Robust PID based power system stabiliser: Design and real-time implementation

H. Bevrani, T. Hiyama, H. Bevrani

Published (to be published) in: ***Electrical Power and Energy Systems***

(Expected) publication date: **2011**

Electrical Power and Energy Systems 33 (2011) 179–188

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Robust PID based power system stabiliser: Design and real-time implementation

Hassan Bevrani [a,*], Takashi Hiyama [b], Hossein Bevrani [c]

[a] Department of Electrical and Computer Eng., University of Kurdistan, Sanandaj, Iran
[b] Department of Electrical and Computer Eng., Kumamoto University, Kumamoto, Japan
[c] Department of Statistics, University of Tabriz, Tabriz, Iran

ARTICLE INFO

Article history:
Received 9 May 2009
Received in revised form 21 June 2010
Accepted 13 August 2010

Keywords:
Power system stabiliser
PID
Static output feedback control
LMI
Robust performance

ABSTRACT

This paper addresses a new robust control strategy to synthesis of robust proportional-integral-derivative (PID) based power system stabilisers (PSS). The PID based PSS design problem is reduced to find an optimal gain vector via an H∞ static output feedback control (H∞-SOF) technique, and the solution is easily carried out using a developed iterative linear matrix inequalities algorithm. To illustrate the developed approach, a real-time experiment has been performed for a longitudinal four-machine infinite-bus system using the Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Company. The results of the proposed control strategy are compared with full-order H∞ and conventional PSS designs. The robust PSS is shown to maintain the robust performance and minimise the effect of disturbances properly.

1. Introduction

From the view point of control engineering, a power system is a highly nonlinear and large scale multi-input multi-output (MIMO) dynamical system including numerous variables, protection devices, and control loops, with different dynamic responses and characteristics [1]. The *power systems stabilisers* (PSSs) which are widely used for mitigating the effects of low frequency oscillation modes improve the performance and functions of power systems during normal and abnormal operations. The PSSs keep the power system in a secure state and protect it from dangerous phenomena.

Most of continuous control loops such as PSSs operate directly on generator units, and are located at power plants. These controls are usually linear, continuously active, and use local measurements. Recently, several advanced control design approaches based on optimal control, robust control, adaptive control and intelligent control have been developed for power system stabilisation and oscillation damping [2–10]. Despite of the merits of such controls, power system utilities still prefer the simple proportional-integral-derivative (PID) and lag-lead PSS structures.

The parameters of conventional PSSs with simple structures are commonly tuned online based on experiences and trial and error approaches, they are incapable of obtaining good dynamical performance for a variety of disturbances and operating conditions. Complex and high order power system stabilisers are also inapplicable for real-world power systems. On the other hand, the modern and post modern control theory such as H∞ optimal control cannot be directly applied to the PID based PSS design problem. Indeed, until recently, it was not known how to even determine whether stabilisation of a nominal system was possible using PID controllers [11]. Therefore, an appropriate formulation of PSS in a robust PID control design (such as presented one in this paper) can be considered as a significant contribution.

The PID controller, because of its functional simplicity, is widely used in industrial applications. However, their parameters are often tuned using experiences or trial and error methods. Unfortunately, it has been quite difficult to properly tune of PID gains, because many industrial systems are often burdened with problems such as structure complexity, uncertainties and nonlinearities.

Over the years, many different parameter tuning methods have been presented for PID controllers. A survey up to 2002 is given in Refs. [12,13]. Most of these methods present modifications of the frequency response method introduced by Ziegler and Nichols [14]. Some efforts have also been made to find analytical approaches to tune the parameters [15–17]. Several tuning methodology based on robust and optimal control techniques are introduced to design of PI/PID controllers [18–22].

In parallel with other industries, the PID controllers are commonly used in power systems control and operation. However, because of expanding physical setups, functionality and complexity of power systems, it is very difficult to maintain a desired performance for a wide range of operation using conventionally tuned PID based power system controllers. Although the most of recent addressed approaches introduce high order control structure which have been proposed based on new contributions in modern

* Corresponding author.
E-mail address: bevrani@ieee.org (H. Bevrani).

0142-0615/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2010.08.013

control systems, because of complexity of control structure, numerous unknown design parameters and neglecting real constraints, they are not well suited to meet the design objectives in a real multi-machine power system.

Recently, some techniques have been proposed for tuning of PID based power system stabilisers (PSSs). Several self-tuning PID–PSSs were presented for improving the dynamic stability of single or multi-machine power systems [23–25]. In [26–28], state space eigenvalue analysis is carried out to determine the stable operating gain regions for PI and PID controllers to stabilise of power systems. The IEEE working group publications [29,30] summarise generally accepted PID controller tuning guidelines in terms of generator parameters with margins for stability. Some fuzzy logic based PID–PSSs were proposed in [31–33]. Refs. [34–36] used genetic algorithm (GA) and particle swarm optimisation (PSO) technique to set the PID gains of a power system stabiliser.

In the present paper, the PID based PSS design problem is transferred to an H∞ static output feedback (H∞-SOF) control problem. The main merit of this transformation is in possibility of using the well-known SOF control techniques to calculate the fixed gains, and once the SOF gain vector is obtained, the PID gains are ready in hand and no additional computation is needed.

In a given PID-based control system i, the measured output signal (for example the speed deviation ω_i) performs the input signal for the controller and we can write

$$u_i = k_{Pi}\omega_i + k_{Ii}\int \omega_i + k_{Di}\frac{d\omega_i}{dt}. \tag{1}$$

where k_{Pi}, k_{Ii} and k_{Di} are constant real numbers. In order to change (1) to a simple SOF control as $u_i = K_i y_i$, we can rewrite it as follows:

$$u_i = \begin{bmatrix} k_{Pi} & k_{Ii} & k_{Di} \end{bmatrix}\begin{bmatrix} \omega_i & \int\omega_i & \frac{d\omega_i}{dt} \end{bmatrix}^T \tag{2}$$

Therefore, by augmenting the power system description to include the ω_i, it's integral and derivative as a new measured output vector (y_i), the PID control problem becomes one of finding a SOF that satisfied prescribed performance requirements.

Finally, since the solution of resulted non convex inequalities using the general linear matrix inequalities (LMI) technique is not possible, to solve the H∞-SOF control problem and to obtain the optimal static gains (PID parameters), an iterative LMI algorithm is developed. The preliminary step of this work has been presented in [37].

The proposed controller only uses system frequency ω, which is a measurable signal; and the designed algorithm provides merely proportional gains; so gives considerable promise for implementation, especially in a multi-machine system. In fact, the proposed control strategy attempts to make a bridge between the simplicity of control structure (simple PID) and robustness of stability and performance (using H∞ theory) to satisfy the PSS tasks. In the proposed PSS solution, robust performance index, resulting from solution of the optimal H∞ synthesis, has been used as a robust performance measure for the sake of closed-loop stability and performance analysis.

To demonstrate the efficiency of the proposed control method, a real-time experience has been performed on a four-machine infinite-bus system using a large scale Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Company (Japan). The obtained results are compared with conventional and full-order H∞ controllers. The robust PID based PSS is properly shown to maintain the robust performance and minimise the effect of disturbances.

2. Power system modeling

In order to design a robust power system controller, it is first necessary to consider an appropriate linear mathematical description of multi-machine power system with two axis generator models. In the view point of 'generator unit i', the state space representation model for such a system has the form

$$\begin{aligned}
\dot{x}_{1i} &= x_{2i} \\
\dot{x}_{2i} &= -(D_i/M_i)x_{2i} - (1/M_i)\Delta P_{ei}(x) \\
\dot{x}_{3i} &= -(1/T'_{d0i})x_{3i} - (\Delta x_{di}(x)/T'_{d0i})\Delta I_{di}(x) + u_i \\
\dot{x}_{4i} &= -(1/T'_{q0i})x_{4i} - (\Delta x_{qi}(x)/T'_{q0i})\Delta I_{qi}(x)
\end{aligned} \tag{3}$$

where the states

$$x_i^T = \begin{bmatrix} x_{1i} & x_{2i} & x_{3i} & x_{4i} \end{bmatrix} = \begin{bmatrix} \delta_i & \omega_i & E'_{qi} & E'_{di} \end{bmatrix} \tag{4}$$

are defined as deviation form the equilibrium values

$$x_{ei}^T = \begin{bmatrix} \delta_{1i}^e & \omega_{2i}^e & E'^e_{qi} & E'^e_{di} \end{bmatrix} \tag{5}$$

and, here

$$\Delta x_{di} = x_{di} - x'_{di}, \Delta x_{qi} = x_{qi} - x'_{di} \tag{6}$$

$$\Delta P_{ei}(x) = (E'_{di}I_{di} + E'_{qi}I_{qi}) - (E'^e_{di}I^e_{di} + E'^e_{qi}I^e_{qi}) \tag{7}$$

$$\begin{aligned}
I_{di} = &\sum_k [G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}]E'_{dk} + \sum_k [G_{ik}\sin\delta_{ik} - B_{ik} \\
&\times \cos\delta_{ik}]E'_{qk}
\end{aligned} \tag{8}$$

$$\begin{aligned}
I_{qi} = &\sum_k [B_{ik}\cos\delta_{ik} - G_{ik}\sin\delta_{ik}]E'_{dk} \\
&+ \sum_k [G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}]E'_{qk}
\end{aligned} \tag{9}$$

A detailed description of all symbols and quantities can be found in [1]. Using the linearisation technique and after some manipulation, the nonlinear state Eq. (3) can be expressed in the form of following linear state space model.

$$\dot{x}_i = A_i x_i + B_i u_i \tag{10}$$

where

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & -\frac{D_i}{M_i} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & -\frac{G_{ii}\Delta x_{di}}{T'_{d0i}} \\ a_{41} & 0 & \frac{G_{ii}\Delta x_{qi}}{T'_{q0i}} & a_{44} \end{bmatrix}, \quad B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T'_{d0i}} \\ 0 \end{bmatrix} \tag{11}$$

3. H∞ SOF design

This section gives a brief overview for the H∞ based static output feedback (H∞-SOF) control design. Consider a linear time invariant system $G(s)$ with the following state-space realisation.

$$G_i(s): \begin{aligned} \dot{x}_i &= A_i x_i + B_{1i}w_i + B_{2i}u_i \\ z_i &= C_{1i}x_i + D_{12i}u_i \\ y_i &= C_{2i}x_i \end{aligned} \tag{12}$$

where x_i is the state variable vector, w_i is the disturbance vector, z_i is the controlled output vector and y_i is the measured output vector. The A_i, B_{1i}, B_{2i}, C_{1i}, C_{2i} and D_{12i} are known real matrices of appropriate dimensions.

The H∞-SOF control problem for the linear time invariant system $G_i(s)$ with the state-space realisation of (12) is to find a gain matrix K_i ($u_i = K_i y_i$), such that the resulted closed-loop system is

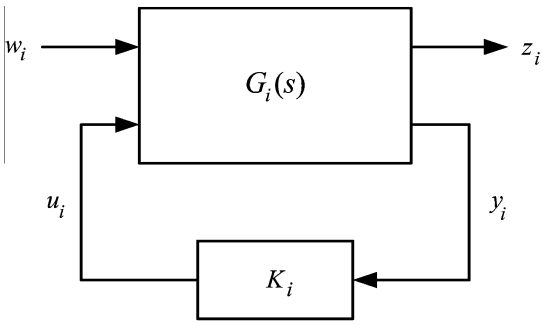

Fig. 1. Closed-loop system via H∞-SOF control.

internally stable, and the H∞ norm from w_i to z_i (Fig. 1) is smaller than γ, a specified positive number, i.e.

$$\|T_{z_i w_i}(s)\|_\infty < \gamma \tag{13}$$

$T_{z_i w_i}(s)$ is the transfer function from input disturbances (w_i) to output controlled signals (z_i). The vector z_i covers all significant output signals which must be minimised.

The H∞ norm of a system is the peak value of the magnitude of the transfer function over the whole frequency range. In a MIMO system, it is taken as the peak value of the maximum singular value response as function of frequency. Since the singular value provides maximum gain in the principal direction, H∞ norm is seen as the magnitude of some loop transfer function in the worst direction over the entire frequency range.

If required to find a controller to robustly stabilise the largest possible set of perturbations, in the sense of H∞ norm, it is then clear that we need to solve the minimisation problem of $\min_{K stabilising} \|T_{z_i w_i}(s)\|_\infty$. Since the control solution (K_i) must be obtained through the minimising of an H∞ optimisation problem, the designed feedback system satisfies the robust stability and robust performance for the overall closed-loop system.

This optimisation problem can be also interpreted as the design objectives of nominal performance, good tracking, disturbance attenuation, and robust stabilisation. In order to adopt a unified solution procedure, the above optimisation problem can be recast into a standard configuration as shown in Fig. 1. This can be obtained by using the linear fractional transformation (LFT) technique [38] and by specifying/grouping signals into sets of external inputs, outputs, input to the controller and output from the controller which of course is the control signal.

It is noteworthy that in Fig. 1, all the external inputs are denoted by w_i, while z_i denotes the output signals to be minimised which includes performance and robustness measures, y is the vector of measurements available to the controller K, and u_i the vector of control signals.

As mentioned, the objective is to find a stabilising controller K to minimise the output z_i, in the sense of energy, over all w with energy less than γ. Thus, it is equivalent to minimise the H∞ norm of the transfer function from w_i to z_i. The solution to the optimisation problem (13) is not unique except in the scalar case [39]. In practical design, it is usually sufficient to find a stabilising controller K such that the H∞ norm of the closed-loop transfer function is less than a given positive number, i.e., γ.

It is notable that the H∞-SOF control problem can be transferred to a generalised SOF stabilisation problem which is expressed via the following theorem [40].

Theorem. *The system (A, B, C) is stabilisable via SOF if and only if there exist $P > 0$, $X > 0$ and K_i satisfying the following quadratic matrix inequality*

$$\begin{bmatrix} A^T X + XA - PBB^T X - XBB^T P + PBB^T P & (B^T X + K_i C)^T \\ B^T X + K_i C & -I \end{bmatrix} < 0 \tag{14}$$

Here, the matrices A, B and C are constant and have appropriate dimensions. The X and P are symmetric and positive-definite matrices (Proof is given in [40]).

Since a solution for the consequent non convex optimisation problem (14) can not be directly achieved by using general LMI technique [41], a variety of methods were proposed by many researchers with many analytical and numerical methods to approach a local/global solution. In Section 4, to solve the resulted SOF problem, an iterative LMI is introduced based on the existence necessary and sufficient condition for SOF stabilisation via H∞ control technique.

The necessary condition for the existence of a solution is that the nominal transfer function $T_C(s) = kC_2[sI - A]^{-1}B$ should be strictly positive real [42], but satisfying this condition for dynamical systems in the presence of strong constraints and tight objectives are few and restrictive, and the inequality (14) may not approach a strictly feasible solution.

Here, the PID based PSS design problem is transferred to a SOF control design and the H∞ control is used via an iterative LMI algorithm to approach an optimal solution for the specified PSS design objectives. In comparison of other alternatives, the present methodology provides a more relaxed control strategy to invoke the strict positive realness condition, and to cover a wide range of design performance targets.

Since the solution for the PID based PSS design problem is obtained through minimising the H∞ performance index γ subject to the given constraints on the controller gain and behavior, the designed PID controller satisfies the robustness of the closed-loop system. In other words, the basis of designing the SOF controller is to stabilise the power system and guarantee the H∞ norm bound γ of the closed-loop transfer function T_{zw}, namely, $\|T_{zw}\|_\infty < \gamma$; $\gamma > 0$.

4. Proposed control strategy

4.1. Control framework

The overall block diagram of closed-loop control system is shown in Fig. 2a, where Δv_{refi} and d_i show the reference voltage deviation and system disturbance input, respectively. Using the linearised model for a given power system "*i*" in the form of (12) and performing the standard H∞-SOF configuration, which is shown in Fig. 2b, with considering appropriate controlled output signals results an effective control framework. This control structure adapts the H∞-SOF control technique with the described power system control targets and allows direct trade-off between robust performance and robust stability by merely tuning of a vector gain.

Here, disturbance input vector w_i, controlled output vector z_i and measured output vector y_i are considered as follows:

$$w_i^T = [\,\Delta v_{refi} \quad d_i\,] \tag{15}$$

$$z_i^T = [\,\eta_{1i} v_{ti} \quad \eta_{2i}\delta_i \quad \eta_{3i} u_i\,] \tag{16}$$

$$y_i^T = \begin{bmatrix} \omega_i & \int \omega_i & \frac{d\omega_i}{dt} \end{bmatrix} \tag{17}$$

where the ω_i and δ_i are the speed and rotor angle deviations. The η_{1i}, η_{2i} and η_{3i} are constant weights that must be chosen by designer to get the desired closed-loop performance.

Since the vector z_i properly covers all significant controlled signals which must be minimised by an ideal PSS design, it is expected that the proposed robust controller could be able to

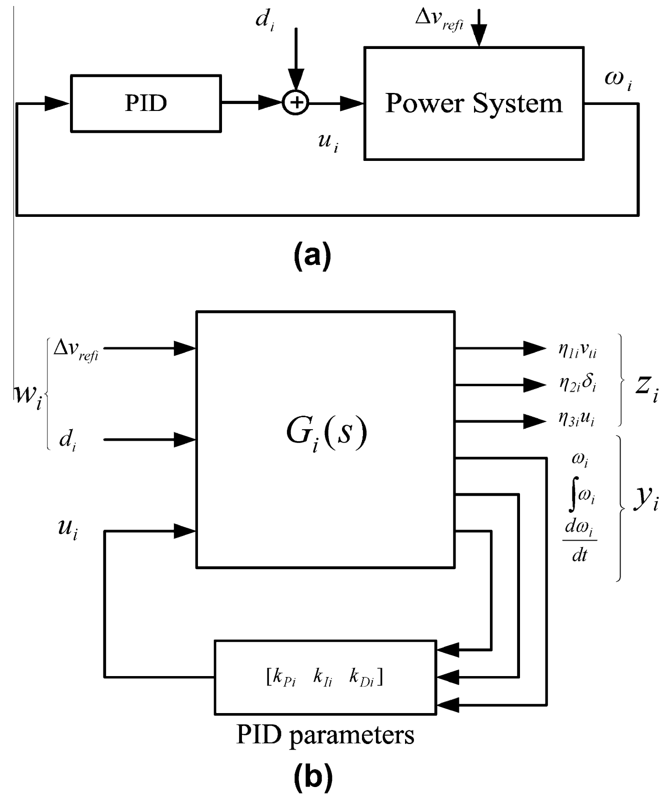

Fig. 2. The proposed control framework; (a) closed-loop block diagram and (b) H∞-SOF control configuration.

satisfy the voltage regulation and stabilising objectives, simultaneously. It is notable that, since the solution must be obtained trough the minimising of an H∞ optimisation problem, the designed feedback system satisfies the robust stability and robust performance for the overall closed-loop system. Moreover, the developed iterative LMI algorithm (which is described in the next section) provides an effective and flexible tool to find an appropriate solution in the form of a simple static gain controller.

4.2. Developed ILMI algorithm

In order to solve the H∞-SOF, an iterative LMI algorithm has been used. The key point is to formulate the H∞ problem via a generalised static output stabilisation feedback such that all eigenvalues of $(A - BK_iC)$ shift towards the left half plane in the complex s-plane, to close to feasibility of (14). The described theorem in the previous section gives a family of internally stabilising SOF gains is defined as K_{sof}. The desirable solution K_i is an admissible SOF law

$$u_i = K_i y_i, K_i \in K_{\text{sof}} \tag{18}$$

such that

$$\|T_{ziwi}(s)\|_\infty < \gamma^*, \; |\gamma - \gamma^*| < \varepsilon \tag{19}$$

where ε is a small positive number. The performance index γ^* indicates a lower bound such that the closed-loop system is H∞ stabilisable. The optimal performance index (γ), can be obtained from the application of a full dynamic H∞ dynamic output feedback control method.

The proposed algorithm, which gives an iterative LMI solution for above optimisation problem, includes the following steps:

Step 1. Set initial values (for constant weights and other parameters) and compute the new (generalised) system (A_g, B_g, C_g) for the given power system (12) as follows:

$$A_g = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix},$$
$$B_g = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix}, \quad C_g = [C_{2i} \quad 0 \quad 0] \tag{20}$$

Step 2. Set $i = 1$, $\Delta\gamma = \Delta\gamma_0$ and let $\gamma_i = \gamma_0 > \gamma$. $\Delta\gamma_0$ and γ_0 are positive real numbers.
Step 3. Select $Q > 0$, and solve $\overline{X}$ from the following algebraic Riccati equation

$$A_g^T\overline{X} + \overline{X}A_g - \overline{X}B_gB_g^T\overline{X} + Q = 0 \tag{21}$$

Set $P_1 = \overline{X}$.
Step 4. Solve the following optimisation problem for $\overline{X}_i$, K_i and a_i.

Minimise a_i subject to the LMI constraints:

$$\begin{bmatrix} A_g^T\overline{X}_i + \overline{X}_iA_g - P_iB_gB_g^T\overline{X}_i - \overline{X}_iB_gB_g^TP_i + P_iB_gB_g^TP_i - a_i\overline{X}_i & (B_g^T\overline{X}_i + K_iC_g)^T \\ B_g^T\overline{X}_i + K_iC_g & -I \end{bmatrix} < 0 \tag{22}$$

$$\overline{X}_i = \overline{X}_i^T > 0. \tag{23}$$

Denote a_i^* as the minimised value of a_i.
Step 5. If $a_i^* \le 0$, go to step 8.
Step 6. For $i > 1$, if $a_{i-1}^* \le 0$, $K_{i-1} \in K_{\text{sof}}$ is an H∞ controller and $\gamma^* = \gamma i + \Delta\gamma$ indicates a lower bound such that the above system is H∞ stabilisable via SOF control. Go to step 10.
Step 7. If $i = 1$, solve the following optimisation problem for $\overline{X}_i$ and K_i:
Minimise trace $(\overline{X}_i)$ subject to the above LMI constraints (22), (23) with $a_i = a_i^*$. Denote $\overline{X}_i^*$ as the $\overline{X}_i$ that minimised trace $(\overline{X}_i)$. Go to step 9.
Step 8. Set $\gamma_i = \gamma_i - \Delta\gamma$, $i = i + 1$. Then do steps 3–5.
Step 9. Set $i = i + 1$ and $P_i = \overline{X}_{i-1}^*$, then go to step 4.
Step 10. If the obtained solution (K_{i-1}) satisfies the gain constraint and performance requirement, it is desirable, otherwise retune constant weights (η_i) and go to step 3.

The proposed iterative LMI algorithm shows that if we simply perturb A_g to $A_g - (a/2)I$ for some $a > 0$, then we will find a solution of the matrix inequality (12) for the performed generalised plant. That is, there exist a real number ($a > 0$) and a matrix $P > 0$ to satisfy inequality (22). Consequently, the closed-loop system matrix $A_g - B_gKC_g$ has eigenvalues on the left-hand side of the line $\Re\,(s) = a$ in the complex s-plane. Based on the idea that all eigenvalues of $A_g - B_gKC_g$ are shifted progressively towards the left half plane through the reduction of a. The given generalised eigenvalue minimisation in the developed iterative LMI algorithm guarantees this progressive reduction.

4.3. Tuning of constant weights

The vector $\eta = [\eta_1 \; \eta_2 \; \eta_3]$ is a constant weight vector, and as mentioned it must be chosen by the designer to get a desired closed-loop performance. The selection of performance constant weights η_1 and η_2 is dependent on the specified voltage regulation and damping performance goals. In fact an important issue with regard to selection of these weights is the degree to which they can guarantee the satisfaction of design performance objectives. Furthermore, η_3 sets a limit on the allowed control signal to penalise fast changes, large overshoot with a reasonable control gain to meet the feasibility and the corresponded physical constraints.

The proposed H∞ control strategy includes enough flexibility to set a desired level of performance to cover the practical constraint on the control action signal. It is easily performed by proper tuning of constant weights, specifically η_3 (16), in the fictitious controlled outputs. Here, the weights selection process will be done automatically through the ILMI algorithm. At the first step (step 1), an initial value for η ($\eta^0 = [\eta_1^0\ \eta_2^0\ \eta_3^0]$, e.g. [1 1 1]) is considered as well as for other parameters. Finally in step 10, the H∞ solution will be checked to meet the gain constraint and desirable performance. In case of failing, the algorithm will be rerun for another weight values, and so on.

5. Real-time implementation

In the proposed PSS design methodology, an important goal was to keep the simplicity of control algorithms (as well as control structure) for computing the PID parameters. For the reasons of simplicity, flexibility, and straight forwardness of the control algorithms, this work acts as a catalyst to bridge the gap between robust H∞ control theory and real-world PSS synthesis as well as the gap between classical and modern PSS tuning methods.

To illustrate the effectiveness of the proposed control strategy, a real-time experiment has been performed on the large scale Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Company.

5.1. Test system

The test system is a modified 12-bus, 4-machine model of the West Japan Power System. A single line representation of the study system is shown in Fig. 3. Although, in the given model the number of generators is reduced to four, it closely represents the dynamic behavior of the west part of the West Japan Power System, and it is widely used by Japanese researchers [3,5,8]. The most important global and local oscillation modes of actual system are included. Each unit is considered as a thermal unit, which uses a separate conventional excitation control system as shown in Fig. 4a and b.

Each unit has a full set of governor-turbine system including governor, steam valve servo-system, high-pressure turbine, intermediate-pressure turbine, and low-pressure turbine, which is shown in Fig. 5. The generators, lines, conventional excitation system and governor-turbine parameters are given in Tables 1–4 (Appendix A), respectively.

5.2. Laboratory implementation

The whole power system (shown in Fig. 3) has been implemented in the mentioned laboratory. Fig. 6 shows an overview of the applied laboratory experiment devices including the hardware and control/monitoring desk.

Unit 1 is selected to be equipped with robust PID control, and therefore our objective is to apply the control strategy described in the previous section to controller design for unit 1. Using the

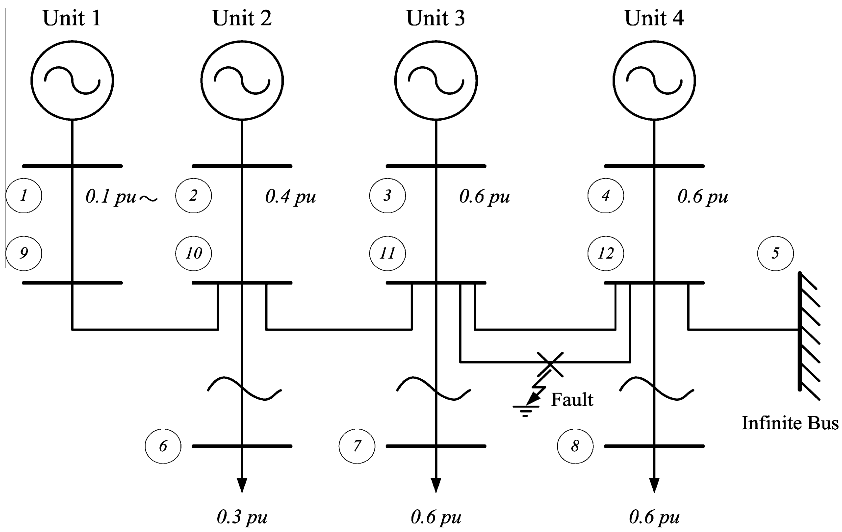

Fig. 3. Four-machine infinite-bus power system.

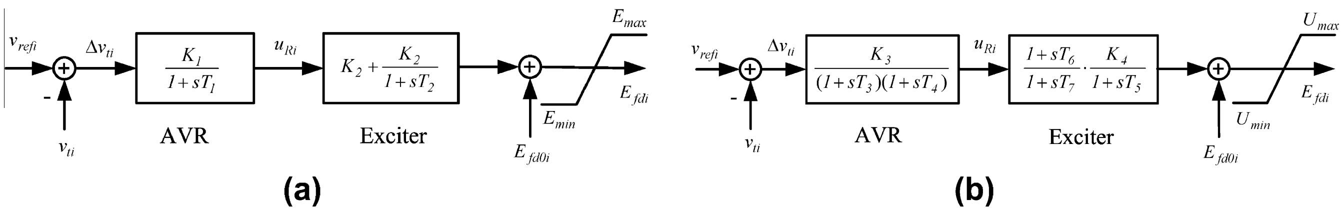

Fig. 4. Conventional excitation control system; (a) for units 2 and 3 and (b) for units 1 and 4.

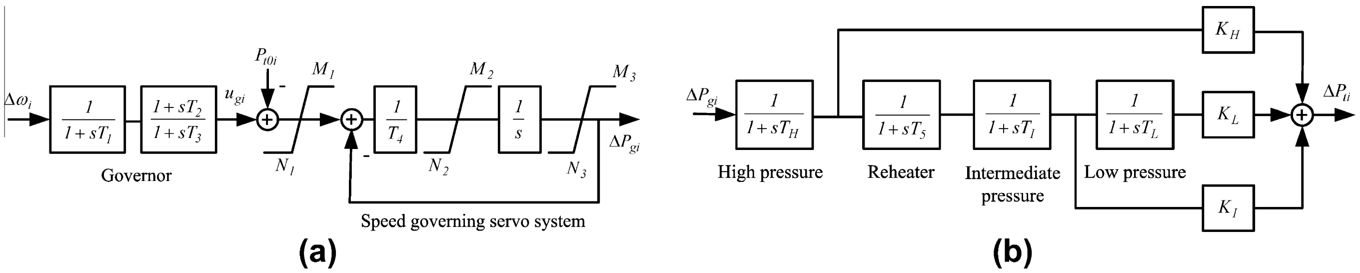

Fig. 5. Governor-turbine system; (a) speed governing system and (b) detailed turbine system.

Table 1
Generator constants.

Unit no.	M_i (s)	D_i	x_{di} (pu)	x'_{di} (pu)	x_{qi} (pu)	x'_{qi} (pu)	T'_{d0i} (s)	T'_{q0i} (s)	MVA
1	8.05	0.002	1.860	0.440	1.350	1.340	0.733	0.0873	1000
2	7.00	0.002	1.490	0.252	0.822	0.821	1.500	0.1270	600
3	6.00	0.002	1.485	0.509	1.420	1.410	1.550	0.2675	1000
4	8.05	0.002	1.860	0.440	1.350	1.340	0.733	0.0873	900

Table 2
Line parameters.

Line no.	Bus–Bus	R_{ij} (pu)	X_{ij} (pu)	S_{ij} (pu)
1	1–9	0.02700	0.1304	0.0000
2	2–10	0.07000	0.1701	0.0000
3	3–11	0.04400	0.1718	0.0000
4	4–12	0.02700	0.1288	0.0000
5	10–6	0.02700	0.2238	0.0000
6	11–7	0.04000	0.1718	0.0000
7	12–8	0.06130	0.2535	0.0000
8	9–10	0.01101	0.0829	0.0246
9	10–11	0.01101	0.0829	0.0246
10	11–12	0.01468	0.1105	0.0328
11	12–5	0.12480	0.9085	0.1640

Table 3
Excitation parameters.

K_1	K_2	K_3	K_4	$\|E_{\max(\min)}\|$	$U_{\max}$	$U_{\min}$
1.00	19.21	10.00	6.48	5.71	7.60	−5.20
T_1 (s)	T_2 (s)	T_3 (s)	T_4 (s)	T_5 (s)	T_6 (s)	T_7 (s)
0.010	1.560	0.013	0.013	0.200	3.000	10.000

Table 4
Governor and turbine parameters.

Parameters	Unit 1	Unit 2	Unit 3	Unit 4
T_1 (s)	0.08	0.06	0.07	0.07
T_2 (s)	0.10	0.10	0.10	0.10
T_3 (s)	0.10	0.10	0.10	0.10
T_4 (s)	0.40	0.36	0.42	0.42
T_5 (s)	10.0	10.0	10.0	10.0
T_H (s)	0.05	0.05	0.05	0.05
T_I (s)	0.08	0.08	0.08	0.08
T_L (s)	0.58	0.58	0.58	0.58
K_H (pu)	0.31	0.31	0.31	0.31
K_I (pu)	0.24	0.24	0.24	0.24
K_L (pu)	0.45	0.45	0.45	0.45
M_1 (pu/min)	0.50	0.50	0.50	0.50
M_2 (pu/min)	0.20	0.20	0.20	0.20
M_3(pu/min)	1.50	1.50	1.50	1.50
N_1 (pu/min)	−0.50	−0.50	−0.50	−0.50
N_2 (pu/min)	−0.20	−0.20	−0.20	−0.20
N_3 (pu/min)	−0.50	−0.50	−0.50	−0.50

described control methodology in Section 4, a set of suitable constant weights and optimal PID parameters for the problem at hand is obtained as follows:

$$\eta = [0.80 \quad 0.25 \quad 10] \tag{24}$$

$$K_{\mathrm{PID}} = [k_P \quad k_I \quad k_D] = [0.9615 \quad 0.5308 \quad 0.2140] \tag{25}$$

The proposed PID control loop has been built in a personal computer (PC) connected to the power system using a digital signal processing board equipped with analog to digital (A/D) and digital to analog (D/A) converters as the physical interfaces between the PC and the Analog Power System hardware. The PC based PID configuration is shown in Fig. 7. In order to signal conditioning, the input/output scaling blocks are used to match the PC based controller and the Analog Power System hardware, and, high frequency noises are removed by an appropriate washout filter. The considered constraints on limiters and control loop gains are set according to the real power system control units and close to ones that exist for the conventional PSS unit.

6. Experiment results

The performance of the proposed robust PID (RPID) controller when a voltage deviation, fault and system disturbance is injected into the interconnected system is studied, and, the controller is compared with a conventional PSS (CPSS). The configuration of the applied CPSS that was accurately tuned by the expert operators (who have worked on the system for the several past years), is illustrated in Fig. 8; and its parameters are given in Table 5 (Appendix A). Furthermore, to provide a comparison of what is lost in performance using the simple PID controller over a high order controller to achieve the same purpose, an H∞ controller [43] is applied and its performance is compared with the RPID controller.

The robust PSS (as well as conventional one) is designed to damp the low frequency oscillation modes in range of 0.1–5 HZ which covers all significant oscillation modes of the system. The essential global oscillation mode of actual West Japan Power System is around 0.3 HZ. Depending on the individual generators, the local oscillation modes are varied in the frequency range of 0.1–2.5 HZ. There also exists an inter-area oscillation mode around 0.7 HZ.

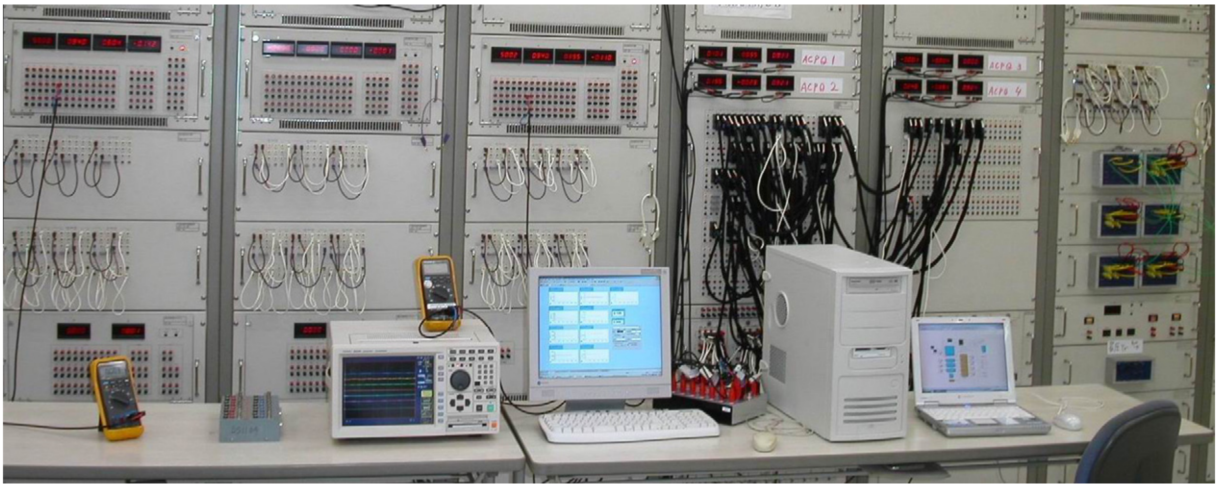

Fig. 6. Performed laboratory experiment.

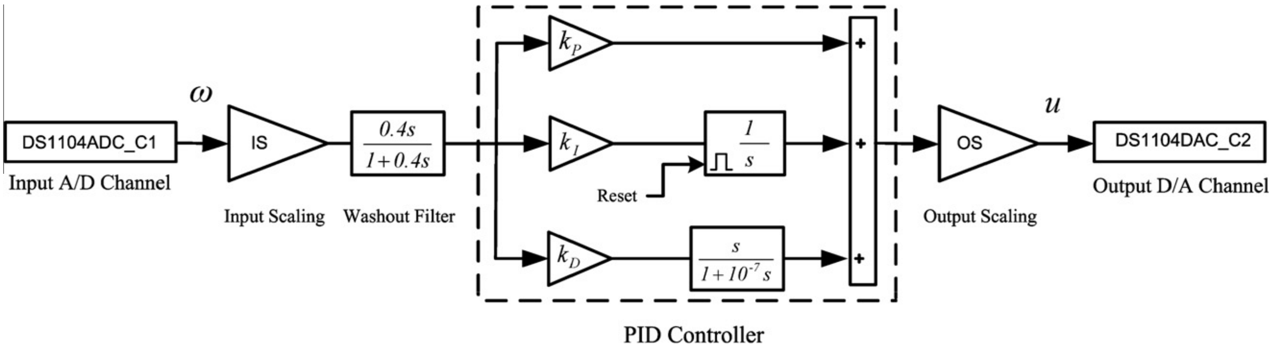

Fig. 7. PC-based implemented robust PID controller.

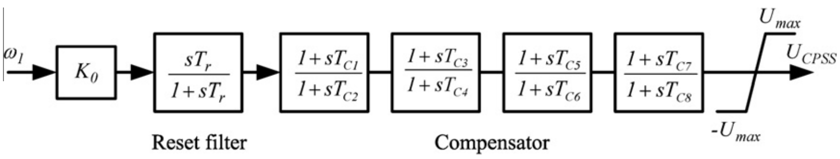

Fig. 8. Conventional power system stabiliser.

Table 5
Conventional PSS parameters.

K_0	T_r	T_{C1}	T_{C2}	T_{C3}	T_{C4}
10.0	5.00	0.01	0.02	0.00	0.03
T_{C5}	T_{C6}	T_{C7}	T_{C8}	U_{max}	
0.06	0.5	0.04	0.53	1.00	

Fig. 9 shows the electrical power of all units, with the terminal voltage, machine speed, and control signal of unit 1, following a fault on the line between buses 11 and 12 at 2 s. The fault was three-phase to ground short circuit type. To force a more critical test scenario, the faulted line was isolated from the network just after four cycles from the faulted starting point. It can be seen that in comparison of CPPS, the system response is quite improved using the designed RPID controller. Fig. 9 shows that although the proposed PID controller has a very simple structure, however it is able to maintain the robust performance as well as full-order H_∞ controller.

Furthermore, the size of resulted stable region by the proposed method is significantly enlarged in comparison of CPSS controller. To show this fact, the critical power output from unit 1 in the presence of a three-phase to ground fault is considered as a measure tool. To investigate the critical point, the real power output of unit 1 is increased from 0.1 pu (the setting of the real power output from the other units is fixed at the values shown in Fig. 3). Using the CPSS structure, the resulted critical power output from unit 1 to be 0.31 pu [5,8]; and in case of tight tuning of CPSS parameters (similar to the performed experiment in the present work) it could not be higher than 0.52 pu. The critical power output for the applied three PSS is given in Table 6.

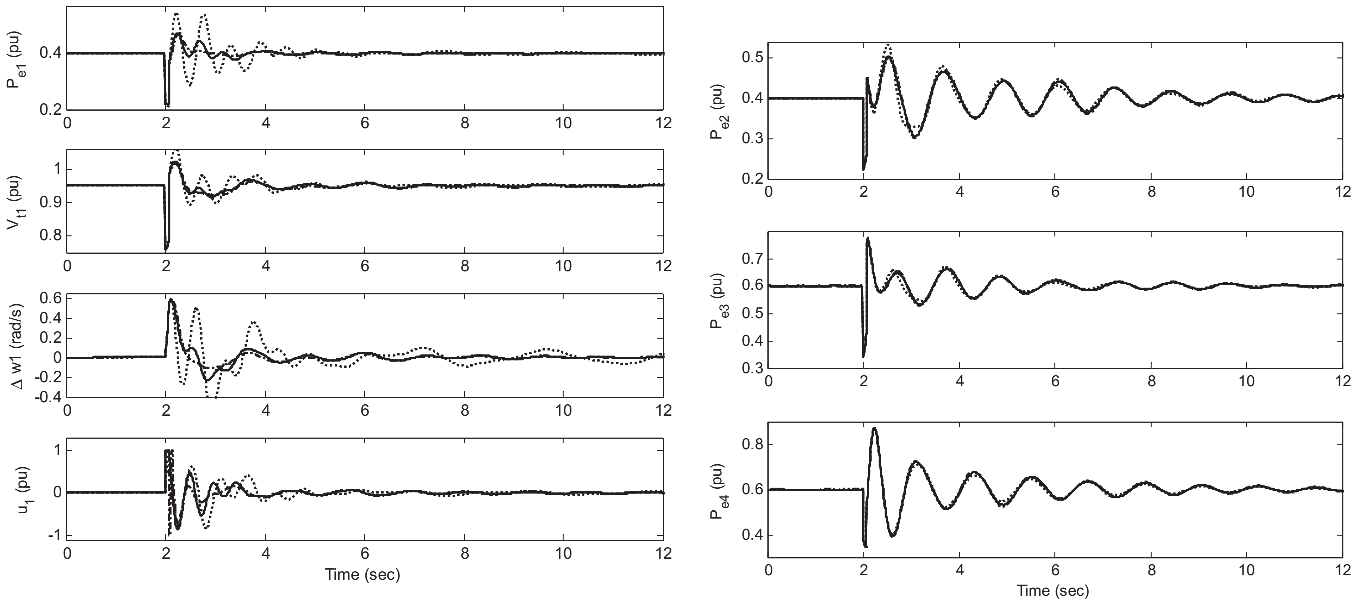

Fig. 9. System response for a fault between buses 11 and 12, while the output setting of unit 1 is fixed to 0.4 pu; solid (RPID), dash-dotted (H∞), dotted (CPSS).

Table 6
Critical power output of unit 1.

Control design	Critical power output (pu)
RPID	0.94
CPSS	0.52
H∞	0.96

It can be seen that the simple PID controller designed by this method has a stability margin that is comparable to the more complex H∞ controller. During the test scenarios appeared in this paper, the output setting of unit 1 is fixed to 0.4 pu.

In the second test case, the performance of designed controllers was evaluated in the presence of a 0.05 pu step disturbance injected at the voltage reference input of unit 1 at 20 s. Fig. 10 shows the closed-loop response of the power systems fitted with the CPSS, H∞ and the proposed RPID controllers. In comparison of CPSS, the better performance is achieved by the developed control strategy. Finally, the system response in the face of a step disturbance (d) in the closed-loop system (Fig. 2a) at 20 s, is shown in Fig. 11. Comparing the experiment results shows that the robust design achieves robustness against the voltage deviation, disturbance and line fault with a quite good damping performance.

7. Conclusion

In this work, to provide robust performance and stability over a wide range of power system operating points, a new tuning methodology has been proposed for robust PID based power system stabilisers. For this purpose, a control strategy is developed using H∞-SOF control technique via an iterative LMI algorithm.

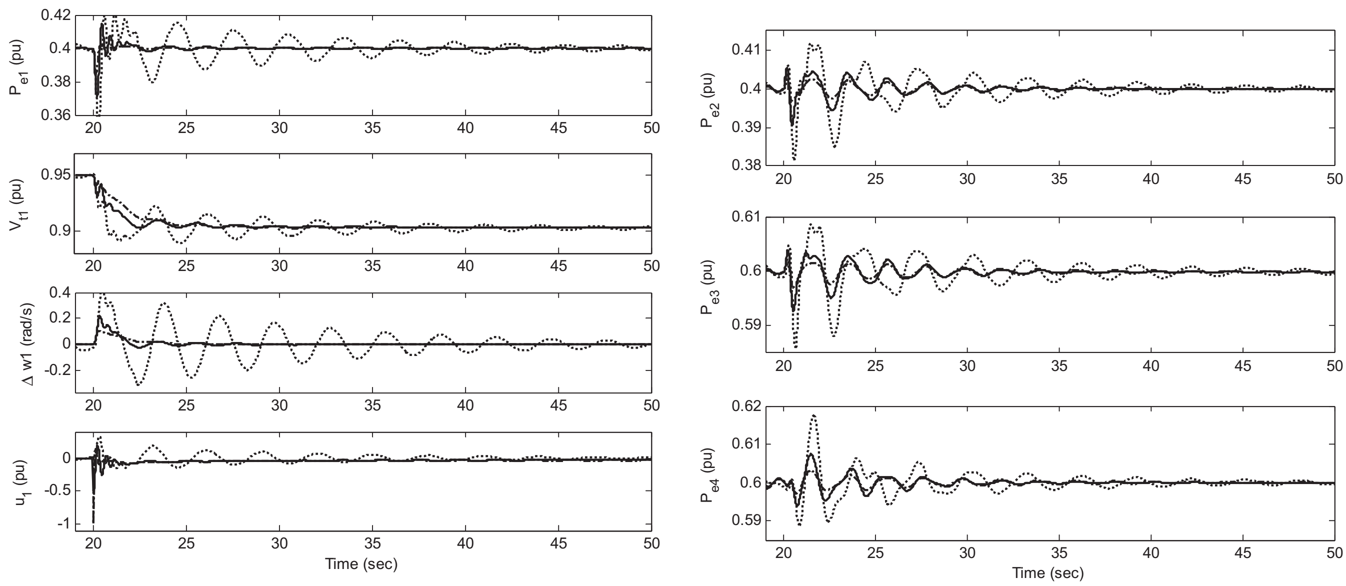

Fig. 10. System response for a 0.05 pu step change at the voltage reference input of unit 1; solid (RPID), dash-dotted (H∞), dotted (CPSS).

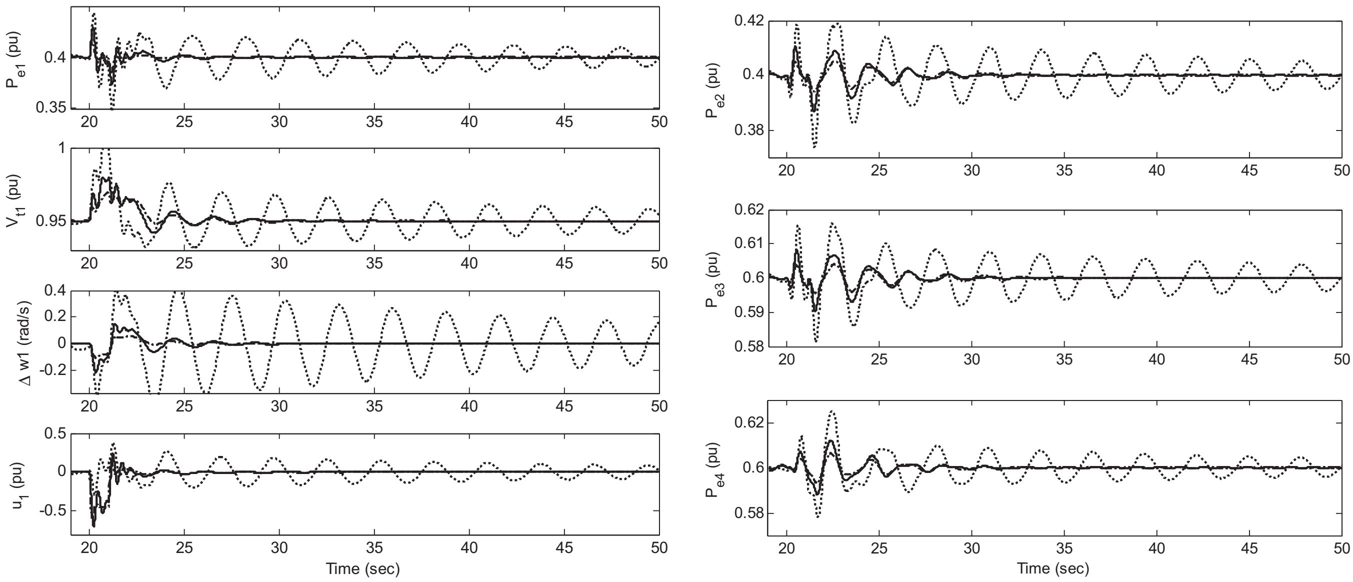

Fig. 11. System response for a step disturbance at 20 s; solid (RPID), dash-dotted (H∞), dotted (CPSS).

The proposed method was applied to a four-machine infinite-bus power system, through a real-time experiment, and the results are compared with conventional PSS and complex H∞ control designs. The performance of the resulting closed-loop system is shown to be satisfactory over a wide range of operating conditions.

As shown in the performed real-time laboratory experiments, the proposed robust PID control loop has brought a significant effect to improve the power system performance and to widen the stable region. It has been shown that the simple PID controller designed by this method has a performance and robust stability that is comparable with the more complex H∞ controller. Furthermore, because of simplicity of structure, decentralised property, ease of formulation and flexibility of design methodology, it is practically desirable.

Acknowledgments

This work is supported in part by Japan Society for the Promotion of Science (JSPS) under Grant P04346 and the Research Office at the University of Kurdistan. The authors would like to thank N. Wakasugi, A. Matsunaga, Y. Fujimoto, T. Kouichi, Y. Hirofumi and K. Hiroyuki for their helps to make a successful experiment in Research Laboratory of the Kyushu Electric Power Company.

Appendix A

The elements of A_i matrix in (11):

$$a_{21} = -\frac{1}{M_i}\frac{\partial f_{1i}(x)}{\partial x_{1i}}\bigg|_{x_{ei}}$$

$$a_{23} = -\frac{[G_{ii}E'^e_{qi} - B_{ii}E'^e_{di} + I^e_{qi}]}{M_i} - \frac{1}{M_i}\frac{\partial f_{1i}(x)}{\partial x_{3i}}\bigg|_{x_{ei}}$$

$$a_{24} = -\frac{[G_{ii}E'^e_{di} + B_{ii}E'^e_{qi} + I^e_{di}]}{M_i} - \frac{1}{M_i}\frac{\partial f_{1i}(x)}{\partial x_{4i}}\bigg|_{x_{ei}}$$

$$a_{31} = -\frac{\Delta x_{di}}{T'_{d0i}}\frac{\partial f_{2i}(x)}{\partial x_{1i}}\bigg|_{x_{ei}}, \quad a_{33} = -\frac{1}{T'_{d0i}} + \frac{B_{ii}\Delta x_{di}}{T'_{d0i}}$$

$$a_{41} = -\frac{\Delta x_{qi}}{T'_{q0i}}\frac{\partial f_{3i}(x)}{\partial x_{1i}}\bigg|_{x_{ei}}, \quad a_{44} = -\frac{1}{T'_{q0i}} + \frac{B_{ii}\Delta x_{qi}}{T'_{q0i}}$$

where

$$f_{1i}(x) = x_{4i}\Delta I_{di}(x) + x_{3i}\Delta I_{qi}(x) + \sum_{k\neq i}\Big\{[E'^e_{di}\eta_{ik}(\delta) + E'^e_{qi}\hat{\eta}_{ik}(\delta)]x_{4k} + \Big[E'^e_{di}\nu_{ik}(\delta) + E'^e_{qi}\hat{\nu}_{ik}(\delta)\Big]x_{3k} + [E'^e_{di}\upsilon_{ik}(\delta) + E'^e_{qi}\hat{\upsilon}_{ik}(\delta)]\sin\phi_{ik}\Big\}$$

$$f_{2i}(x) = \sum_{k\neq i}[\eta_{ik}(\delta)x_{4k} + \nu_{ik}(\delta)x_{3k} + \upsilon_{ik}(\delta)\sin\phi_{ik}]$$

$$f_{3i}(x) = \sum_{k\neq i}[\hat{\eta}_{ik}(\delta)x_{4k} + \hat{\nu}_{ik}(\delta)x_{3k} + \hat{\upsilon}_{ik}(\delta)\sin\phi_{ik}]$$

$$\eta_{ik}(\delta) = G_{ik}\cos\delta_{ik} + B_{ik}\sin\delta_{ik}, \hat{\eta}_{ik}(\delta) = B_{ik}\cos\delta_{ik} - G_{ik}\sin\delta_{ik}$$

$$\nu_{ik}(\delta) = G_{ik}\sin\delta_{ik} - B_{ik}\cos\delta_{ik}, \hat{\nu}_{ik}(\delta) = B_{ik}\sin\delta_{ik} - G_{ik}\cos\delta_{ik}$$

$$\upsilon_{ik}(\delta) = 2g1_{ik}\sin\frac{\delta^e_{ik} + \delta_{ik}}{2} + 2g2_{ik}\cos\frac{\delta^e_{ik} + \delta_{ik}}{2}, \phi_{ik} = 0.5(x_{1i} - x_{1k})$$

$$\hat{\upsilon}_{ik}(\delta) = 2g2_{ik}\sin\frac{\delta^e_{ik} + \delta_{ik}}{2} - 2g1_{ik}\cos\frac{\delta^e_{ik} + \delta_{ik}}{2}, \delta_{ik} = \delta_i - \delta_k$$

$$g1_{ik} = G_{ik}E'^e_{dk} - B_{ik}E'^e_{qk}, g2_{ik} = G_{ik}E'^e_{qk} + B_{ik}E'^e_{qk}$$

See Tables 1–5

References

[1] Sauer PW, Pai MA. Power system dynamic and stability. NJ, Prentice-Hall: Englewood Cliffs; 1998.
[2] Fernandez-Vargas J, Ledwich G. Variable structure control for power systems stabilization. Int J Electr Power Energy Syst 2010;32:101–7.
[3] Hiyama T, Kawakita M, Ono H. Multi-agent based wide area stabilization control of power systems using power system stabilizer. In: Proceedings of the IEEE international conference on power system technology; 2004.
[4] Wang SK, Chiou JP, Liu CW. Parameters tuning of power system stabilizers using improved ant direction hybrid differential evolution. Int J Electr Power Energy Syst 2009;31:34–42.
[5] Hiyama T, Kojima D, Ohtsu K, Furukawa K. Eigenvalue-based wide area stability monitoring of power systems. Control Eng Pract 2005;13:1515–23.
[6] Kashki M, Abdel-Magid YL, Abido MA. Parameter optimization of multimachine power system conventional stabilizers using CDCARLA method. Int J Electr Power Energy Syst 2010;32:498–506.
[7] Talaat HEA, Abdennour A, Al-Sulaiman AA. Design and experimental investigation of a decentralized GA-optimized neuro-fuzzy power system stabilizer. Int J Electr Power Energy Syst 2010;32:751–9.
[8] Hiyama T, Oniki S, Nagashima H. Evaluation of advanced fuzzy logic PSS on analog network simulator and actual installation on hydro generators. IEEE Trans Energy Convers 1996;11(1):125–31.
[9] Huerta H, Loukianov AG, Canedo JM. Decentralized sliding mode block control of multimachine power systems. Int J Electr Power Energy Syst 2010;32:1–11.

[10] Dou CX, Zhang XZ, Guo SL, Mao CC. Delay-independent excitation control for uncertain large power systems using wide-area measurement signals. Int J Electr Power Energy Syst 2010;32:210–7.

[11] Silva GJ, Datta A, Bhattacharyya SP. PID controllers for time-delay systems. Boston: Birkhauser; 2005.

[12] Astrom KJ, Hagglund T, Hang CC, Ho WK. Automatic tuning and adaptation for PID controllers – a survey. Control Eng Pract 1993;1:699–714.

[13] Cominos P, Munro N. PID controllers: recent tuning methods and design to specification. IEE Proc Control Theory Appl 2002;149(1):46–53.

[14] Ziegler JG, Nichols NB. Optimum setting for automatic controllers. Trans ASME 1942;64(11):759–65.

[15] Ho WK, Hang CC, Cao LS. Tuning of PID controllers based on gain and phase margin specifications. Automatica 1995;31(3):497–502.

[16] Isakson AJ, Graebe SF. Analytical PID parameter expressions for higher order systems. Automatica 1999;35(6):1121–30.

[17] Skogestad S. Simple analytic rules for model reduction and PID controller tuning. J Process Control 2003;13:291–309.

[18] Kristiansson B, Lennartson B. Robust and optimal tuning of PI and PID controllers. IEE Proc Control Theory Appl 2002;149(1):17–25.

[19] Grassi E, Tsakalis K, Dash S, Gaikwad SV, Macarthur W, Stein G. Integrated system identification and PID controller tuning by frequency loop-shaping. IEEE Trans Control Syst Technol 2001;9(2):285–94.

[20] Lin C, Wang QG, Lee TH. An improvement on multivariable PID controller design via iterative LMI approach. Automatica 2004;40:519–25.

[21] Zheng F, Wang QG, Lee TH. On the design of multivariable PID controllers via LMI approach. Automatica 2002;38:517–26.

[22] Ho MT. Synthesis of H_∞ PID controllers: a parametric approach. Automatica 2003;39:1069–75.

[23] Wu CJ, Hsu YY. Self-tuning excitation control for synchronous machine. IEEE Trans AES 1986;22:389–94.

[24] Wu CJ, Hsu YY. Design of self-tuning power system stabilizer for multimachine power systems. IEEE Trans Power Syst 1988;3(3):1059–63.

[25] Cheng S, Malik OP, Hope GS. Design of self-tuning PID stabilizer for a multimachine power system. IEE Proc – Part C 1986;133(4):176–85.

[26] Thrne DH, Hill EF. Field testing and simulation of hydraulic turbine governor performance. IEEE Trans Power App Syst, PAS-93 1974(4):1183–91.

[27] Thrne DH, Hill EF. Extensions of stability boundaries of a hydrolic turbine generating unit. IEEE Trans Power App Syst, PAS-94 1975(4): 1401–8.

[28] Phi DT, Bourque EJ, Thorme DH, Hill EF. Analysis and application of stability limits of a hydro-generating unit. IEEE Trans Power App Syst, PAS-100 1981:3203–11.

[29] IEEE Committee Report, Dynamic models for steam and hydro turbines in power system studies. IEEE Trans Power App Syst, PAS-92 1973(6):1904–15.

[30] IEEE working group on prime mover and energy supply models for system dynamic performance studies, hydraulic turbine and turbine control models for system dynamic studies. IEEE Trans Power Syst 1992;7(1):167–79.

[31] Hiyama T, Fujiki T. Fuzzy logic power system stabilizer using PID information of generator speed. IEEE Trans Power Energy 1993;113(12):1353–61.

[32] Hiyama T, kugimiya M, Satoh H. Advanced PID type fuzzy logic power system stabilizer. IEEE Trans Energy Convers 1994;9(3):514–20.

[33] Mrad F, Karaki S, Copti B. An adaptive Fuzzy-synchronous machine stabilizer. IEEE Trans Syst Man Cybern – Part C 2000;30(1):131–7.

[34] Wang YP, Watson NR, Chong HH. Modified genetic algorithm to design of an optimal PID controller for AC–DC transmission systems. Int J Electr Power Energy Syst 2002;24:59–69.

[35] Bera P, Das D, Basu TK, Design of PID power system stabilizer for multimachine system. In: Proceedings of the IEEE India annual conference (INDCON); 2004. p. 446–50.

[36] Chatterjee A, Mukherjee V, Ghoshal SP. Velocity relaxed and craziness-based swarm optimized intelligent PID and PSS controlled AVR system. Int J Electr Power Energy Syst 2009;31:323–33.

[37] Bevrani H, Hiyama T. Stability and voltage regulation enhancement using an optimal gain vector. In: Proceedings of the IEEE PES general meeting; 2006. p. 1–6 [Canada].

[38] Zhou K, Doyle JC, Glover K. Robust and optimal control. New Jersey: Prentice-Hall; 1995.

[39] Sanchez-Pena RS, Sznair M. Robust systems: theory and applications. John Wiley & Sons, Inc.; 1998.

[40] Cao YY, Lam J, Sun YX, Mao WJ. Static output feedback stabilization: an ILMI approach. Automatica 1998;34(12):1641–5.

[41] Boyed SP, El Chaoui L, Feron E, Balakrishnan V. Linear matrix inequalities in systems and control theory. Philadelphia (PA): SIAM; 1994.

[42] Narendra KS, Annaswamy AM. Stable adaptive systems. Englewood Cliffs (NJ): Prentice-Hall; 1989.

[43] Bevrani H, Hiyama T. Robust design of power system stabilizer: an LMI approach. In: Proceedings of the IASTED international conference on energy and power systems (CD ROM), Chiang Mai, Thailand; 2006.