustness of each controller by performing transient stability calculations after changing the outputs and the total load of generator 2 and generator 3 from 0 to ±30%. The fault case used is the same as in the scenario described in Section 5. We use the maximum value of the phase angle and the settling time (±5%) as the evaluation index of PSS performance for power oscillations.

Table 2. Conventional PSS parameters

Input	K	T_1	T_2	T_3	T_4
ΔP	0. 30	0.15	0.20	0.15	0.20
$\Delta\omega$	0.20	0.20	0.25	0.20	0.25

7.2. Results

The values of the evaluation indices for changes of the operating points are shown in Fig. 2 and Fig. 3. From these results, we can confirm that the proposed PSS has better performance than the conventional PSS. When the outputs increase, the proposed PSS suppresses power oscillations effectively. However, at the operating points where the outputs are decreased by more than 15%, the settling time of the proposed PSS is longer than that of the conventional PSS. This result is caused by the characteristics of the H_∞ PSS, as shown below. The PSS based on H_∞ control theory is evaluated for high control performance at non-nominal and severe conditions.

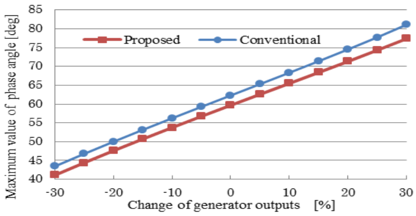

Fig. 2. Maximum values of phase angle at each operating point.

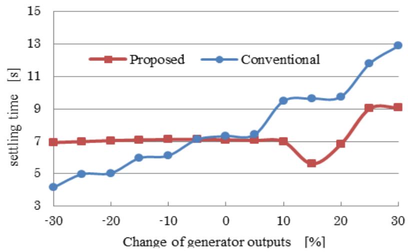

Fig. 3. Values of the settling time at each operating point.

8. Conclusion

In this paper, we proposed a smart design method of a lead-lag PSS using direct dimensional reduction. We optimized the PSS parameters by a PSO whose evaluation function considers the H_∞ norm and the oscillation of the phase angle. We carried out simulations for three-phase to ground faults at some operating points to verify the robustness of the proposed PSS. From the simulation results, we verified the effectiveness of the proposed PSS for the nominal model and under severe system conditions. We can achieve H_∞ performance in a smart manner and thereby solve the problems that come from the complexity and difficulty of a system with a high-dimensional controller.

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