TUNING OF POWER SYSTEM STABILIZERS VIA IMC

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Abstract: *A new method for tuning the parameters of a conventional power system stabilizer (CPSS) using the internal model control (IMC) method is presented. It is shown that the controller designed by the IMC method for a power system model can be reduced to the CPSS form, and the performance of the IMC-based CPSS is related to two tuning parameters so on-line tuning is easy. Simulation studies on a single machine infinite bus (SMIB) system and a four-machine two-area system show that the IMC-based CPSS can achieve good performance in damping both the local modes and the intra-area modes.*

Key words: *Power system stabilizer (PSS), internal model control (IMC), single machine infinite bus (SMIB) system, tuning, robustness*

1. Introduction

In the past five decades power system stabilizers (PSS) have been used to provide additional damping to automatic voltage regulators (AVR). High gain, fast acting AVRs are often designed in many generators to enhance large scale stability to hold the generator in synchronism with the power system during large transient fault conditions. But the high gain of excitation systems can decrease the damping torque of generator. Thus a supplementary excitation controller referred to as PSS have been added to synchronous generators to counteract the effect of high gain AVRs and other sources of negative damping [1]. With the growth of interconnected power systems and particularly the deregulation of the industry, PSSs become more important in suppressing the low-frequency oscillation and enhancing the system dynamic stability.

Conventional PSS (CPSS) is widely used in existing power systems. The parameters of CPSS are usually determined based on a linearized model of the power system around a nominal operating point where they can provide good performance [2]. Since power systems are highly non-linear systems, with configurations and parameters that change with time, the CPSS design based on the linearized model of the power system may not guarantee its performance in a practical operating environment.

To improve the performance of CPSS, numerous techniques have been proposed for the PSS design, e.g, pole-placement [3-6], damping torque concepts [2,7], robust [8-14], adaptive [15,16], nonlinear and variable structure [17-19], and the different optimizations and artificial intelligence techniques [20-25]. Simulation results have demonstrated the potential of these methods for practical applications. However, most methods have not yet been widely adopted in practical power utilities, especially those methods having a controller structure different from the CPSS form. Some of the reasons are [26]:

- Not easy to tune on-line. On-line tuning is important for practical applications, since there are always modeling and other errors. One cannot expect that controllers can be successfully put into operation for a complicated system without any final on-line tuning.
- Not enough robustness. Stabilizers are normally designed for the particular operating condition where they are most needed, however, they should also work under other operating conditions. Moreover, the design method should be insensitive to inaccurate data and unmodeled system dynamics.
- Not reliable in the long run. Theoretically self-tuning control can solve the above robustness issue. However, the convergence of the identification is difficult to guarantee. Furthermore, since inclusion of a self-tuning controller produces an additional non-linear system, it is also difficult to prove stability.

In this paper, a robust tuning method for the PSS will be proposed using the internal model control (IMC) method. It is shown that the controller designed by the IMC method can be reduced to the CPSS form, and the performance of the IMC-based CPSS is related to two tuning parameters so on-line tuning is easy. Simulation studies on a single machine infinite bus (SMIB) system and a four-machine two-area system show that the IMC-based CPSS can achieve good performance in damping both the local modes and the intra-area modes.

The paper is organized as follows: In Section 2, the power system model for PSS tuning is discussed and a transfer function model suitable for IMC tuning is proposed. In Section 3, the IMC design method is reviewed. Then the PSS is designed using the IMC method in Section 4, and the designed PSS is reduced to the CPSS form. In Section 5, the effectiveness of the IMC-based PSS tuning is demonstrated on two test systems. Finally, the paper is concluded in Section 6.

All the symbols used in this paper are listed in Table 1. All quantities are in pu except M in seconds, the time constants in seconds and δ in radians.

Table 1 List of Symbols

Δ	small deviation
δ	rotor angle
ω	rotor angle speed
ω_B	base speed
H	rotor inertia constant
D	rotor damping
x_d, x_q	d and q axes synchronous reactances
$x_d^{'}$	d-axis transient reactance
i_d, i_q	d and q axes generator currents
v_d, v_q	d and q axes generator voltages
V_t	generator terminal voltage
$E_q^{'}$	voltage proportional to field flux linkage
$T_{d0}^{'}$	d-axis transient open-circuit time constant
E_b	infinite bus voltage
E_{fd}	generator field voltage
T_m	mechanical torque
T_e	electrical torque
K_A	AVR gain
T_A	AVR time constant
V_{ref}	AVR reference input
x_e	external (line) reactance
P, Q	real and reactive power loading
$K_1, \cdots, K_6$	parameters of linearized system model
s	Laplace operator

2. Power system model

We consider the SMIB system. The model is simple but captures the essential dynamics of a power system and has been widely used for PSS design purpose.

It is assumed that the machine is equipped with an automatic voltage regulator (AVR) and a fast static excitation system. The d- and q-axis damper windings are ignored, and the machine is represented as follows:

$$\dot{\omega} = \frac{1}{2H}(T_m - T_e - D\omega) \tag{1a}$$

$$\dot{\delta} = \omega_B(\omega - 1) \tag{1b}$$

$$\dot{E}_q^{'} = \frac{1}{T_{d0}^{'}}(E_{fd} - E_q^{'} - (x_d - x_d^{'})i_d) \tag{1c}$$

$$\dot{E}_{fd} = -\frac{1}{T_A}E_{fd} + K_A(V_{\text{ref}} - V_t + u_{\text{PSS}}) \tag{1d}$$

$$T_e = v_d i_d + v_q i_q \tag{1e}$$

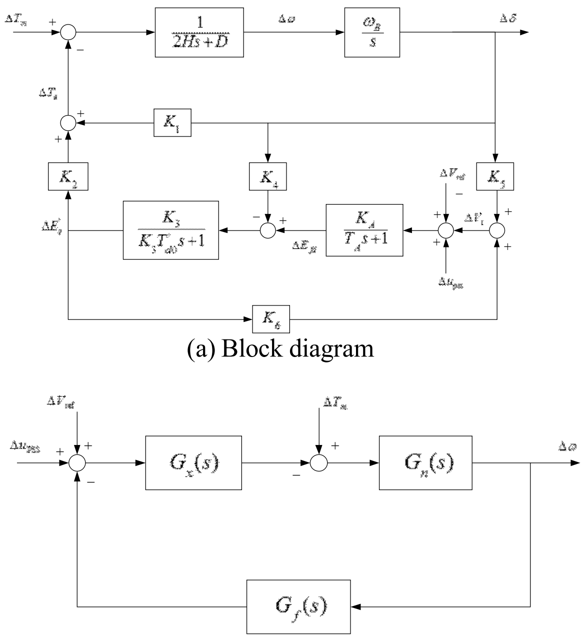
$$v_d = x_q i_q \tag{1f}$$

$$v_q = E_q^{'} - x_d^{'} i_d \tag{1g}$$

$$V_t^2 = v_q^2 + v_d^2 \tag{1h}$$

The linear time invariant model for this system is constructed by linearizing the system equations (1) around a given steady-state operating condition. The block diagram of the linearized system is shown in Fig.1(a) [27].

Three variables can be used as inputs to the PSS, i.e., $\Delta\omega$, $\Delta\delta$ and $\Delta(T_m - T_e)$. $\Delta\omega$ is the most often used variable, and in this paper we will discuss such case. By block diagram reduction, it is found that Fig.1(a) can be reduced to Fig.1(b), where



(b) Equivalent structure

Fig.1 Linearized model of SMIB

$$G_x(s) = \frac{K_x}{s^2 + 2\zeta_x\omega_x s + \omega_x^2} \tag{2}$$

with

$$K_x = \frac{K_2K_A}{T_{d0}^{\prime}T_A}, \omega_x = \sqrt{\frac{K_6K_A + 1/K_3}{T_{d0}^{\prime}T_A}},$$

$$\zeta_x = \frac{T_A + K_3T_{d0}^{\prime}}{2\omega_xK_3T_{d0}^{\prime}T_A}$$

and

$$G_n(s) = \frac{K_n s}{s^2 + 2\zeta_n\omega_n s + \omega_n^2} \tag{3}$$

with

$$K_n = \frac{1}{2H}, \omega_n = \sqrt{\frac{K_1\omega_B}{2H}}, \zeta_n = \frac{D}{4HK_1\omega_B}$$

and

$$G_f(s) = \tilde{k}_p + \frac{\tilde{k}_i}{s} \tag{4}$$

with

$$\tilde{k}_p = \frac{K_4\omega_BT_A}{K_A}, \tilde{k}_i = \frac{K_4\omega_B}{K_A} + K_5\omega_B$$

The objective of the PSS design is to find a controller

$$\Delta u_{\text{PSS}} = K_{\text{PSS}}(s)\Delta\omega \tag{5}$$

such that the effect from the disturbance (ΔT_m or

ΔV_{ref}) to the output ($\Delta\omega$) is minimized while keeping the internal stability of the closed-loop system. In other words, $K_{\text{PSS}}(s)$ must stabilize the transfer function from Δu_{PSS} to $\Delta\omega$,

$$P(s) = -\frac{G_x(s)G_n(s)}{1 + G_x(s)G_n(s)G_f(s)} \quad (6)$$

and minimize the transfer function

$$S(s) = \frac{P_d(s)}{1 + P(s)K_{\text{PSS}}(s)} \quad (7)$$

where

$$P_d(s) = \frac{G_n(s)}{1 + G_x(s)G_n(s)G_f(s)} \quad (8)$$

for rejecting ΔT_m, or

$$P_d(s) = \frac{G_x(s)G_n(s)}{1 + G_x(s)G_n(s)G_f(s)} \quad (9)$$

for rejecting ΔV_{ref}.

We are interested in the conventional PSS, i.e.,

$$K_{\text{CPSS}}(s) = K_s \frac{(T_1 s + 1)(T_3 s + 1)}{(T_2 s + 1)(T_4 s + 1)} \quad (10)$$

In practical power utilities, an optional washout filter of the form $\frac{T_w s}{T_w s + 1}$ is cascaded with (10) to filter the low frequency noise.

3. TDF-IMC design

Internal model control (IMC) is a popular control method in process control [28] and is widely used to tune PID controllers in chemical processes. In [29] the method was shown to be very effective in tuning load frequency controller for power systems, which motivated us to investigate IMC method for PSS design. The TDF-IMC tuning procedure goes as follows [29]:

1) Decompose the plant model $\tilde{P}(s)$ into two parts:

$$\tilde{P}(s) = P_M(s)P_A(s) \quad (11)$$

where $P_M(s)$ is the minimum-phase (invertible) part and $P_A(s)$ is the allpass (nonminimum-phase with unity magnitude) part.

2) Design a setpoint-tracking IMC controller

$$Q(s) = P_M^{-1}(s)\frac{1}{(\lambda s + 1)^r} \quad (12)$$

where λ is a tuning parameter such that the desired setpoint response is $\frac{1}{(\lambda s+1)^r}$, and *r* is the relative degree of $P_M(s)$.

3) Design a disturbance-rejecting IMC controller of the form

$$Q_d(s) = \frac{\alpha_m s^m + \cdots + \alpha_1 s + 1}{(\lambda_d s + 1)^m} \quad (13)$$

where λ_d is a tuning parameter for disturbance rejection, *m* is the number of poles of $\tilde{P}(s)$ such that $Q_d(s)$ needs to cancel. Suppose $p_1, \cdots, p_m$ are the poles to be canceled, then $\alpha_1, \cdots, \alpha_m$ should satisfy

$$\left(1 - \tilde{P}(s)Q(s)Q_d(s)\right)\Big|_{s=p_1,\cdots,p_m} = 0 \quad (14)$$

4) Transform it to a conventional unity feedback controller

$$K(s) = \frac{Q(s)Q_d(s)}{1 - \tilde{P}(s)Q(s)Q_d(s)} \quad (15)$$

The TDF-IMC design requires tuning two parameters (λ and λ_d) to achieve the desired tracking and disturbance performance. Usually the smaller they are, the better performance the IMC-based controller can achieve at a sacrifice on robustness.

4. Design of PSS via IMC

The above IMC design procedure can be applied directly to design PSS using model (6). However, such a design will lead to a high-order controller and cannot be realized as a conventional PSS. Since a CPSS is widely accepted in power utilities, we would like to have an IMC design that leads to CPSS structure.

To achieve the goal, we notice that $G_f(s)$ in Fig.1(b) is in the feedback loop, so when we design the PSS we can first ignore it. In other words, we can design a controller $K_{\text{IMC}}(s)$ for the forward-path transfer function in Fig.1(b) .

$$\tilde{P}(s) = G_x(s)G_n(s) = \frac{K_x}{s^2 + 2\zeta_x\omega_x s + \omega_x^2}\frac{K_n s}{s^2 + 2\zeta_n\omega_n s + \omega_n^2} \quad (16)$$

and then add the PI controller $G_f(s)$ to form the final PSS, i.e.,

$$K_{\text{PSS}}(s) = K_{\text{IMC}}(s) + G_f(s) \quad (17)$$

The procedure is illustrated in Fig.2.

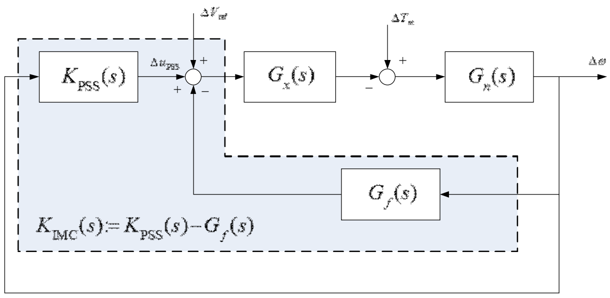


Fig.2 IMC design for SMIB

Now by the IMC design procedure, the setpoint-tracking IMC for (16) is

$$Q(s) = \frac{(s^2 + 2\zeta_x\omega_x s + \omega_x^2)(s^2 + 2\zeta_n\omega_n s + \omega_n^2)}{K_x K_n s(\lambda s + 1)^3} \quad (18)$$

We note that ω_n is the natural frequency of the SMIB system and the source of oscillations (small or negative damping ratio ζ_n. So the disturbance- rejection IMC $Q_d(s)$ can be used to cancel the poles of $G_n(s)$ to improve damping.

The disturbance-rejection IMC for (16) has the form

$$Q_d(s) = \frac{\alpha_2 s^2 + \alpha_1 s + 1}{(\lambda_d s + 1)^2} \quad (19)$$

with α_1, α_2 satisfying

$$\left(1 - \tilde{P}(s)Q(s)Q_d(s)\right)\Big|_{s=s_{1,2}} \quad (20)$$

where s_1, s_2 are two poles of $G_n(s)$, i.e.,

$$s_1 = -\zeta_n\omega_n + j\sqrt{1 - \zeta_n^2}\omega_n,$$

$$s_2 = -\zeta_n\omega_n - j\sqrt{1-\zeta_n^2}\omega_n \quad (21)$$

So α_1, α_2 can be solved from the following equations

$$\alpha_2 s_1^2 + \alpha_1 s_1 + 1 = (\lambda s_1 + 1)^3(\lambda_d s_1 + 1)^2$$
$$\alpha_2 s_2^2 + \alpha_1 s_2 + 1 = (\lambda s_2 + 1)^3(\lambda_d s_2 + 1)^2 \quad (22)$$

It should be pointed out that a fourth-order $Q_d(s)$ can be used to further cancel the poles of $G_x(s)$, but it is not necessary since ω_x is the frequency due to the fast static excitation system and generally has positive damping ratio ζ_x. Furthermore, the final controller will be too complex to explore the potential structure if a fourth-order $Q_d(s)$ is used.

Now transform the TDF-IMC controller to the conventional feedback controller

$$K_{\mathrm{IMC}}(s) = \frac{QQ_d}{1-\tilde{P}QQ_d} =: \frac{n(s)}{K_x K_n s d(s)} \quad (23)$$

where

$$n(s) = (s^2 + 2\zeta_x\omega_x s + \omega_x^2) \times (s^2 + 2\zeta_n\omega_n s + \omega_n^2) \times (\alpha_2 s^2 + \alpha_1 s + 1) \quad (24)$$
$$d(s) = (\lambda s + 1)^3(\lambda_d s + 1)^2 - (\alpha_2 s^2 + \alpha_1 s + 1)$$

By (22), $d(s)$ must have two zeros at s_1, s_2, so it contains the factor $s^2 + 2\zeta_n\omega_n s + \omega_n^2$. It is also obvious that $d(s)$ has a zero at $s = 0$, so $d(s)$ can be factored as

$$d(s) = K_z s(s^2 + 2\zeta_n\omega_n s + \omega_n^2)(s^2 + \beta_1 s + \beta_0) \quad (25)$$

where the parameters K_z, β_1, β_0 are

$$K_z = \lambda^3\lambda_d^2$$
$$\beta_0 = \frac{3\lambda + 2\lambda_d - \alpha_1}{\omega_n^2 K_z} \quad (26)$$
$$\beta_1 = \frac{3\lambda^2 + 6\lambda\lambda_d + \lambda_d^2 - \alpha_2}{\omega_n^2 K_z} - 2\zeta_n\omega_n\beta_0$$

So we have

$$K_{\mathrm{IMC}}(s) = \frac{(s^2 + 2\zeta_x\omega_x s + \omega_x^2)(\alpha_2 s^2 + \alpha_1 s + 1)}{K_x K_n K_z (s^2 + \beta_1 s + \beta_0) s^2} \quad (27)$$

This controller contains a double integrator. Since the PSS aims to damp out local and inter-area mode oscillations with frequency around 0.1-5.0Hz, the high gain at low frequency ($<$ 0.1Hz) is undesired, so the double integrator can be removed from the controller by approximating $\frac{\alpha_2 s^2 + \alpha_1 s + 1}{s^2}$ with α_2.

So the final IMC-based PSS has the following form

$$K(s) = \frac{\alpha_2(s^2 + 2\zeta_x\omega_x s + \omega_x^2)}{K_x K_n K_z (s^2 + \beta_1 s + \beta_0)} \quad (28)$$

It can be implemented in the conventional PSS form (10) with

$$T_1 = -\frac{1}{z_1}, T_3 = -\frac{1}{z_2}, T_2 = -\frac{1}{p_1}, T_4 = -\frac{1}{p_2}$$
$$K_s = \frac{\alpha_2}{K_x K_n K_z}\frac{T_2 T_4}{T_1 T_3} \quad (29)$$

where z_1, z_2 are zeros of $s^2 + 2\zeta_x\omega_x s + \omega_x^2$. If z_1, z_2 are complex, they can be set to $z_1 = z_2 = -\omega_x$. Similarly, p_1, p_2 are zeros of $s^2 + \beta_1 s + \beta_0$, and if p_1, p_2 are complex, they can be set to $p_1 = p_2 = -\sqrt{\beta_0}$.

Sample responses of a SMIB system with the three controllers ((27), (28) and (10), $G_f(s)$ is added to form the final PSS) are shown in Fig.3 when there is a step disturbance $\Delta T_m = 0.1$pu at $t = 1$. The system is discussed in [30] and the six parameters of the linearized model are

$$K_1 = 0.97, K_2 = 0.97, K_3 = 0.36,$$
$$K_4 = 1.24, K_5 = -0.05, K_6 = 0.46 \quad (30)$$

under nominal loading condition: $P_0 = 0.8$, $Q_0 = 0.55$ and $V_{t0} = 1.0$.

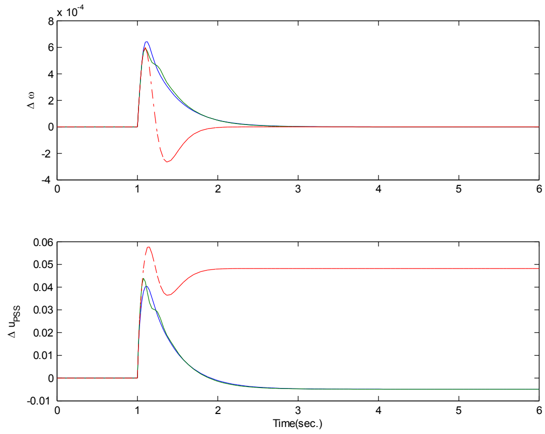


Fig.3 Responses of a SMIB system under designed PSSs with $G_f(s)$ (solid: (10)+G_f ; dashed:(28)+G_f; dashdotted: (27)+G_f)

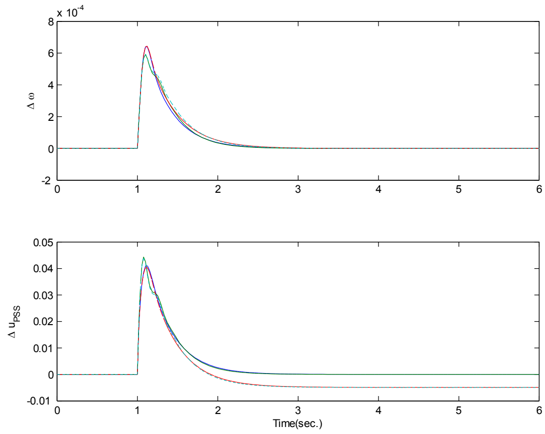


Fig.4 Responses of a SMIB system under designed PSSs without $G_f(s)$ (solid: (10) ; dashed:(28); dashdotted: (10)+G_f; dotted: (28)+G_f)

The zeros and poles of the controller (28) are complex so the controller (10) is different from (28). However, it can be observed that the responses of the two controllers are very close and (28) is just slightly better. So generally it is no harm to implement (28) in the form of (10). It is also observed that the double integrator in (27) causes large undershoot thus undesired.

While the final PSS formed by adding $G_f(s)$ to (28) or (10) achieves good damping performance, the PSS output (Δu_{PSS}) does not return to zero as $G_f(s)$ contains an integrator. To make sure that the PSS output returns zero the integrator can be removed. Furthermore, K_4, T_A are small compared with K_A thus $\tilde{k}_p$ is small. With the above reasons, $G_f(s)$ does not need to be added to the designed controller (28) or (10). In fact, with the same SMIB system the responses of the two controllers are shown in Fig.4. It is observed that without $G_f(s)$ the damping performance slightly degrades. However, compared with degradation due to possible low frequency noise, it is no harm and convenient to take (28) or (10) as the final PSS.

In summary, by some simplifications the TDF-IMC -based PSS has the CPSS form and the parameters of the CPSS are directly related to system parameters and two tuning parameters (λ, λ_d). Disturbance-rejection performance and robustness of the CPSS are determined by careful choice of the two tuning parameters.

5. Case studies

Two examples are used to illustrate the proposed tuning method. One is a SMIB system to test the performance for local mode oscillations and the robustness with different operating conditions. The other is a four-machine two-area system to test the performance for intra-area mode oscillations and performance under large perturbations.

5.1 Test in SMIB system

Consider the SMIB system discussed in [11,14] with

$$x_d = 2.0, x_q = 1.91, x'_d = 0.244$$
$$T'_{d0} = 4.18, H = 3.25, \omega_B = 2\pi \times 50$$
$$E_b = 1.0, K_A = 50.0, T_A = 0.05 \quad (31)$$

The operating condition for the system is completely defined by the values of the real power P and the reactive power Q at the generator terminals and the impedance of the transmission line x_e.

To test the robustness of the tuned PSS, suppose P, Q, and x_e vary independently over the range $P \in [0.4, 1.0]$, $Q \in [-0.2, 0.5]$, and $x_e \in [0.2, 0.7]$. This encompasses almost all practical operating conditions for the generator and very weak to very strong transmission systems. The nominal operating point is $P = 0.5, Q = 0.0, x_e = 0.2$ as in [11]. The final CPSS (10) has the following parameters tuned with $\lambda = 0.05, \lambda_d = 0.1$:

$$K_s = 21.3946, T_1 = 0.0722, T_2 = 0.0203$$
$$T_3 = 0.1362, T_4 = 0.0203 \quad (32)$$

The Bode diagrams of the proposed CPSS and the CPSS optimized in [11] by the simplex method using QFT and the PSS designed in [14] using LMI method are shown in Fig.5. It is clear at the interested frequencies the proposed CPSS has the largest magnitude and is expected to have the best disturbance-rejection performance.

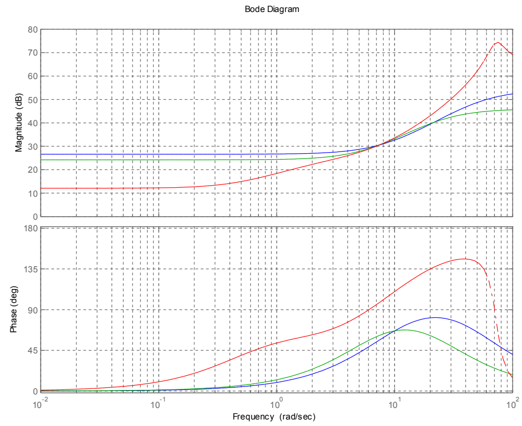
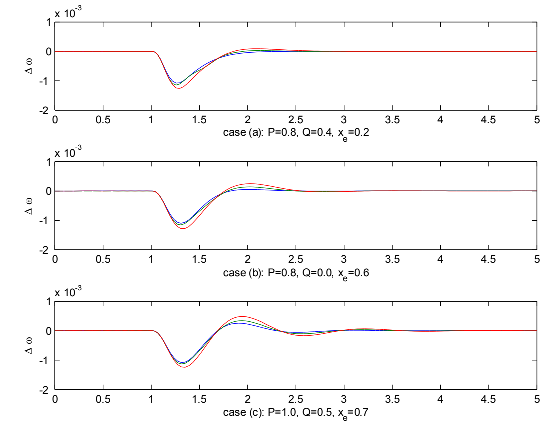
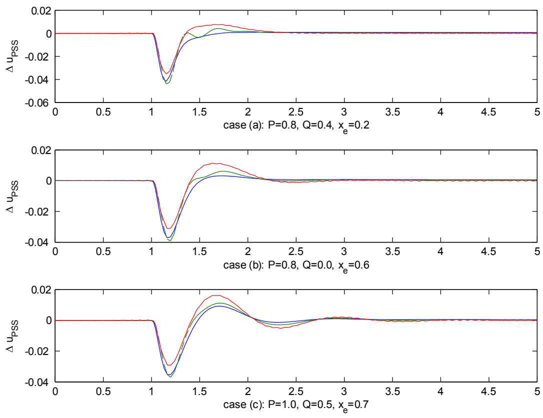


Fig.5 Bode plots of PSSs for SMIB test system (solid: proposed; dashed: [11]; dashdotted: [14])



(a) Rotor angle speed



(b) PSS ouput

Fig.6 Responses of SMIB test system (solid: proposed; dashed: [11]; dashdotted: [14])

To show the performance of the proposed CPSS, suppose at t=1 the SMIB system is subject to a 5% step disturbance at the reference voltage at three typical operating conditions:

Case (a): $P = 0.8, Q = 0.4, x_e = 0.2$;
Case (b): $P = 0.8, Q = 0.0, x_e = 0.6$;
Case (c): $P = 1.0, Q = 0.5, x_e = 0.7$.

The responses of the power system with the proposed CPSS and the PSSs in [11] and [14] are shown in Fig.6. The proposed PSS achieves the best damping without loss of robustness.

5.2 Test in Multimachine Power System

The PSS tuning for a SMIB system shows that the tuned PSS is satisfactory in damping local modes, we will show that it can achieve good performance in a multimachine system with a strong inter-area mode. For this purpose, we designed CPSSs for the well-known four-machine, two-area benchmark system shown in Fig.7. The data of this system is given in [1].

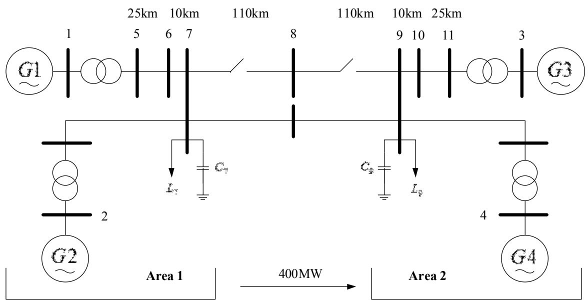


Fig.7 Four-machine two-area benchmark system

The two areas are assumed to be identical thus only two PSSs are needed to be tuned for generator G1 and G2. It is also noted that G1 and G2 differs only in the inertia constants (H) and other parameters are the same, so it is simple to use one parameter setting for both G1 and G2. We get the following parameters for the CPSS with $\lambda = 0.1$ and $\lambda_d = 0.1$:

$$K_s = 18.09, T_1 = 0.1392, T_2 = 0.0323$$
$$T_3 = 0.0010, T_4 = 0.0323 \qquad (33)$$

The Bode diagrams of the proposed CPSS and the CPSS given in [1] are shown in Fig.8. A washout filter with time constant $T_w = 10$ is cascaded in the implementation. It is observed that at the interested frequencies the proposed CPSS has larger magnitude and phase lead thus has better disturbance-rejection performance.

To test the performance of the proposed CPSS, suppose there is a 12-cycle pulse on the voltage reference of G1 at t=1, the responses of the system with the proposed CPSS and CPSS given in [1] are shown in Fig.9. It is observed that the proposed CPSS achieves better damping.

If we need to further improve the damping, we just need to decrease λ or λ_d. For instance, if λ_d is decreased to 0.05, then we get a CPSS with the following parameters:

$$K_s = 26.20, T_1 = 0.1392, T_2 = 0.0232$$
$$T_3 = 0.0010, T_4 = 0.0232 \qquad (34)$$

The rotor angle speed responses of the system with the re-tuned CPSS are shown in Fig.10. The performance is indeed improved.

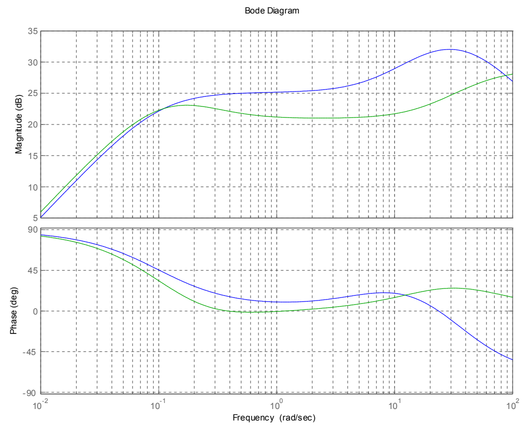
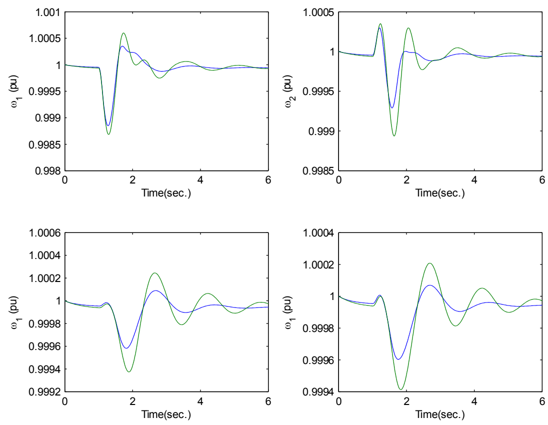
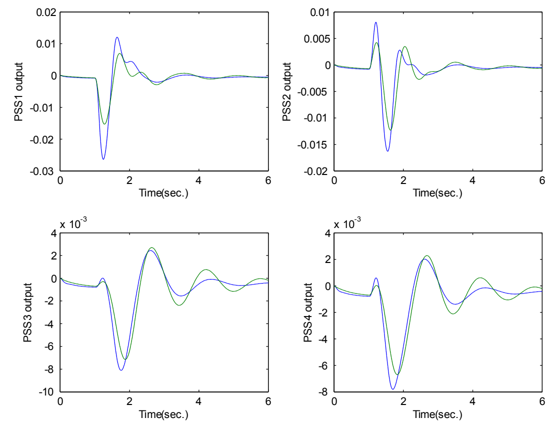


Fig.8 Bode plots of PSSs (solid: proposed; dashed: [1])



(a) Rotor angle speed



(b) PSS output

Fig.9 Responses of four-machine two-area system: small signal disturbance (solid: proposed;dashed: [1])

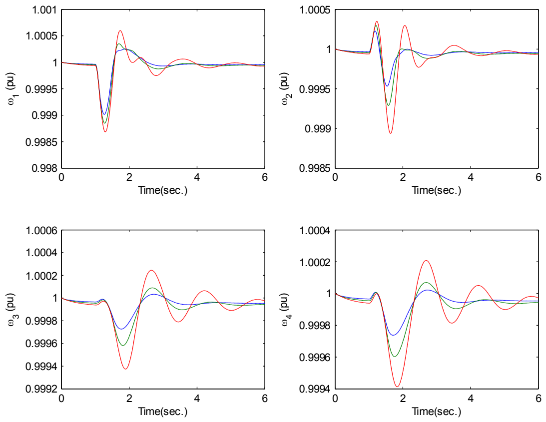


Fig.10 Responses of four-machine two-area system with re-tuned CPSS: small signal disturbance (solid: CPSS tuned with $\lambda = 0.1$, $\lambda_d = 0.05$; dashed: CPSS tuned with $\lambda = 0.1$, $\lambda_d = 0.1$; dashdotted: [1])

A PSS should not only have good small-signal performance, but also good performance during large perturbations and good robustness with respect to changing operating conditions. To show the performance of the PSSs against large perturbations, suppose there is a 8-cycle three-phase fault with the outage of one 230kV line at t=1, the responses of the system are shown in Fig.11. The proposed two CPSSs can ensure a smooth transition into another stable operating point as the CPSS given in [1].

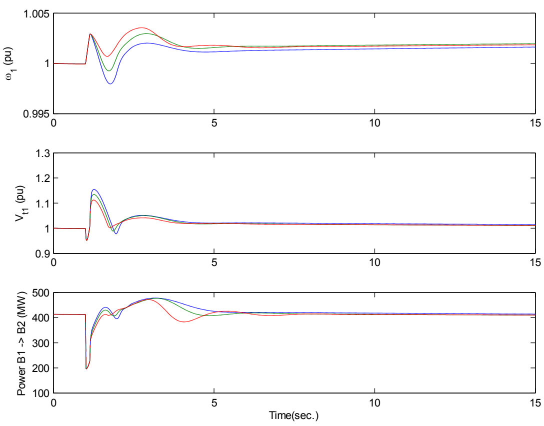


Fig.11 Responses of four-machine two-area system with re-tuned CPSS: large signal disturbance (solid: CPSS tuned with $\lambda = 0.1$, $\lambda_d = 0.05$; dashed: CPSS tuned with $\lambda = 0.1$, $\lambda_d = 0.1$; dashdotted: [1])

6. Conclusion

IMC method was applied to design PSS for power systems. By some simplifications, the IMC-based PSS was found to be able to be reduced to the conventional PSS structure. The parameters of the CPSS are directly related to the system parameters and two tuning parameters, which makes it easy to tune on-line. Simulations on a SMIB system and a multimachine system showed that with careful choice of the tuning parameters the tuned CPSS can achieve good performance with respect to both local and intra-area modes under wide range operating conditions and large disturbances.

IMC method is known to be able to achieve good compromise between robustness and disturbance-rejection performance for PID tuning. It is possible to use the guidelines on selecting tuning parameters for PID controllers in PSS tuning, however, due to the difference between the dynamics of the power systems and the simple first-order or second-order plus dead-time models in PID tuning, the selection of tuning parameters are not straightforward. Further research on this topic is under investigation.

Large power systems may exist strong inter-connections. Whether the method is effective in PSS tuning for large interconnected power system will also be investigated.

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