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A Study on Power System Stabilizer Using Output Feedback Adaptive Variable Structure Control

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Abstract

In this paper, an output feedback adaptive variable structure control scheme is presented for stabilization of large scale power systems. An additional input signal which is called a power system stabilizer (PSS) is needed to improve the stability of a power system and to maintain the synchronization of generators. The proposed PSS scheme does not require a priori knowledge of uncertainty bounds. It is guaranteed that the closed-loop system is globally uniformly ultimately bounded by the Lyapunov stability theory. Simulation results for a multimachine power system are given to show the feasibility of the proposed scheme and the superiority of the proposed PSS in comparison with the conventional lead-lag PSS of PID-type.

1 Introduction

Large scale power systems including the exciters and speed governors are usually subject to be affected by parameter variations and external disturbances. In the presence of severe disturbances, a power system accelerates quickly one or more generators, and then their synchronizations become lose. To improve the power system stability, an additional stabilizing signal is inserted into the excitation system. The controller generating this additional stabilizing signal is so-called the *power system stabilizer (PSS)* [1] ~ [6].

There are several methods used in power system stabilizers. Especially, the following three control methods for power systems have been developed and used: the conventional lead-lag compensator of PID-type controller [2] [3]; the optimal control theory [4]; the variable structure control [5] [6]. The above each method has the several typical problems. First, in the case of using the lead-lag circuit, the control gain tuning is not easy and tedious process, furthermore, time-consuming. Secondly, the optimal control requires a nonlinear Riccati matrix equation to obtain the optimal feedback gain, and thus it needs a lot of computational time. Finally, as a kind of general robust control, the variable structure control (VSC) such that the prescribed performance is achieved with the robustness to uncertainties has been much researched. It has been well-known in generally that this control method has the following problems: chattering phenominon, reaching time and a priori knowledge of uncertainty bounds. Third problem of the above three problems is critical in practical implementations and large scale complex systems.

In multivariable large scale real application systems, to measure all states is not easy, and requires very high costs and many good equipments [7]. Specially, the general power system is large scale and very multivariable one. It is necessary to develop an output feedback control scheme achieving the desired purpose by measuring a few available states, namely output signals.

In this paper, we present an output feedback adaptive variable structure control (OFAVSC) scheme using the Lyapunov stability theory. The proposed control scheme is applied to the power system stabilizer in order to overcome the problems mentioned in the above statements. The presented scheme is based on elimination of the restrictive assumption that the uncertainty bounds must be a priori known in the conventional robust control including VSC. The proposed scheme does not require the matching condition for uncertainties. To show the feasibility and usefulness of the presented stabilization scheme, simulation results for a multimachine system are presented.

2 Problem Formulation

The incremental model of exciter-generator power systems can be expressed as the following state-ouput equations.

$$\dot{x} = A(t)\,x + B(t)\,u + d(t) \quad (1)$$

$$y = C\,x \quad (2)$$

where $x \in \Re^n$ is the state vector; $u \in \Re^m$ is the control input vector, namely the output of PSS; $y \in \Re^p$ is the output vector of measurable signals or states; $d(t) \in \Re^n$ is the disturbance vector such as load power and mechanical torque variations, etc.; $A(t) = A_o + \Delta A(t) \in \Re^{n\times n}$ is the system matrix; $B(t) = B_o + \Delta B(t) \in \Re^{n\times m}$ is the input matrix; A_o and B_o are known constant nominal values and the pair (A_o, B_o) are completely controllable;

$\Delta A(t)$ and $\Delta B(t)$ represent unknown parameter variations; $\Delta A(t), \Delta B(t)$ and $d(t)$ represent the uncertainty terms and are continuous functions; $C \in \Re^{p\times n}$ is the output matrix.

The objective of the work is to develop a control law which guarantees that the closed-loop system has the uniformly ultimate bounded solution with a tolerable error under no knowledge of the uncertainty bounds.

The following assumptions are needed to develop a controller.

Assumption 1: (Lumped uncertainty)
It is assumed that all the uncertainties can be lumped. Rewriting the state equation (1),

$$\dot{x} = A_o x + B_o u + \eta(t) \quad (3)$$
$$y = C x \quad (4)$$

where $\eta(t) = \Delta A(t)\, x + \Delta B(t)\, u + d(t) \in \Re^n$ is called the *lumped uncertainty.*

Assumption 2: (Bound of uncertainty)
There exists an unknown positive constant ρ such that for all $t \in \Re^+$,

$$\|\eta\| \le \rho \quad (5)$$

Throughout this paper, the norm $\|\cdot\|$ is assumed to be the Euclidean vector norm, that is, $\|x\| = (x^T x)^{\frac{1}{2}}, x \in \Re^n$.

3 Output Feedback Adaptive Variable Structure Control

In the case that all state variables are measurable, the sliding hyperplane of the state feedback VSC/AVSC system is usually defined as the following equation.

$$s(x) = P\, x \quad (6)$$

where $P \in \Re^{m\times n}$, $s \in \Re^m$, P is full rank, and PB_o is a nonsingular matrix.

Now, the dynamic sliding hyperplane can be defined to construct an output feedback controller as follows.

$$\sigma(y,z) = S_1\, y + S_2\, z \quad (7)$$

where $S_1 \in \Re^{m\times p}$ and z is the controller state variable of the following dynamic observer found as several kinds of the order.

$$\dot{z} = F\, z + D\, y + E\, u \quad (8)$$

where S_2, F, D and E are constant matrices whose dimensions are determined according to the order of z. z is a vector satisfying the following in steady state.

$$z = T\, x \quad (9)$$

The meeting conditions of the sliding hyperplane σ with s are found by the following lemma.

Lemma 1: [7] The asymptotic coincidence condition of $s(x)$ and $\sigma(y,z)$, namely $\lim_{t\to\infty} \sigma(y,z) = s(x)$.

i) $$S_1 C + S_2 T = P \quad (10)$$
ii) $$TA_o - DC = FT \quad (11)$$
iii) $$E = TB_o \quad (12)$$
iv) All eigenvalues of a matrix F must have negative real parts. In other words, F must be Hurwitz matrix.

Proof: Substituting (7) into (4) and (9), the dynamic sliding hyperplane in steady state is as follows.

$$\sigma = S_1 y + S_2 z = (S_1 C + S_2 T)x = Px. \quad (13)$$

The above equation shows the condition i). The conditions ii) and iii) are obtained by comparing the equivalent control system. The equivalent control system using (6) and the equivalent control system using (7) are as follows, respectively.

$$\dot{x} = [A_o - B_o(PB_o)^{-1}PA_o]x = A_{eqs}x \quad (14)$$
$$\dot{x} = [A_o - B_o(S_1 C B_o + S_2 E)^{-1} (S_1 C A_o + S_2 DC + S_2 FT)]x = A_{eqo}x \quad (15)$$

Here, substituting the condition i) and setting such that A_{eqo} is equal to A_{eqs}, the conditions ii) and iii) are easily obtained. Defining the error $e = Tx - z$, the final condition iv) is found by obtaining the dynamic equation for e in the equivalent system.

$$T\dot{x} = (TA_o - DC)x + Dy + Eu_{eq} \quad (16)$$
$$\dot{z} = Fz + Dy + Eu_{eq} \quad (17)$$

Subtracting (17) from (16), the following error equation is obtained.

$$\dot{e} = F\, e \quad (18)$$

Therefore, if F is Hurwitz matrix like the condition iv), then since $e \to 0$ as $t \to \infty$, thus $\sigma(y,z) \to s(x)$ as $t \to \infty$.

□

We now consider the form of an adaptive variable structure controller as follows.

$$u = u_{eq} + u_\sigma + u_\Delta \quad (19)$$

where u_{eq} is the equivalent control input, u_σ is the control input determining the dynamics of $\sigma(y,z)$ and u_Δ the control input overcoming the uncertainties.

First, u_{eq} is found from $\dot{\sigma}_{nom} = 0$.

$$\dot{\sigma}_{nom} = S_1 \dot{y}_{nom} + S_2 \dot{z}_{nom} = (PA_o - S_2 FT)x + S_2 Fz + (PB_o)u_{eq} = 0 \quad (20)$$

$$u_{eq} = -(k_y y + k_z z) \quad (21)$$

where

$$k_y y + k_z z = (PB_o)^{-1}[(PA_o - S_2 FT)x + S_2 Fz] \quad (22)$$

Since $y = Cx$, equation (22) can be expressed as the following two equations.

$$k_y C = (PB_o)^{-1}(PA_o - S_2 FT) \quad (23)$$
$$k_z = (PB_o)^{-1} S_2 F \quad (24)$$

where k_z can be directly determined from (24), but it is very difficult to exactly and directly determine k_y in general from (23). Therefore, it is necessary that we use the method for finding k_y and k_z approximately.

Now, let's consider an approximate decision method of k_y and k_z. It is assumed that k_y and k_z are approximately determined by the following equation [7].

$$\begin{bmatrix} k_y & k_z \end{bmatrix} = (PB_o)^{-1} PA_o \begin{bmatrix} C \\ T \end{bmatrix}^{-1} \quad (25)$$

From the above equation, $\begin{bmatrix} C \\ T \end{bmatrix}$ is a square and nonsingular matrix. For $\begin{bmatrix} C \\ T \end{bmatrix}$ to be the square matrix, the dimension of a matrix T is $(n-p) \times n$. Thus, the dimension of z becomes $(n-p)$.

When the above k_y and k_z are used, the following equation is obtained.

$$\begin{aligned} k_y y + k_z z &= k_y Cx + k_z Tx - k_z Tx + k_z z \quad (26) \\ &= (PB_o)^{-1} PA_o x - k_z e \quad (27) \end{aligned}$$

Then, u_{eq} is as follows.

$$u_{eq} = -(k_y y + k_z z) = -(PB_o)^{-1} PA_o x + k_z e \quad (28)$$

Substituting the above u_{eq} into (20), we obtain

$$\dot{\sigma}_{nom} = (PB_o k_z - S_2 F)\, e = Q\, e \quad (29)$$

where $Q = PB_o k_z - S_2 F \in \Re^{m \times (n-p)}$. Therefore, k_y and k_z of (25) cause the error as much as Qe as it can be seen in the above equation. This error term Qe can be considered as the modeling error and is overcome by the following adaptive variable structure controller.

Now, to define u_σ, finding the dynamics of the sliding hyperplane,

$$\begin{aligned} \dot{\sigma} &= S_1 \dot{y} + S_2 \dot{z} \\ &= S_1 C(A_o x + B_o u + \eta) + S_2(Fz + DCx + Eu) \\ &= (PA_o - S_2 FT)x + S_2 Fz + (PB_o)u + S_1 C\eta. \quad (30) \end{aligned}$$

u_σ is defined as follows.

$$u_\sigma = -(PB_o)^{-1} K \sigma \quad (31)$$

where $K = K^T > 0 \in \Re^{m \times m}$ is a constant matrix.

Inserting (19), (28) and (31) into (30), the dynamics of the consequent sliding hyperplane is

$$\dot{\sigma} = -K\sigma + (PB_o)u_\Delta + \bar{\eta}. \quad (32)$$

where the uncertainty term is as follows.

$$\bar{\eta} = Qe + S_1 C\eta. \quad (33)$$

We can assume the following like equation (5).

Assumption 3: (Bound of uncertainty)
There exists an unknown positive constant $\bar{\rho}$ such that for all $t \in \Re^+$,

$$\|\bar{\eta}\| \le \bar{\rho} \quad (34)$$

The control input u_Δ stabilizing the dynamics (32) is defined as follows.

$$u_\Delta = (PB_o)^{-1}\, \bar{u}_\Delta, \quad \bar{u}_\Delta = -\hat{\rho}\frac{\alpha}{\|\alpha\| + \epsilon}, \quad \alpha = G\ \sigma(y, z) \quad (35)$$

where $G = G^T > 0 \in \Re^{m \times m}$ is a given constant matrix. $\hat{\rho}$ is the estimate of ρ and called the adaptive bound. ϵ is a positive-valued function, namely $\epsilon(t) > 0\ \forall t$. A special choice of ϵ is $\epsilon(t) = \lambda_1 e^{-\lambda_2 t}$, and λ_1 and λ_2 are positive constants.

Defining an adaptation law as follows,

$$\dot{\hat{\rho}} = h[\frac{\|\alpha\|^2}{\|\alpha\| + \epsilon} - \gamma(t)\hat{\rho}]. \quad (36)$$

where $h > 0$ is a constant and $\gamma(t)$ is a positive-valued function defined as follows.

$$\gamma = \bar{\gamma}\frac{\|\alpha\|\epsilon}{\|\alpha\| + \epsilon} > 0 \quad \forall t, \quad \bar{\gamma} > 0 \in \Re. \quad (37)$$

The above presented controller is summarized below.

$$\begin{aligned} u &= u_{eq} + u_\sigma + u_\Delta \quad (38) \\ u_{eq} &= -(k_y y + k_z z),\ \begin{bmatrix} k_y & k_z \end{bmatrix} = (PB_o)^{-1} PA_o \begin{bmatrix} C \\ T \end{bmatrix}^{-1} \quad (39) \\ u_\sigma &= -(PB_o)^{-1} K\sigma \quad (40) \\ u_\Delta &= (PB_o)^{-1}\bar{u}_\Delta,\quad \bar{u}_\Delta = -\hat{\rho}\frac{\alpha}{\|\alpha\| + \epsilon}, \quad \alpha = G\,\sigma \quad (41) \\ \dot{\hat{\rho}} &= h[\frac{\|\alpha\|^2}{\|\alpha\| + \epsilon} - \gamma\hat{\rho}], \quad \gamma = \bar{\gamma}\frac{\|\alpha\|\epsilon}{\|\alpha\| + \epsilon}, \quad \bar{\gamma} > 0. \quad (42) \end{aligned}$$

The stability of the closed-loop system is analyzed by the following theorem.

Theorem 1: Under assumptions 1 ~ 3, the dynamical system (3) and (4) with an adaptive variable structure control law (38) ~ (42), is globally uniformly ultimately bounded.

Proof : Consider a following Lyapunov function candidate.

$$V = \frac{1}{2}\sigma^T G\sigma + \frac{1}{2h}\tilde{\rho}^2 \quad (43)$$

where $\tilde{\rho} = \hat{\rho} - \rho$.

Taking the time derivative of V yields

$$\begin{aligned} \dot{V} &= \sigma^T G\dot{\sigma} + \frac{1}{h}\tilde{\rho}\dot{\tilde{\rho}} = \sigma^T G[S_1 C(A_o x + B_o u + \eta) \\ &\quad + S_2(Fz + Dy + Eu)] + \frac{1}{h}\tilde{\rho}\dot{\hat{\rho}} \\ &= \sigma^T G[(PA_o - S_2 FT)x + S_2 Fz + (PB_o)u + S_1 C\eta] + \frac{1}{h}\tilde{\rho}\dot{\hat{\rho}}. \end{aligned}$$

Rewriting the above equation by substituting u_{eq} and u_σ of (39) and (40) and using assumption 3,

$$\begin{aligned} \dot{V} &= -\sigma^T GK\sigma + \sigma^T GPB_o u_\Delta + \alpha^T\bar{\eta} + \frac{1}{h}\tilde{\rho}\dot{\hat{\rho}} \\ &\le -\sigma^T GK\sigma + \sigma^T GPB_o u_\Delta + \rho\|\alpha\| + \frac{1}{h}\tilde{\rho}\dot{\hat{\rho}}. \end{aligned}$$

Substituting u_Δ of (41) into the above equation

$$\dot{V} \leq -\sigma^T G K \sigma + \frac{-\tilde{\rho}\|\alpha\|^2 + \rho\|\alpha\|\epsilon}{\|\alpha\| + \epsilon} + \frac{1}{h}\tilde{\rho}\dot{\tilde{\rho}} \quad (44)$$

where $\dot{\tilde{\rho}} = \dot{\hat{\rho}}$.

Subsituting the adaptation law (42) into the above equation,

$$\dot{V} \leq -\sigma^T G K \sigma + w \leq -\lambda_{min}(GK)\|\sigma\|^2 + w \quad (45)$$

where GK is a positive definite matrix according to the definitions of G and K, $\lambda_{min}(GK)$ is the minimum eigenvalue of GK and w is as follows.

$$w = \frac{\|\alpha\|\epsilon}{\|\alpha\| + \epsilon}(\rho - \bar{\gamma}\hat{\rho}\hat{\rho}). \quad (46)$$

It is found that $\dot{V} < 0$ for $\|\sigma\| > \bar{w}$ where $\bar{w}^2 = \frac{w}{\lambda_{min}(GK)}$.

Therefore, as can be found in the above results, σ is globally uniformly ultimately bounded (g. u. u. b.).

In the case that $\epsilon = \lambda_1 e^{-\lambda_2 t}$, $\lambda_1 > 0$, $\lambda_2 > 0$, $\epsilon \to 0$ as $t \to \infty$. Here, we can find the following fact: If $\epsilon \to 0$, then the uniformly ultimately boundedness approaches the asymptotic stability, however, it causes the chattering phenomina.

□

Remark 1: From Theorem 1, we can find the trade-off between the magnitude of tracking error and the chattering of control input due to ϵ.

By the above Theorem 1, the uniform ultimate boundedness of the sliding hyperplane has been shown. Now, the stability of the state vector x is shown by the following theorem.

Theorem 2: In the case that the sliding hyperplane σ is equal to zero, if a matrix P is selected so that a matrix $A_c = [A_o - B_o(PB_o)^{-1}PA_o]$ is asymptotically stable matrix, then the state vector x is also asymptotically stable.

Proof: The proof is achieved by analyzing the equivalent control system. The augmented equivalent control system composed of state vectors x and e is found as follows.

$$\dot{x} = A_o x + B_o u_{eq} = [A_o - B_o(PB_o)^{-1}PA_o]x + B_o k_z e \quad (47)$$

$$\begin{aligned} \dot{e} &= T\dot{x} - \dot{z} = T(A_o x + B_o u_{eq}) - (Fz + Dy + Eu_{eq}) \\ &= (TA_o - DC)x + (TB_o - E)u_{eq} - Fz \\ &= FTx - Fz = Fe \end{aligned} \quad (48)$$

Therefore,

$$\begin{bmatrix} \dot{x} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_c & B_c \\ O & F \end{bmatrix} \begin{bmatrix} x \\ e \end{bmatrix} = A_{eq} \begin{bmatrix} x \\ e \end{bmatrix} \quad (49)$$

where $A_c = A_o - B_o(PB_o)^{-1}PA_o \in \Re^{n\times n}$, $B_c = B_o k_z \in \Re^{n\times(n-p)}$, $O \in \Re^{(n-p)\times n}$ and $A_{eq} \in \Re^{(2n-p)\times(2n-p)}$.

The eigenvalues of A_{eq} is made by the eigenvalues of A_c and F. Hence, in order that A_{eq} is Hurwitz matrix, that is, to be asymptotically stable matrix, both A_c and F must be Hurwitz matrix. Since the condition that a matrix F is Hurwitz has been given in Lemma 1, now only A_c has to be Hurwitz matrix. Therefore, if a matrix P is selected so that the matrix A_c is asymptotically stable, then the state vector x is also asymptotically stable.

□

By Theorem 1 and 2, the global stability of the closed-loop system has been completely guaranteed.

4 Simulation Results

To show the feasibility of the power system stabilizer using the proposed output feedback adaptive variable structure control scheme, simulation results for a multimachine system are presented.

The multimachine system considered here is a power system which has three generators and bus with long distance as shown in Fig. 1 [6]. Fig. 1 shows the three plant/infinite bus system. In Fig. 1, plant #4 effectively represents an infinite bus. Each plant is represented by a single equivalent machine with machines #1, #2 and #3 rated 360 MVA, 503 MVA and 1673 MVA, respectively. Each machine was provided with a static exciter.

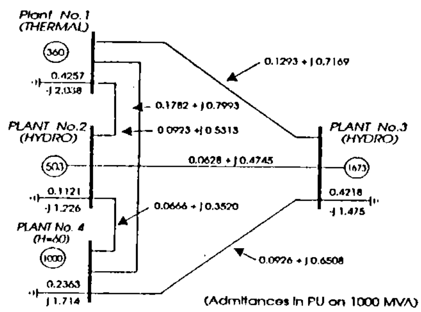

Fig. 1. Three machine/infinite bus system.

The linearized system model is expressed as the following state-output equation.

$$\dot{x} = A_o x + B_o u + \eta \quad (50)$$

$$y = C x \quad (51)$$

where $x = [\Delta\delta_1,\ \Delta\omega_1,\ \Delta e'_{q_1},\ \Delta e'_{FD_1},\ \Delta\delta_2,\ \Delta\omega_2,\ \Delta e'_{q_2},\ \Delta e'_{FD_2},\ \Delta\delta_3,\ \Delta\omega_3,\ \Delta e'_{q_3},\ \Delta e'_{FD_3}]^T$,

$$B_1 = \begin{bmatrix} 0 & 0 & 0 & 800 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 900 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1000 \end{bmatrix}^T,$$

$$B_2 = \begin{bmatrix} 0 & 0.22 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.15 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.11 & 0 & 0 \end{bmatrix}^T,$$

$B_o = B_1 + B_2$, $\eta = B_1\,\Delta v_{ref} + B_2\,\Delta T_m$,

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix},$$

$u = [u_1,\ u_2,\ u_3]^T \in \Re^3$, $y = [\Delta\delta_1,\ \Delta\delta_2,\ \Delta\delta_3]^T \in \Re^3$.

$$A_o = \begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.147 & -0.039 & -0.013 & 0 & 0.022 & 0.004 & 0 & 0 & 0.046 & 0.02 & 0.003 & 0 \\ -0.266 & -3.393 & -0.922 & 1 & -0.087 & 0.754 & 0.024 & 0 & -0.25 & 1.131 & 0.072 & 0 \\ -30.1 & -309.14 & -60.943 & -20 & 24.599 & -91.99 & -3.501 & 0 & 62.051 & -1675 & -10.194 & 0 \\ 0 & 0 & 0 & 0 & 0 & 377 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.004 & -0.034 & -0.087 & 0 & -0.149 & 0.032 & -0.008 & 0 & 0.079 & -0.028 & 0 & 0 \\ 0.121 & 1.131 & 0.021 & 0 & -1.6 & -1.885 & -0.21 & 1 & 0.46 & 0.754 & 0.06 & 0 \\ -18.48 & -64.47 & -12.55 & 0 & 106.09 & -516.11 & -21.67 & -20 & 16.99 & -171.91 & -11.41 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 377 & 0 & 0 \\ 0.001 & -0.017 & -0.003 & 0 & 0.017 & -0.01 & 0 & 0 & -0.056 & -0.017 & -0.009 & 0 \\ 0.083 & 0 & -0.002 & 0 & 0.22 & 0 & 0.011 & 0 & -1.2 & -1.131 & -0.197 & 1 \\ -10.1 & -33.93 & -6.78 & 0 & 1.7 & -46.37 & -2.1 & 0 & 70.1 & -893.49 & -54.4 & -20 \end{bmatrix}$$

The physical meanings of the above variables are as follows.

Δ : linearized incremental quantity (variation).

δ : power angle or torque angle.

ω : angular velocity.

e'_q : q-axis component of voltage behind transient reactance.

e_{FD_i} : equivalent excitation voltage.

v_{ref} : reference voltage.

T_m : mechanical torque.

The transfer function of the power system stabilizer composed of the lead-lag compensator and filter is as follows.

$$H(s) = \frac{K_0 T_0 s}{1 + T_0 s} \frac{1 + T_1 s}{1 + T_2 s} \frac{1 + T_3 s}{1 + T_4 s}. \tag{52}$$

By tuning the parameters K_0, T_0, T_1, T_2, T_3 and T_4 appropriately, the power system can be stabilized. In this simulation, three above conventional PSS are inserted in the system. The parameters of three lead-lag compensator used in this simulation are given as follows.

$$K_{01} = 0.5, \quad K_{02} = K_{03} = 50.0, \quad T_{01} = T_{02} = T_{03} = 3.0,$$
$$T_{11} = T_{31} = T_{12} = T_{32} = T_{13} = T_{33} = 0.15,$$
$$T_{21} = T_{41} = T_{22} = T_{42} = T_{23} = T_{43} = 0.05.$$

The control gains and parameters of the proposed OFAVSC used in this simulation are given as follows.

$$K = \begin{bmatrix} 15 & 0 & 0 \\ 0 & 15 & 0 \\ 0 & 0 & 15 \end{bmatrix}, \quad G = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix},$$
$$\lambda_1 = 0.01, \; \lambda_2 = 0.01, \; \bar{\gamma} = 0.1. \; h = 1.7.$$

Two kinds of disturbances are given as the step change at 5 seconds at the same time.

1. Variations of mechanical torques : step change of $\Delta T_{m_1} = \Delta T_{m_2} = \Delta T_{m_3} = 0.05\, p.u.$
2. Variations of reference voltages : step change of $\Delta v_{ref_1} = \Delta v_{ref_2} = \Delta v_{ref_3} = 0.05\, p.u.$

This simulation has the comparison between the proposed OFAVS-PSS (output feedback adaptive variable structure-power system stabilizer) and the conventional lead-lag PSS. The results are shown in Fig. 2 ~ Fig. 7. Fig. 2 ~ Fig. 4 show the angular velocity deviation profiles of each generator, that is, Fig. 2 for generator 1, Fig. 3 for generator 2 and Fig. 4 for generator 3, respectively. In other words, Fig. 2, Fig. 3 and Fig. 4 show the responses of x_2, x_6 and x_{10}, respectively. The response of the sliding hyperplane σ is shown in Fig. 5. The corresponding control input u and adaptive bound $\hat{\rho}$ are shown in Fig. 6 and Fig. 7, respectively.

Consequently, the proposed PSS has been simply and successfuly applied to the interconnected complex multimachine system. It is found that the proposed PSS stabilizes suitably and quickly the system even under abrupt disturbances. Comparing the proposed PSS with the lead-lag PSS, it is shown that the dynamic performance of the proposed PSS is superior to that of the lead-lag PSS. Therefore, it is found that the proposed OFAVS-PSS is feasible and effective.

5 Conclusions

In this paper, a power system stabilizer using an output feedback adaptive variable structure control scheme has been proposed for robust stabilization of the power system under external disturbances. The control scheme does not require a priori knowledge of the bound of norm on uncertain disturbances such as variations of mechanical torques and reference voltages. The proposed output feedback control scheme is very effective and useful due to simple measurement of available output signal in practical large scale complex and interconnected systems.

Simulation results for a multimachine power system have been presented to show the feasibility of the proposed control scheme. Comparing the proposed scheme with the conventional PID-type lead-lag compensator, it is shown that the dynamic performance of the proposed scheme is superior to that of the PID-type lead-lag scheme, for example, shorter settling time, small oscillation, etc..

Unlike VSC, the dynamic performance of AVSC cannot be usually predetermined because of the adaptation mechanism. In other words, that reason is the same that the dynamic response of adaptive control cannot be prescribed. A study that the dynamic performance of AVSC can be predetermined like VSC by more improving current AVSC theory is left to the further work.

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Fig. 2 ~ 4 : Dashed line : The conventional lead-lag PSS; Solid line: The proposed OFAVS-PSS.

Fig. 5 : Solid line : σ_1; Dashed line: σ_2; Dashdot line: σ_3.

Fig. 6 : Solid line : u_1; Dashed line: u_2; Dashdot line: u_3.

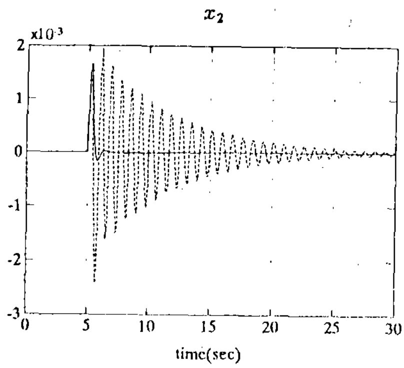

Fig. 2. The profiles of angular velocity deviation in machine 1.

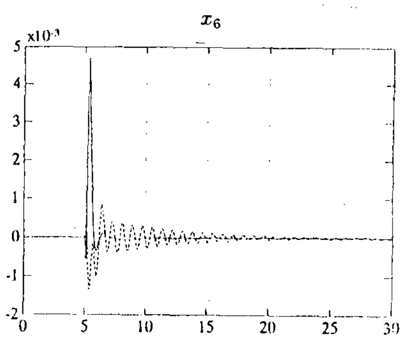

Fig. 3. The profiles of angular velocity deviation in machine 2.

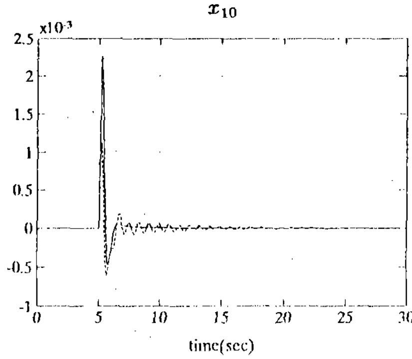

Fig. 4. The profiles of angular velocity deviation in machine 3.

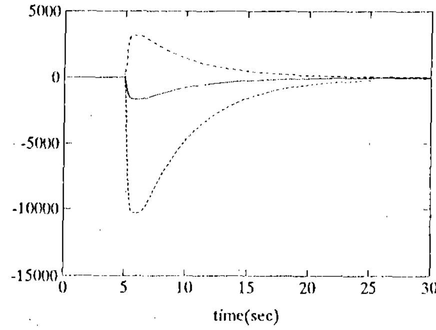

Fig. 5. Sliding hyperplane σ when the proposed PSS is used.

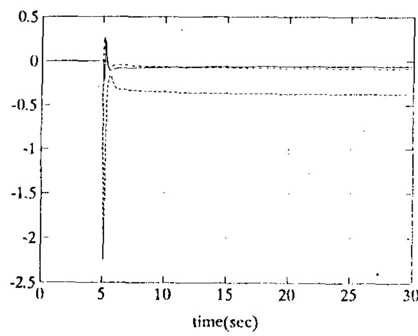

Fig. 6. Control input u when the proposed PSS is used.

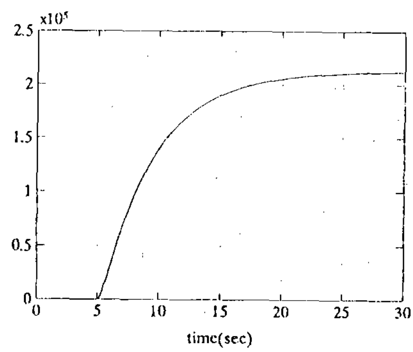

Fig. 7. Adaptive bound $\hat{\rho}$ when the proposed PSS is used.