New Sliding Mode Observer-Model Following Power System Stabilizer Including CLF for Unmeasurable State Variables

Sang-Seung Lee and Jong-Keun Park

Abstract

This paper presents the sliding mode observer-model following(SMO-MF) power system stabilizer(PSS) for unmeasurable state variables. This SMO-MF PSS is obtained by combining the sliding mode-model following(SM-MF) including closed-loop feedback(CLF) with the full-order observer(FOO). The control input of the proposed SMO-MF PSS is derived by Lyapunov's second method to determine a control input that keeps the system stable for unmeasurable plant state variables. Simulation results show that the proposed SMO-MF PSS including CLF is able to reduce the low frequency oscillation and to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions.

I. Introduction

With the development of modern control theory, various new control schemes have been introduced for PSS design[1-3]. Among these PSSs design methods, sliding mode control theories [4] have been developed as a controller which offers an effective way of the design of transient stability controllers for power system[5, 6]. And the sliding mode-model following(SM-MF) control method for full state feedback[7] has been applied for an uncertain generator system with voltage regulator and exciter for a single machine to the infinite bus system[8]. Moreover, the SM-MF including closed-loop feedback(CLF) has been applied to the PSS[9, 10]. These controllers[7-10] are all based on assumption that the complete state is available.

To solve these problems mentioned above the full state feedback, the sliding observer-model following(SMO-MF) for unmeasurable plant state variables is developed in this paper.

This SMO-MF is obtained by combining the sliding mode-model following(SM-MF) including CLF[9, 10] with the full-order observer(FOO)[11-13].

The estimated control input is derived by Lyapunov's second method to determine a control input that keeps the system stable for unmeasurable plant state variables. An IEEE type-1 excitation system model is considered which neglects saturation of the exciter and voltage limits of amplifier output.

The main results of this paper are as follows:

1. Combining the SM-MF including CLF with the full-order observer(FOO).
2. Deriving the estimated control input by Lyapunov's second method.
3. Applying the proposed SMO-MF including CLF to the PSS for unmeasurable state variables.
4. Reducing low frequency oscillation by CLF.
5. Obtaining asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions.

Simulation results are shown that the proposed SMO-MF PSS including CLF is able to reduce the low frequency oscillation and to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions.

The organizations of this paper are as follows: In section II we briefly review the synchronous generator model with voltage regulator and exciter. In section III we present the proposed SMO-MF including CLF. In section IV we present a data analysis used in simulation. Finally we show the dynamic performance of the proposed SMO-MF PSS design.

II. Synchronous Generator Model

Manuscript received December 30, 1996; accepted April 30, 1997.
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Ⅲ. Synchronous Generator Model

In this section, we briefly review the synchronous generator model with voltage regulator and exciter.

The block diagram of synchronous generator model with voltage regulator and exciter for a single machine to the infinite bus system is shown in Fig. 1[5, 8, 9].

An IEEE type-1 excitation system model is considered which neglects saturation of the exciter and voltage limits of amplifier output.

The linear differential equations of the one-machine, infinite bus system in Fig. 1 can be written as

$$\Delta \dot{v}_t(t) = K_6 \cdot \lambda_1 \cdot \Delta v_t(t) + 377 \cdot K_5 \cdot \Delta\omega(t) + K_6 \cdot \lambda_2 \cdot \Delta T_e(t) + \frac{K_6}{T'_{do}} \cdot \Delta e_{FD}(t) \tag{1}$$

$$\Delta \dot{w}(t) = -\frac{1}{M} \cdot \Delta T_e(t) \tag{2}$$

$$\Delta \dot{T}_e(t) = K_2 \cdot \lambda_1 \cdot \Delta v_t(t) + 377 \cdot K_1 \cdot \Delta\omega(t) + K_2 \cdot \lambda_2 \cdot \Delta T_e(t) + \frac{K_2}{T'_{do}} \cdot \Delta e_{FD}(t) \tag{3}$$

$$\Delta \dot{e}_{FD}(t) = -\frac{K_A}{T_A} \cdot \Delta v_t(t) - \frac{1}{T_A} \cdot \Delta e_{FD}(t) - \frac{K_A}{T_A} \cdot \Delta v_F(t) + \frac{K_A}{T_A} \cdot u_E(t) \tag{4}$$

$$\Delta \dot{v}_F(t) = -\frac{K_A K_F}{T_A T_F} \cdot \Delta v_t(t) - \frac{K_F}{T_A T_F} \cdot \Delta e_{FD}(t) - \left(\frac{1}{T_F} + \frac{K_A K_F}{T_A T_F}\right) \cdot \Delta v_F(t) + \frac{K_A K_F}{T_A T_F} \cdot u_E(t) \tag{5}$$

where $$\lambda_1 = \frac{K_1 - K_2 K_3 K_4}{K_3 T'_{do}(K_5 K_2 - K_1 K_6)} \tag{6}$$

$$\lambda_2 = \frac{K_3 K_4 K_6 - K_5}{K_3 T'_{do}(K_5 K_2 - K_1 K_6)} \tag{7}$$

K_1 and K_2 : constants derived from electrical torque.
K_3 and K_4 : constants derived from field voltage equation.
K_5 and K_6 : contants derived from terminal voltage magnitude.
T_A and T_F : voltage regulator and stabilizing transformer time constant.
K_A and K_F : voltage regulator and stabilizing transformer gain.
T'_{do} : d-axis transient open circuit time constant.
M : inertia coefficient(=2H).
u_E : supplementary excitation control input.

The 5×5 system matrix A_m and the 5×1 control vector B_m for a reference model from eq. (1)~eq. (5) can be expressed as

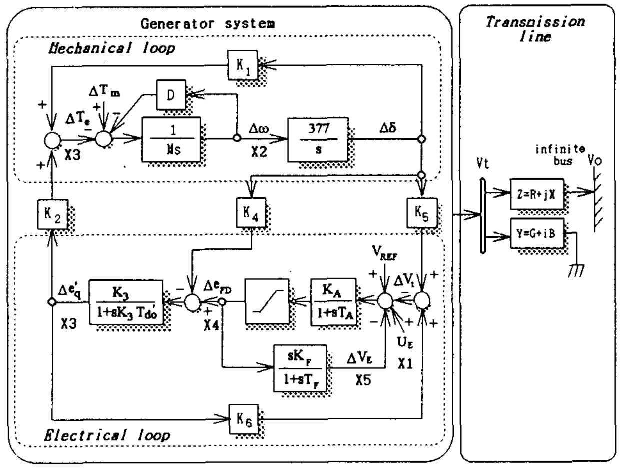

Fig. 1. Block diagram for synchronous generator model.

$$A_m = \begin{bmatrix} K_6\lambda_1 & 377K_5 & K_6\lambda_2 & \frac{K_6}{T'_{do}} & 0 \\ 0 & 0 & -\frac{1}{M} & 0 & 0 \\ K_2\lambda_1 & 377K_1 & K_2\lambda_2 & \frac{K_2}{T'_{do}} & 0 \\ -\frac{K_A}{T_A} & 0 & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} \\ -\frac{K_A K_F}{T_A T_F} & 0 & 0 & -\frac{K_F}{T_A T_F} & -\frac{1}{T_F} - \frac{K_A K_F}{T_A T_F} \end{bmatrix} \tag{8}$$

$$B_m = [0 \ 0 \ 0 \ \frac{K_A}{T_A} \ \frac{K_A K_F}{T_A T_F}]^T \tag{9}$$

The 5th-order states for reference model can be expressed as

$$x_m(t) = [\Delta v_{tm}(t), \Delta w_m(t), \Delta T_{em}(t), \Delta e_{FDm}(t), \Delta v_{Fm}(t)]^T \tag{10}$$

where

$\Delta v_{tm}(t)$ is a terminal voltage for model.
$\Delta w_m(t)$ is an angular velocity for model.
$\Delta T_{em}(t)$ is an electrical torque for moddel.
$\Delta e_{FDm}(t)$ is an equivalent excitation voltage for model.
$\Delta v_{Fm}(t)$ is a stabilizing transformer voltage for model.

The 5th-order states for the controlled plant can be expressed as

$$x_p(t) = [\Delta v_{tp}(t), \Delta w_p(t), \Delta T_{ep}(t), \Delta e_{FDp}(t), \Delta v_{Fp}(t)]^T \tag{11}$$

where

$\Delta v_{tp}(t)$ is a terminal voltage for plant.
$\Delta w_p(t)$ is an angular velocity for plant.
$\Delta T_{ep}(t)$ is an electrical torque for plant.
$\Delta e_{FDp}(t)$ is an equivalent excitaion voltage for plant.
$\Delta v_{Fp}(t)$ is a stabilizing transformer voltage for plant.

III. A SMO-MF Controller with CLF for Unmeasurable State Variables

In this section, the new sliding mode observer-model following (SMO-MF) including closed-loop feedback(CLF) is presented.

The aim of this SMO-MF including CLF is to achieve stable system(only with left-hand poles) by using CLF for unstable model and then is to obtain asymptotic tracking error between the reference model state and the controlled plant state for unmeasurable state variables.

The state equation for reference model can be expressed as

$$\dot{x}_m(t) = A_m \cdot x_m(t) + B_m \cdot u_m(t) \tag{12}$$

where A_m is a $n \times n$ system matrix for model and B_m a $n \times 1$ control vector for model.

The detailed description for full-order state feedback is found in Reference[9, 10, 13] and the control input of a reference model with r_m can expressed as

$$u_m(t) = -K_m \cdot x_m(t) + r_m(t) \tag{13}$$

where K_m is a $1 \times n$ feedback gain for model and can be obtained by pole placement. And $r_m \in R^1$ is a reference input vector for model.

The closed loop feedback system for a reference model is

$$\dot{x}_m(t) = (A_m - B_m \cdot K_m) \cdot x_m(t) + B_m \cdot r_m(t) \tag{14}$$

Let $A_{km} = A_m - B_m \cdot K_m$ (15)

The state equation for the reference model including CLF can be reformed as

$$\dot{x}_m(t) = A_{km} \cdot x_m(t) + B_m \cdot r_m(t) \tag{16}$$

where A_{km} is a $n \times n$ system matrix including CLF for model.

The state equation for the controlled plant with the parameter variations and the output equation can be formed as

$$\begin{aligned} \dot{x}_p(t) &= (A_p + \Delta A_p) \cdot x_p(t) + (B_p + \Delta B_p) \cdot u_p(t) \\ &= \bar{A}_p \cdot x_p(t) + \bar{B}_p \cdot u_p(t) \end{aligned} \tag{17}$$

$$y_p(t) = C_p \cdot x_p(t) \tag{18}$$

where $x_p \in R^n$ is a state vector for plant, $u_p \in R^1$ a control input for plant and $y_p \in R^l$ an available measured output for plant.

$\bar{A}_p = A_p + \Delta A_p$ is a $n \times n$ system matrix with the parameter variations for plant.

$\bar{B}_p = B_p + \Delta B_p$ is a $n \times 1$ control matrix with the parameter variations for plant.

C_p is the $1 \times n$ output matrix for plant.

The following full-order observer equation of the controlled plant for unmeasurable state variables can be expressed as

$$\begin{aligned} \dot{\hat{x}}_p(t) &= \bar{A}_p \cdot \hat{x}_p(t) + \bar{B}_p \cdot u_p(t) + L_p \cdot (y_p(t) - C_p \cdot \hat{x}_p(t)) \\ &= (\bar{A}_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \bar{B}_p \cdot u_p(t) + L_p \cdot y_p(t) \end{aligned} \tag{19}$$

where $\hat{x}_p \in R^n$ is the estimated state for plant.

$$L_p = P_p \cdot C_p^T \cdot R_p^{-1} \tag{20}$$

is the $n \times 1$ output injection matrix for plant.

P_p is the symmetric positive definite solution of

$$\bar{A}_p \cdot P_p + P_p \cdot \bar{A}_p^T - P_p \cdot C_p^T \cdot R_p^{-1} \cdot C_p \cdot P_p + Q_p = 0 \tag{21}$$

Q_p and R_p are positive definite matrices chosen by the designer. From eq. (19), the following assumptions are made:

$(\bar{A}_p, \bar{B}_p)$ *is controllable and* $(\bar{A}_p, C_p)$ *is observable.*

The input control vector with a feedback gain for unmeasurable state is expressed

$$\begin{aligned} u_p(t) &= u_{CLF}(t) + u_{SMO}(t) \\ &= -K_p \cdot \hat{x}_p(t) + u_{SMO}(t) \end{aligned} \tag{22}$$

where $u_{CLF}(t)$ is the closed-loop feedback control input and $u_{SMO}(t)$ the sliding mode observer control input. And K_p is a $1 \times n$ feedback gain for plant and can be obtained by pole placement.

Substituting eq. (22) into eq. (19), for unmeasurable state variables, the following full-order observer equation of the controlled plant including CLF can be expressed as

$$\begin{aligned} \dot{\hat{x}}_p(t) &= (\bar{A}_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \bar{B}_p \cdot u_p(t) + L_p \cdot y_p(t) \\ &= (\bar{A}_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \bar{B}_p \cdot (-K_p \cdot \hat{x}_p(t) + u_{SMO}(t)) \\ &\quad + L_p \cdot y_p(t) \\ &= (\bar{A}_p - \bar{B}_p \cdot K_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \bar{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t) \\ &= (\bar{A}_{kp} - L_p \cdot C_p) \cdot \hat{x}_p(t) + \bar{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t) \end{aligned} \tag{23}$$

where $\bar{A}_{kp} = (\bar{A}_p - \bar{B}_p \cdot K_p)$ is a $n \times n$ system matrix with the parameter variations including CLF for plant.

To minimize the error in the difference between the state $x_m(t)$ of the reference model and the estimated state $\hat{x}_p$ of the controlled plant for unmeasurable state variables, the error vector and the differential error vector can be expressed as

$$e(t) = x_m(t) - \hat{x}_p(t) \tag{24}$$

$$\dot{e}(t) = \dot{x}_m(t) - \dot{\hat{x}}_p(t) \tag{25}$$

By substituting eq. (16) and eq. (23) into eq. (25), we have

$$\dot{e}(t)=\dot{x}_m(t)-\dot{\hat{x}}_p(t)$$
$$=[A_{km}\cdot x_m(t)+B_m\cdot r_m(t)]-[(\tilde{A}_{kp}-L_p\cdot C_p)\cdot\hat{x}_p(t)+\tilde{B}_p\cdot u_{SMO}(t)+L_p\cdot y_p(t)] \quad (26)$$

$$x_m(t)=e(t)+\hat{x}_p(t) \quad (27)$$

By substituting eq. (27) into eq. (26), we have

$$\dot{e}(t)=A_{km}\cdot x_m(t)+B_m\cdot r_m(t)-(\tilde{A}_{kp}-L_p\cdot C_p)\cdot\hat{x}_p(t)-\tilde{B}_p\cdot u_{SMO}(t)-L_p\cdot y_p(t)$$
$$=A_{km}\cdot(e(t)+\hat{x}_p(t))+B_m\cdot r_m(t)-(\tilde{A}_{kp}-L_p\cdot C_p)\cdot\hat{x}_p(t)-\tilde{B}_p\cdot u_{SMO}(t)-L_p\cdot y_p(t)$$
$$=A_{km}\cdot e(t)-(\tilde{A}_{kp}-L_p\cdot C_p-A_{km})\cdot\hat{x}_p(t)+B_m\cdot r_m(t)-\tilde{B}_p\cdot u_{SMO}(t)-L_p\cdot y_p(t) \quad (28)$$

Suppose the sliding mode exists on all hyperplanes.

The sliding surface vector and the differential sliding surface vector can be expressed as

$$s(e(t))=G^T\cdot e(t) \quad (29)$$

$$\dot{s}(e(t))=G^T\cdot\dot{e}(t) \quad (30)$$

where G^T is the slidung surface gain. And the calculation algorithm of G^T for eq. (29) has been found in reference[5, 9].

To determine a control law that keeps the system on $s(e(t))=>0$, we introduce the Lyapunov's function

$$V(e(t))=s^2(e(t))/2 \quad (31)$$

The time derivative of $V(e(t))$ is given by

$$\dot{V}(e(t))=s(e(t))\cdot\dot{s}(e(t)) \quad (32)$$
$$=G^T\cdot e(t)\cdot G^T\cdot\dot{e}(t) \quad (33)$$

By substituting eq. (28) into eq. (33), we have

$$\dot{V}(e(t))=G^T\cdot e(t)\cdot G^T\cdot[A_{km}\cdot e(t)-(\tilde{A}_{kp}-L_p\cdot C_p-A_{km})\cdot\hat{x}_p(t)+B_m\cdot r_m(t)-\tilde{B}_p\cdot u_{SMO}(t)-L_p\cdot y_p(t)]$$
$$=G^T\cdot e(t)\cdot[G^T\cdot A_{km}\cdot e(t)-G^T\cdot(\tilde{A}_{kp}-L_p\cdot C_p-A_{km})\cdot\hat{x}_p(t)+G^T\cdot B_m\cdot r_m(t)-G^T\cdot\tilde{B}_p\cdot u_{SMO}(t)-G^T\cdot L_p\cdot y_p(t)]$$
$$\leq 0 \quad (34)$$

From eq. (34), the control input vector with switching for the controlled plant can be represented by

$$u^+_{SMO}(t)\geq(G^T\cdot\tilde{B}_p)^{-1}\cdot[G^T\cdot A_{km}\cdot e(t)-G^T\cdot(\tilde{A}_{kp}-L_p\cdot C_p-A_{km})\cdot\hat{x}_p(t)+G^T\cdot B_m\cdot r_m(t)-G^T\cdot L_p\cdot y_p(t)]$$
$$\text{for } G^T\cdot e(k)>0 \quad (35)$$

$$u^-_{SMO}(t)\leq(G^T\cdot\tilde{B}_p)^{-1}\cdot[G^T\cdot A_{km}\cdot e(t)-G^T\cdot(\tilde{A}_{kp}-L_p\cdot C_p-A_{km})\cdot\hat{x}_p(t)+G^T\cdot B_m\cdot r_m(t)-G^T\cdot L_p\cdot y_p(t)]$$
$$\text{for } G^T\cdot e(k)<0 \quad (36)$$

The detailed block diagram of the proposed SMO-MF including CLF for unmeasurable state variables in Fig. 2 can be shown as

From eq. (35) and eq. (36), the control input vector with sign function for the controlled plant can be reformed

$$u^{sign}_{SMO}(t)=[SE_{gain}\cdot e(t)+SP_{gain}\cdot\hat{x}_p(t)+SU_{gain}\cdot r_m(t)+SO_{gain}\cdot y_p(t)]\cdot\mu\cdot sign(s(e(t))) \quad (37)$$

where μ is the bias gain.

$$SE_{gain}:=(G^T\cdot\tilde{B}_p)^{-1}\cdot G^T\cdot A_{km} \quad (38)$$

is a sliding equal error feedback gain.

$$SP_{gain}:=-(G^T\cdot\tilde{B}_p)^{-1}\cdot G^T\cdot(\tilde{A}_{kp}-A_{km}-L_p\cdot C_p) \quad (39)$$

is a sliding equal estimated plant feedback gain.

$$SU_{gain}:=(G^T\cdot\tilde{B}_p)^{-1}\cdot G^T\cdot B_m \quad (40)$$

is a sliding equal input gain.

$$SO_{gain}:=-(G^T\cdot\tilde{B}_p)^{-1}\cdot G^T\cdot L_p \quad (41)$$

is a sliding equal measured output gain.

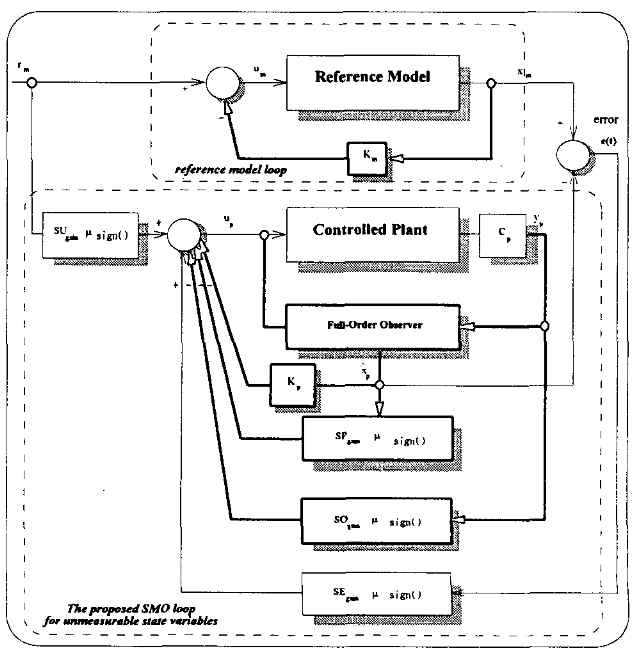

Fig. 2. Block diagram of the proposed SMO-MF including CLF for unmeasurable state variables.

Ⅳ. Data Analysis for SMO-MF PSS

In this section, the data analysis for new sliding mode observer-model following(SMO-MF) including closed-loop feedback(CLF) is presented.

The values for the initial conditions to determine the values of the above A_m and B_m in Table 1 [3] are as follows

The values of A_m and B_m for a reference model are given as

$$A_m = \begin{bmatrix} -0.6872 & -34.393 & 0.5640 & 0.1114 & 0 \\ 0 & 0 & -0.108 & 0 & 0 \\ -0.665 & 66.04 & 0.5223 & 0.1032 & 0 \\ -2600 & 0 & 0 & -20 & -2600 \\ -78 & 0 & 0 & -0.6 & -79 \end{bmatrix}$$

$$B_m = [0\ 0\ 0\ 2600\ 78]^T$$

By considering nonlinear characteristics, the controlled plant system matrix and the plant input vector are given by adding the plant parameter uncertainties.

$$\tilde{A}_p = A_m + \Delta A_m = A_m + 10\%\ of\ A_m$$

$$\tilde{B}_p = B_m + \Delta B_m = B_m + 10\%\ of\ B_m$$

The values of the output C_p are obtained by measuring angular velocity (Δw_p)

$$C_p = [0\ 1\ 0\ 0\ 0]$$

The optimal feedback gain K is

$$K = [-0.0943\ \ -21.4484\ \ 2.6695\ \ 0.0154\ \ -0.4211]$$

The output injection gain L is

$$L = 1.0e{-006} \cdot [-0.0002\ \ 0.0\ \ -0.0002\ \ 0.1861\ \ 0.0056]^T$$

The sliding surface vector from reference[5,9] is obtained as

$$S = [1.2431\ \ 8.2801\ \ -8.9434\ \ -3.1229\ \ 1.000]^T$$

The value of bais gain μ is -0.92.

Table 1. Data under normal load condition.

Item	Terminology and Value
Initial state	P_{e0} = 0.75, Q_{e0} = 0.9, v_{t0} = 1.05
Generator	M = 9.26, T'_{do} = 7.76, $D \cong 0$ x_d = 0.973, x'_d = 0.19, x''_d = 0.19 x_q = 0.55
Excitation	k_A = 130, T_A = 0.05
Line and load	R = -0.034, X = 0.997 G = 0.249, B = 0.262

Ⅴ. Time Domain Simulation

In this section, the time domain simulation for SMO-MF including CLF for unmeasurable plant state variables is presented.

Under a normal load operating condition of $P_{eo} = 0.75[p.u]$, the time domain simulations considering nonlinear characteristics for different initial conditions are carried out for a 10 sec.

For a SMO-MF PSS including CLF, Fig. 3 shows the simulation waveforms with 10% parameter variation around operating point for considering nonlinear characteristics at model initial condition $x_m(0) = [-0.05\ 0\ -0.05\ 0\ 0]$ & plant initial condition $x_p\text{hat}\ (0) = [-0.05\ 0\ -0.05\ 0\ 0]$.

For the proposed SMO-MF PSS including CLF, in this paper, Fig. 4 also shows the simulation waveforms at $x_m(0) = [-0.05\ 0\ 0\ 0\ 0]$ & $x_p\text{hat}\ (0) = [-.06\ 0\ 0\ 0\ 0]$. And Fig. 5 shows the simulation waveforms at $x_m(0) = [0\ 0\ -.05\ 0\ 0]$ & $x_p\text{hat}\ (0) = [0\ 0\ -0.06\ 0\ 0]$.

Fig. 3, Fig. 4 and Fig. 5 show that the proposed SMO-MF PSS is able to reduce the low frequency oscillation and to achieve asympotic tracking error between the reference model state $x_m(t)$ and the estimated plant state $\hat{x}_p(t)$ for generator system which is subject to the internal parameter variations (ΔA_p & ΔB_p) for considering nonlinear characteristics at different initial conditions.

Ⅵ. Conclusion

The sliding mode observer-model following(SMO-MF) PSS including closed-loop feedback(CLF) for unmeasurable plant state variables at different initial conditions has been presented.

Simulation results have been shown that the proposed SMO-MF PSS including CLF is able to reduce the low frequency oscillation and to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions.

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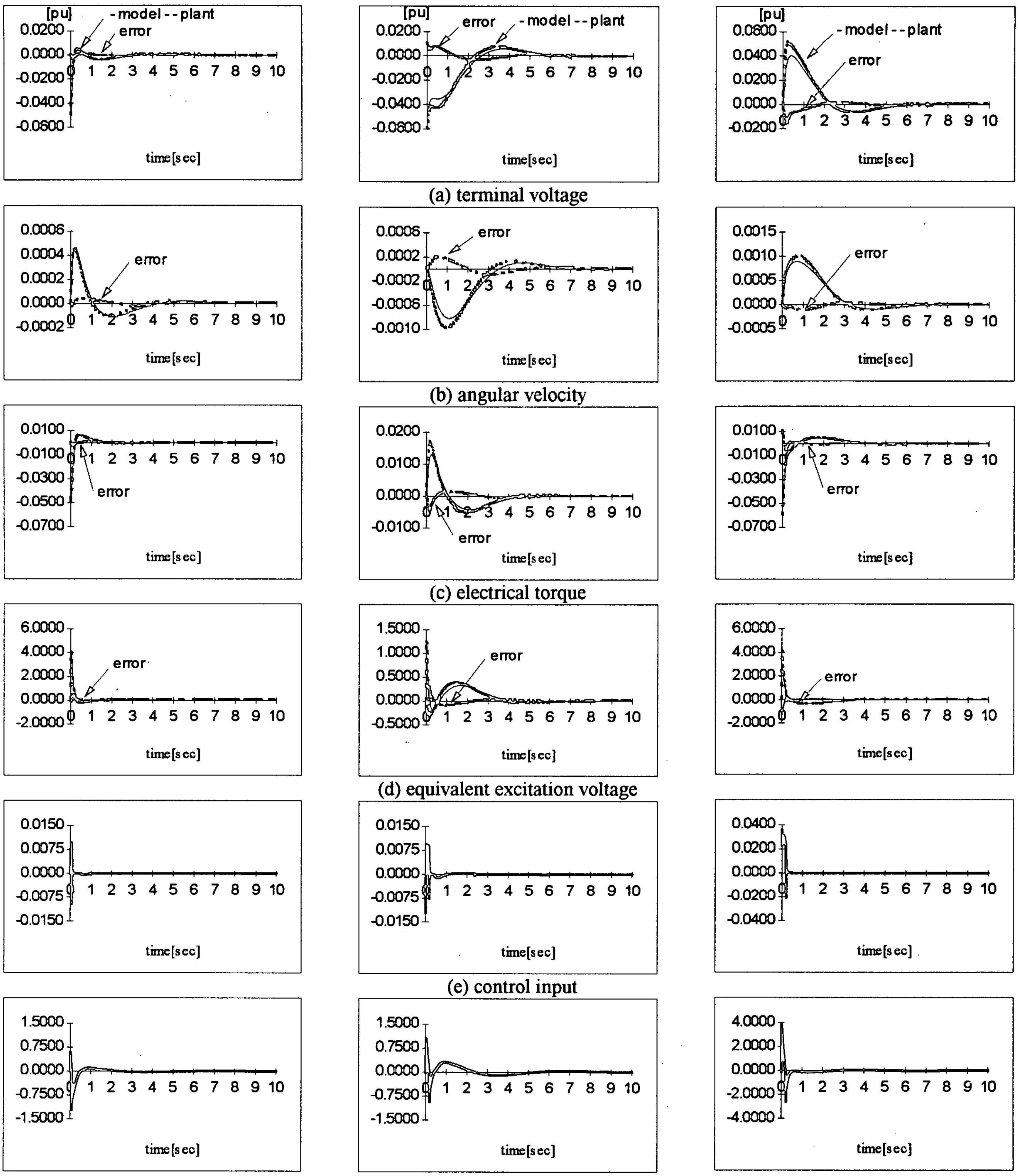

(a) terminal voltage

(b) angular velocity

(c) electrical torque

(d) equivalent excitation voltage

(e) control input

(f) sliding surface

Fig. 3. The proposed SMO-MF waveforms at
$x_m(0)$=[-0.05 0 -0.05 0 0]
$x_p(0)$=[-0.05 0 -0.05 0 0].

Fig. 4. The proposed SMO-MF waveforms at
$x_m(0)$ =[-0.05 0 0 0 0]
$x_p$hat(0)=[-0.06 0 0 0 0].

Fig. 5. The proposed SMO-MF waveforms at
$x_m(0)$ =[0 0 -0.05 0 0]
$x_p$hat(0)=[0 0 -0.06 0 0].

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