Multimachine Stabilizer using Sliding Mode Observer-Model Following including CLF for Unmeasurable State Variables

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Abstract

In this paper, the power system stabilizer(PSS) using the sliding mode observer-model following(SMO-MF) with closed-loop feedback (CLF) for single machine system is extended to multimachine system. This multimachine SMO-MF PSS for unmeasurable plant state variables is obtained by combining the sliding mode-model following(SM-MF) including closed-loop feedback(CLF) with the full-order observer(FOO). And the estimated control input for unmeasurable plant state variables is derived by Lyapunov's second method to determine a control input that keeps the system stable. Time domain simulation results for the torque angle and for the angular velocity show that the proposed multimachine SMO-MF PSS including CLF for unmeasurable plant state variables is able to damp out the low frequency oscillation and to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions and at step input.

I. Introduction

The sliding mode control(or variable structure control) theory [1] has been developed as a controller which offers an effective way of the design of transient stability controllers for power system[2-9]. And the SM-MF[10] including closed-loop feedback(CLF) has been applied to the PSS[12, 13].

These controllers[11-13] 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 has been developed[14].

In this paper, the power system stabilizer(PSS) using the sliding mode observer-model following(SMO-MF) with closed-loop feedback(CLF) for single machine system is extended to multimachine system.

This multimachine SMO-MF is obtained by combining the sliding mode-model following(SM-MF) with closed-loop feedback (CLF) with the full-order observer(FOO).

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.

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II. Multimachine Generator Model

In this section, we briefly review the three-machine / infinite busbar system.

The block diagram for three-machine/infinite busbar system is represented in Fig. 1[2].

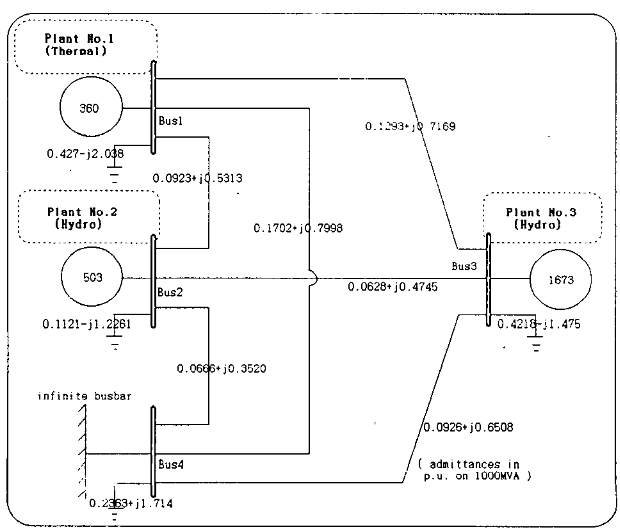


Fig. 1. Three-machine / infinite busbar system.

Fig. 1 is represented by a single equivalent machine with machines 1, 2 and 3, rated 360 MVA(Thermal), 503 MVA(Hydro) and 1673 MVA(Hydro), respectively. And Plant 4 effectively represents an infinite busbar system.

An IEEE type-1 excitation system model for three-machine / infinite busbar system is considered which neglects saturation of the exciter and voltage limits of amplifier output.

The 12th-order state equation for a reference model can be expressed as

$$x_m=[\Delta\delta_{m1},\Delta\omega_{m1},\Delta e'_{qm1},\Delta e_{FDm1},\ \Delta\delta_{m2},\Delta\omega_{m2},\Delta e'_{qm2},\Delta e_{FDm2},\ \Delta\delta_{m3},\Delta\omega_{m3},\Delta e'_{qm3},\Delta e_{FDm3}]^T \tag{1}$$

where $\Delta\delta_m(t)$ is the torque angle for model, $\Delta\omega_m(t)$ the angular velocity for model,, $\Delta e'_{qm}(t)$ the q-axis component of voltage behind transient for model and $\Delta e_{FDm}(t)$ the equivalent excitation voltage for model.

The 12th-order state equation for the controlled plant can be expressed as

$$x_p=[\Delta\delta_{p1},\Delta\omega_{p1},\Delta e'_{qp1},\Delta e_{FDp1},\ \Delta\delta_{p2},\Delta\omega_{p2},\Delta e'_{qp2},\Delta e_{FDp2},\ \Delta\delta_{p3},\Delta\omega_{p3},\Delta e'_{qp3},\Delta e_{FDp3}]^T \tag{2}$$

where $\Delta\delta_p(t)$ is the torque angle for plant, $\Delta\omega_p(t)$ the angular velocity for plant, $\Delta e'_{qp}(t)$ the q-axis component of voltage behind transient reactance for plant and $\Delta e_{FDp}(t)$ the equivalent exciation voltage for plant.

Ⅲ. Multimachine SMO-MF Controller Including CLF for Unmeasurable Plant State Variables

In this section, we present the multimachine SMO-MF including CLF for unmeasurable plant state variables.

The state equation for a reference model can be expressed as

$$\dot{x}_m(t)=A_m\cdot x_m(t)+B_m\cdot u_m(t) \tag{3}$$

where $x_m\in R^n$ is a state vector for model and $u_m\in R^p$ a control input for model. And A_m is a $n\times n$ system matrix for model and B_m a $n\times m$ control vector for model.

The control input of a reference model with r_m can expressed as

$$u_m(t)=-K_m\cdot x_m(t)+r_m(t) \tag{4}$$

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

The closed-loop feedback system for a reference model is

$$\dot{x}_m(t)=(A_m-B_m\cdot K_m)\cdot x_m(t)+B_m\cdot r_m(t) \tag{5}$$

$$\text{Let } A_{km}=A_m-B_m\cdot K_m \tag{6}$$

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

$$\dot{x}_m(t)=A_{km}\cdot x_m(t)+B_m\cdot r_m(t) \tag{7}$$

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

$$\dot{x}_p(t)=(A_p+\Delta A_p)\cdot x_p(t)+(B_p+\Delta B_p)\cdot u_p(t) = \tilde{A}_p\cdot x_p(t)+\tilde{B}_p\cdot u_p(t) \tag{8}$$

$$y_p(t)=C_p\cdot x_p(t) \tag{9}$$

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

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

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

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

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

$$\dot{\hat{x}}_p(t)=\tilde{A}_p\cdot\hat{x}_p(t)+\tilde{B}_p\cdot u_p(t)+L_p\cdot(y_p(t)-C_p\cdot\hat{x}_p(t)) =(\tilde{A}_p-L_p\cdot C_p)\cdot\hat{x}_p(t)+\tilde{B}_p\cdot u_p(t)+L_p\cdot y_p(t) \tag{10}$$

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

$$L_p=P_p\cdot C_p^T\cdot R_p^{-1} \tag{11}$$

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

P_p is the symmetric positive definite solution of

$$\tilde{A}_p\cdot P_p+P_p\cdot\tilde{A}_p^{\,T}-P_p\cdot C_p^T\cdot R_p^{-1}\cdot C_p\cdot P_p+Q_p=0 \tag{12}$$

Q_p and R_p are positive definite matrices chosen by the designer.

From eq. (10), the following assumptions are made:

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

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

$$u_p(t)=u_{CLF}(t)+u_{SMO}(t) =-K_p\cdot\hat{x}_p(t)+u_{SMO}(t) \tag{13}$$

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 $m\times n$ feedback gain for plant and can be obtained by pole placement.

Substituting eq. (13) into eq. (10), for unmeasurable state, the following full-order observer equation of the controlled plant including CLF can be expressed as

$$\begin{aligned}\dot{\hat{x}}_p(t) &= (\tilde{A}_p - L_p \cdot C_p)\cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_p(t) + L_p \cdot y_p(t)\\ &= (\tilde{A}_p - L_p \cdot C_p)\cdot \hat{x}_p(t) + \tilde{B}_p \cdot (-K_p \cdot \hat{x}_p(t) + u_{SMO}(t))\\ &\quad + L_p \cdot y_p(t) \qquad (14)\\ &= (\tilde{A}_p - \tilde{B}_p \cdot K_p - L_p \cdot C_p)\cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t)\\ &= (\tilde{A}_{kp} - L_p \cdot C_p)\cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t)\end{aligned}$$

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

The error vector and the differential error vector 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 can be expressed as

$$e(t) = x_m(t) - \hat{x}_p(t) \qquad (15)$$

$$\dot{e}(t) = \dot{x}_m(t) - \dot{\hat{x}}_p(t) \qquad (16)$$

By substituting eq. (7) and eq. (14) into eq. (16), we have

$$\begin{aligned}\dot{e}(t) &= \dot{x}_m(t) - \dot{\hat{x}}_p(t)\\ &= [A_{km}\cdot x_m(t) + B_m \cdot r_m(t)] - [(\tilde{A}_{kp} - L_p \cdot C_p)\cdot \hat{x}_p(t)\\ &\quad + \tilde{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t)] \qquad (17)\end{aligned}$$

$$x_m(t) = e(t) + \hat{x}_p(t) \qquad (18)$$

By substituting eq. (18) into eq. (17), we have

$$\begin{aligned}\dot{e}(t) &= A_{km}\cdot x_m(t) + B_m \cdot r_m(t) - (\tilde{A}_{kp} - L_p \cdot C_p)\cdot \hat{x}_p(t)\\ &\quad - \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t)\\ &= A_{km}\cdot (e(t) + \hat{x}_p(t)) + B_m \cdot r_m(t) - (\tilde{A}_{kp} - L_p \cdot C_p)\cdot \hat{x}_p(t)\\ &\quad - \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t)\\ &= A_{km}\cdot e(t) - (\tilde{A}_{kp} - L_p \cdot C_p - A_{km})\cdot \hat{x}_p(t) + B_m \cdot r_m(t)\\ &\quad - \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t) \qquad (19)\end{aligned}$$

Suppose the sliding mode exists on all hyperplanes.

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

$$s(e(t)) = G^T \cdot e(t) \qquad (20)$$

$$\dot{s}(e(t)) = G^T \cdot \dot{e}(t) \qquad (21)$$

where G^T is the slidung surface gain. And the calculation algorithm of G^T for eq. (20) has been found in reference[2, 10, 12].

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

$$V(e(t)) = s^2(e(t))/2 \qquad (22)$$

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

$$\begin{aligned}\dot{V}(e(t)) &= s(e(t))\cdot \dot{s}(e(t)) \qquad (23)\\ &= G^T \cdot e(t)\cdot G^T \cdot \dot{e}(t) \qquad (24)\end{aligned}$$

By substituting eq. (19) into eq. (24), we have

$$\begin{aligned}\dot{V}(e(t)) &= G^T \cdot e(t)\cdot G^T \cdot [A_{km}\cdot e(t) - (\tilde{A}_{kp} - L_p \cdot C_p - A_{km})\\ &\quad \cdot \hat{x}_p(t) + B_m \cdot r_m(t) - \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t)]\\ &= G^T \cdot e(t)\cdot [G^T \cdot A_{km}\cdot e(t)\\ &\quad - G^T \cdot (\tilde{A}_{kp} - L_p \cdot C_p - A_{km})\cdot \hat{x}_p(t) + G^T \cdot B_m \cdot r_m(t)\\ &\quad - G^T \cdot \tilde{B}_p \cdot u_{SMO}(t) - G^T \cdot L_p \cdot y_p(t)]\\ &\leq 0 \qquad (25)\end{aligned}$$

From eq. (25), the control input vector with switching for the controlled plant can be represented by

$$\begin{aligned}u^{+}_{SMO}(t) &\geq (G^T \cdot \tilde{B}_p)^{-1}\cdot [G^T \cdot A_{km}\cdot e(t)\\ &\quad - G^T \cdot (\tilde{A}_{kp} - L_p \cdot C_p - A_{km})\cdot \hat{x}_p(t)\\ &\quad + G^T \cdot B_m \cdot r_m(t) - G^T \cdot L_p \cdot y_p(t)]\\ &\qquad for\ G^T \cdot e(t) > 0 \qquad (26)\end{aligned}$$

$$\begin{aligned}u^{-}_{SMO}(t) &\leq (G^T \cdot \tilde{B}_p)^{-1}\cdot [G^T \cdot A_{km}\cdot e(t)\\ &\quad - G^T \cdot (\tilde{A}_{kp} - L_p \cdot C_p - A_{km})\cdot \hat{x}_p(t)\\ &\quad + G^T \cdot B_m \cdot r_m(t) - G^T \cdot L_p \cdot y_p(t)]\\ &\qquad for\ G^T \cdot e(t) < 0 \qquad (27)\end{aligned}$$

From eq. (26) and eq. (27), the control input vector with sign function for the controlled plant can be reformed

$$\begin{aligned}u^{sign}_{SMO}(t) &= [SE_{gain}\cdot e(t) + SP_{gain}\cdot \hat{x}_p(t) + SU_{gain}\cdot r_m(t)\\ &\quad + SO_{gain}\cdot y_p(t)]\cdot \mu \cdot sign(s(e(t))) \qquad (28)\end{aligned}$$

where μ is the bias gain.

$$SE_{gain} := (G^T \cdot \tilde{B}_p)^{-1}\cdot G^T \cdot A_{km} \qquad (29)$$

is a sliding equal error feedback gain.

$$SP_{gain} := -(G^T \cdot \tilde{B}_p)^{-1}\cdot G^T \cdot (\tilde{A}_{kp} - A_{km} - L_p \cdot C_p) \qquad (30)$$

is a sliding equal estimated plant feedback gain.

$$SU_{gain} := (G^T \cdot \tilde{B}_p)^{-1}\cdot G^T \cdot B_m \qquad (31)$$

is a sliding equal input gain.

$$SO_{gain} := -(G^T \cdot \tilde{B}_p)^{-1}\cdot G^T \cdot L_p \qquad (32)$$

is a sliding equal measured output gain.

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

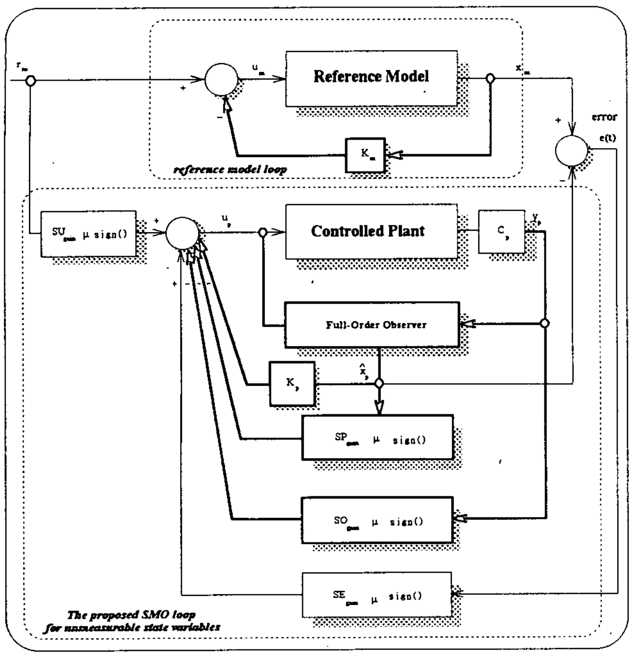


Fig. 2. Block diagram of the proposed SMO-MF including CLF for unmeasurable state variables.

Ⅳ. Data Analysis for Multimachine SMO-MF PSS

In this section, we present the data analysis of the multimachine SMO-MF including CLF for unmeasurable plant state variables.

The data of model and these ratings in reference[2] are found in Appendix A.1.

The 12×12 system matrix A_m are decomposed into the 4-block form

$$A_m=\begin{bmatrix} A_{m11} & A_{m12} \\ A_{m21} & A_{m22} \end{bmatrix}$$

The values of the 12×12 system matrix A_m and the 12×3 control matix B_m are found in Appendix A. 2.

The eigenvalues of A_m are unstable with four poles (right-half) at

$$-18.9080, -17.0096, -14.8564, 0.0335\pm 7.7924i,$$
$$-0.1453\pm 7.2098i, 0.3842\pm 4.2681i, -6.9211, -3.4111, -1.3855$$

The eigenvalues of $(A_m - B_m \cdot K_m)$ including CLF are stable with poles at

$$-38.8911\pm .5201i, -50.6741\pm .8369i, -10.8657\pm .9136i,$$
$$-46.5473\pm .5810i, -1.8338\pm .3041i, -5.1356\pm .4691i$$

The 12×3 sliding surface matrix including CLF is

$$G^T=\begin{bmatrix} .01 & -2590 & 144 & 1 & -41 & -5770 & 343 & 0 & -52 & -5689 & .608 & 0 \\ 9.19 & 110 & .343 & 0 & -3.54 & -529 & 141 & 1 & -3.95 & -444 & .1 & 0 \\ 1.08 & 3430 & .603 & 0 & 3.67 & -993 & .0973 & 1 & -21.5 & -12100 & 72.2 & 1 \end{bmatrix}^T$$

Ⅴ. Time Domain Simulation

In this section, we present the simulation of the multimachine SMO-MF including CLF for unmeasurable plant state variables.

The time domain simulations for the torque angle and for the angular velocity of machine # 1, # 2, and # 3 are carried out for 6 sec. Fig. 3 shows the state waveforms without CLF at model initial condition $X_m(0)=[-.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0]$ & plant initial condition $\widehat{X_p}(0)=[-.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0]$. Fig. 4 shows that the oscillation of the state is reducedat model initial condition $X_m(0)=[-.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0]$ & plant initial condition $\widehat{X_p}(0)=[-.06\ 0\ 0\ 0\ -.06\ 0\ 0\ 0\ -.06\ 0\ 0\ 0]$. Fig. 5 shows the step-input state waveforms with CLF at model initial condition $X_m(0)=[0\ -.05\ 0\ 0\ 0\ -.05\ 0\ 0\ 0\ -.05\ 0\ 0]$ & plant initial condition $\widehat{X_p}(0)=[0\ -.07\ 0\ 0\ 0\ -.07\ 0\ 0\ 0\ -.07\ 0\ 0]$ and also shows that the oscillation of the state is reduced.

Fig. 4 and Fig. 5 for the torque angle and for the angular velocity are designed not only to damp out the low frequency oscillations of the power system by including CLF, but also to achieve asympotic tracking error between the reference model state and the controlled plant state at different initial conditions and at step input.

Ⅵ. Conclusion

The sliding mode-model following(SM-MF) power system stabilizer(PSS) including closed-loop feedback(CLF) for single machine power system has been extended to multimachine systems.

The multimachine SMO-MF PSS with CLF for unmeasurable plant state variables has been designed not only to damp out the low frequency oscillations of the power system by including CLF, but also to achieve asympotic tracking error between the reference model state and the controlled plant state at different initial conditions and at step input.

References

[1] V. I. Utkin, "Variable structure system with sliding modes", IEEE Trans. on Automatic Control, AC-22, No. 2, pp. 212-222, April, 1977.

[2] W. C. Chan and Y. Y. Hsu, "An optimal variable structure stabilizer for power system stabilization", IEEE Trans., PAS-102, pp. 1738-1746, Jun., 1983.

[3] J. J. Lee, "Optimal multidimentional variable structure con-

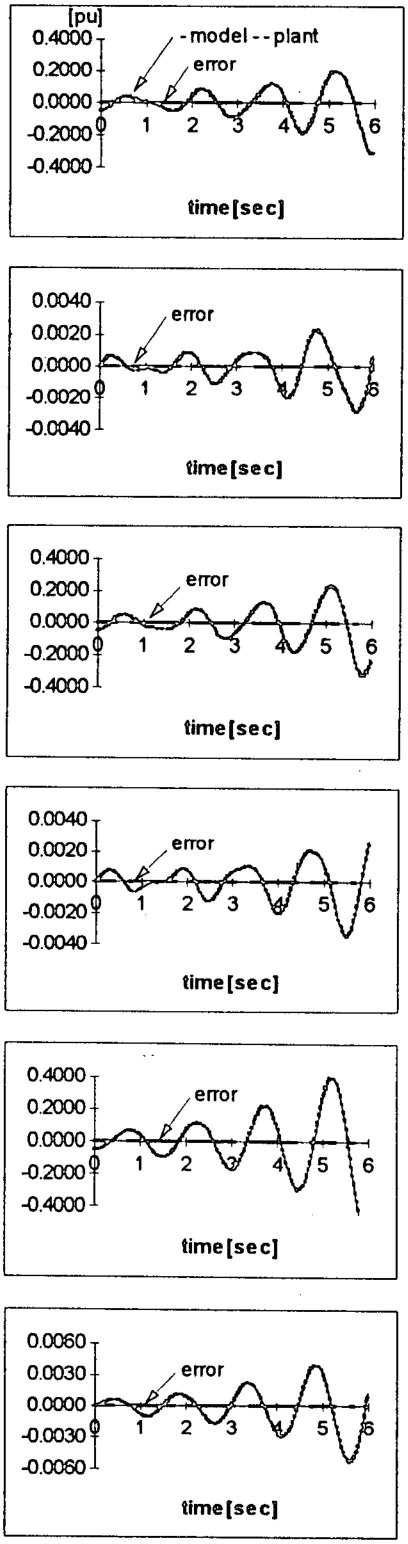
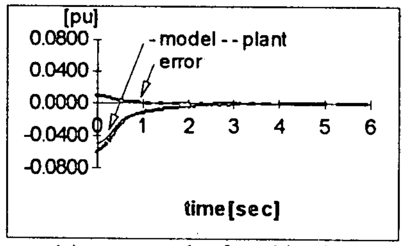


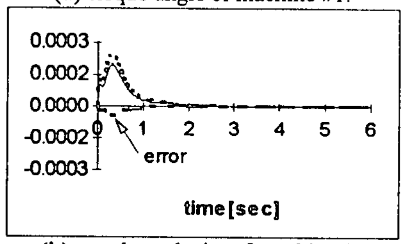
Fig. 3. The SMO-MF waveforms without CLF at

$x_m(0)$=[-.05 0 0 0 -.05 0 0 0 -.05 0 0 0]

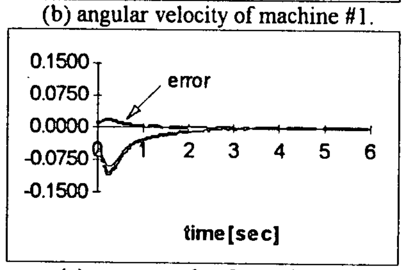
$\hat{x}_p(0)$=[-.05 0 0 0 -.05 0 0 0 -.05 0 0 0]



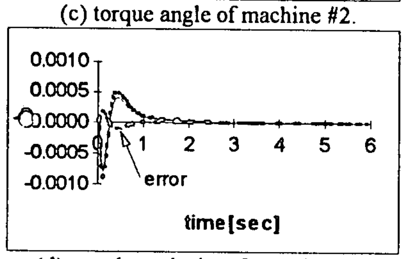
(a) torque angle of machine #1.



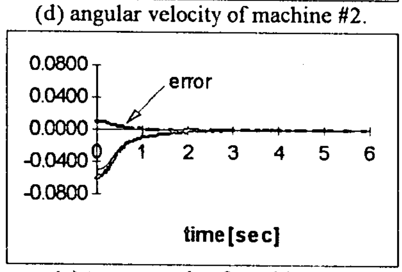
(b) angular velocity of machine #1.



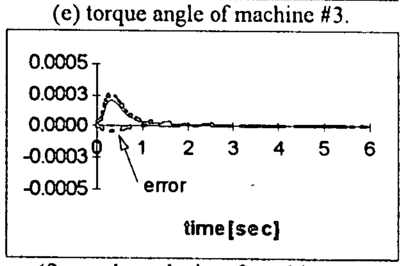
(c) torque angle of machine #2.



(d) angular velocity of machine #2.



(e) torque angle of machine #3.



(f) angular velocity of machine #3.

Fig. 4. The proposed SMO-MF waveforms with CLF at

$x_m(0)$=[-.05 0 0 0 -.05 0 0 0 -.05 0 0 0]

$\hat{x}_p(0)$=[-.06 0 0 0 -.06 0 0 0 -.06 0 0 0]

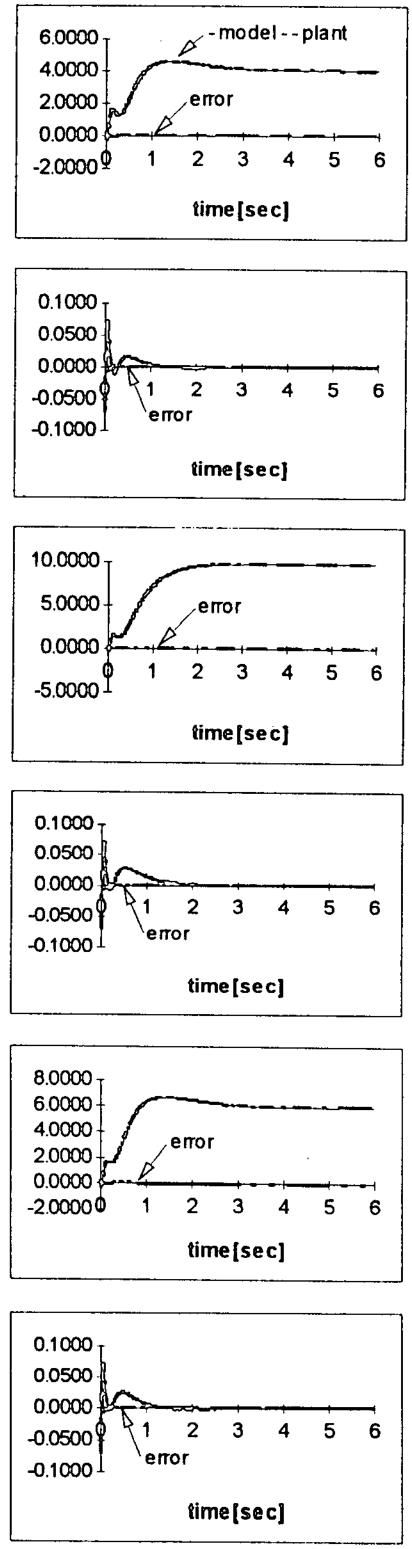


Fig. 5. The proposed SMO-MF step-input waveforms with CLF at

$x_m(0)$=[0 -.05 0 0 0 0 -.05 0 0 0 -.05 0 0]

$\hat{x}_p(0)$=[0 -.07 0 0 0 0 -.07 0 0 0 -.07 0 0]

troller for multi-interconnected power system", Trans. KIEE, Vol. 38, No. 9, pp. 671-683, Sep., 1989.

[4] Y. Wang, R. R. Mohlre, R. Spee and W. Mittelstadt, "VSS facts controller for power system transient stability", IEEE Trans. on Power Systems, Vol. 7, No. 1, pp. 307-313, 1992.

[5] M. L. Kothari, J. Nanda and K. Bhattacharya, "Design of variable structure power system stabilizers with desired eigenvalues in the sliding mode", IEE Proc., C, Vol. 140, No. 4, pp. 263-268, 1993.

[6] S. S. Lee and J. K. Park, "Sliding mode power system stabilizer based on LQR : Part I", Journal of Electrical Engineering and Information Science, Vol. 1, No. 3, pp. 32-38, 1996.

[7] S. S. Lee and J. K. Park, "Sliding mode observer power system stabilizer based on linear full-order observer : Part II", Journal of Electrical Engineering and Information Science, Vol. 1, No. 3, pp. 39-45, 1996.

[8] S. S. Lee and J. K. Park, "H_∞ observer-based sliding mode power system stabilizer for unmeasurable state variables", Journal of Electrical Engineering and Information Science, Vol. 2, No. 1, pp. 70-76, 1997.

[9] S. S. Lee and J. K. Park, "Full-order observer-based sliding mode power system stabilizer with desired eigenvalue-assignment for unmeasurable state variables", Journal of Electrical Engineering and Information Science, Vol. 2, No. 2, 1997.

[10] K. K. D Young, "Design of variable structure model following control systems", IEEE Trans., AC-23, pp. 1079-1085, Dec., 1978.

[11] S. S. Lee, J. K. Park, and J. J. Lee, "Sliding mode-MFAC power system stabilizer", Journal of KIEE, Vol. 5, No. 1, pp. 1-7, Mar., 1992.

[12] S. S. Lee, T. H. Kim, and J. K. Park, "Sliding mode-MFAC power system stabilizer including closed-loop feedback", Journal of KIEE, Vol. 9, No. 3, pp. 132-138, Sep., 1996.

[13] S. S. Lee, J. K. Park, H. S. Koh, S. H. Lee, and W. Y. Chong, "Multimachine stabilizer using sliding mode-model following including closed-loop feedback", Journal of KIEE, Vol. 9, No. 4, pp. 191-197, 1996.

[14] S. S. Lee and J. K. Park, "Sliding mode observer-model following power system stabilizer including CLF for unmeasurable state variables", Journal of Electrical Engineering and Information Science, Vol. 2, No. 3, pp. 88-94, 1997.

Appendix

A. 1 : Machine data and terminal condition data

Table 1. Machine data.

Plant	X'_d	X_d	X_q	X''	T'_{do}	T''_{do}	T''_{qo}	H
1	0.32	1.68	1.66	0.19	4.0	1.9	1.9	2.31
2	0.33	0.88	0.53	0.22	8.0	0.02	0.04	3.4
3	0.20	1.02	0.57	0.14	7.76	0.04	0.09	4.63
4	0.001	–	–	–	–	–	–	60

Table 2. Terminal condition data.

Plant	$P_o(MVA)$	$Q_o(MVA)$	$V_{to}(p.u.)$	°[*degree*]
1	26.5	37.0	1.03	10.0
2	518.0	-31.5	1.025	32.52
3	1582.0	-49.9	1.03	45.95
4	410.0	49.1	1.06	20.69

A. 2 : System matrix(A_m) and control matrix(B_m)

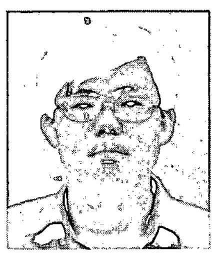
$$A_{m11}=\begin{bmatrix} 0 & 377 & 0 & 0 & 0 & 0 \\ -0.147 & -0.039 & -0.013 & 0 & 0.022 & 0.004 \\ -0.266 & -0.393 & -0.922 & 1 & -0.087 & 0.754 \\ -30.10 & -309.14 & -60.943 & -20 & 24.599 & -91.99 \\ 0 & 0 & 0 & 0 & 0 & 377 \\ 0.004 & -0.034 & -0.087 & 0 & -0.149 & 0.032 \end{bmatrix}$$

$$A_{m12}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.046 & 0.02 & 0.003 & 0 \\ 0.024 & 0 & -0.025 & 1.131 & 0.072 & 0 \\ -3.501 & 0 & 62.051 & -1675 & -10.194 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -0.008 & 0 & 0.097 & -0.028 & 0 & 0 \end{bmatrix}$$

$$A_{m21}=\begin{bmatrix} 0.121 & 1.131 & 0.021 & 0 & -1.6 & -1.885 \\ -18.48 & -64.47 & -12.55 & 0 & 106.09 & -516.11 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0.001 & -0.017 & -0.003 & 0 & 0.017 & -0.01 \\ 0.083 & 0 & -0.002 & 0 & 0.22 & 0 \\ -10.1 & -33.93 & -6.78 & 0 & 1.7 & -46.37 \end{bmatrix}$$

$$A_{m22}=\begin{bmatrix} -0.21 & 1 & 0.46 & 0.754 & 0.06 & 0 \\ -21.67 & -20 & 16.99 & -171.91 & -11.41 & 0 \\ 0 & 0 & 0 & 377 & 0 & 0 \\ 0 & 0 & -0.056 & -0.017 & -0.009 & 0 \\ 0.011 & 0 & -1.2 & -1.131 & -0.19 & 1 \\ -2.1 & 0 & 70.1 & -893.49 & -54.4 & -20 \end{bmatrix}$$

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



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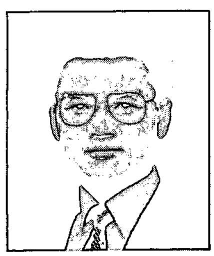

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