전력계통안정기를 위한 폐-루우프 피이드백을 가진 전-차수 관측기에 기준한 SM-MF 제어기 설계 : Part 4

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Design of Full-Order Observer-based SM-MF Controller including CLF for Power System Stabilizer : Part 4

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[Abstract]
This paper presents the sliding mode observer-model following(SMO-MF) power system stabilizer(PSS) for unmeasurable plant state variables. This SMO-MF PSS can be obtained by combining the sliding mode-model following(SM-MF) including closed-loop feedback(CLF) with the linear full-order observer(LFOO).
Keywords : Sliding Mode Observer-Model Following, Closed Loop Feedback, Power System Stabilizer

1. Introduction

In many situations, the entired state vector cannot be measured and the control law must be based on an estimate of the state, rather than the actual state. To solve these problems of the full state feedback[1-4], the sliding mode observer-model following(SMO-MF) for unmeasurable plant state variables is developed in this paper. This SMO-MF PSS can be obtained by combining the sliding mode-model following(SM-MF) including closed-loop feedback(CLF) with the linear full-order observer(LFOO).

2. Synchronous generator model

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

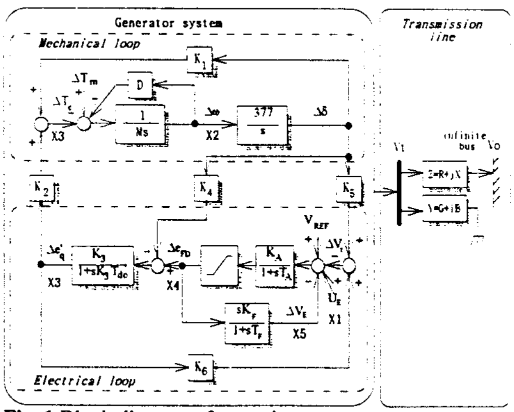

Fig. 1 Block diagram of a synchronous generator system.

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

$$\Delta\dot{v}_t(t) = K_6\cdot\lambda_1\cdot\Delta v_t(t) + 377\cdot K_5\cdot\Delta\omega(t) + K_6\cdot\lambda_2\cdot\Delta T_t(t) + \frac{K_6}{T_{do}}\cdot\Delta e_{FD}(t) \quad (1)$$

$$\Delta\dot{\omega}(t) = -\frac{1}{M}\cdot\Delta T_m(t) \quad (2)$$

$$\Delta\dot{T}_t(t) = K_2\cdot\lambda_1\cdot\Delta v_t(t) + 377\cdot K_1\cdot\Delta\omega(t) + K_2\cdot\lambda_2\cdot\Delta T_t(t) + \frac{K_2}{T_{do}}\cdot\Delta e_{FD}(t) \quad (3)$$

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

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

3. A SMO-MF controller including CLF

The state equation for a reference model can be expressed as

$$\dot{x}_m(t) = A_m\cdot x_m(t) + B_m\cdot u_m(t) \quad (6)$$

where $x_m \in R^n$ is a state vector for model and $u_m \in R^1$ is a control input for model. The control input of a reference model with r_m can be expressed as

$$u_m(t) = -K_m\cdot x_m(t) + r_m(t) \quad (7)$$

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

$$\dot{x}_m(t) = (A_m - B_m\cdot K_m)\cdot x_m(t) + B_m\cdot r_m(t) \quad (8)$$

Let $A_{cm} = A_m - B_m\cdot K_m$ (9)

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

$$\dot{x}_m(t) = A_{tm} \cdot x_m(t) + B_m \cdot r_m(t) \tag{10}$$

where A_{tm} 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

$$\dot{x}_p(t) = (A_p + \Delta A_p) \cdot x_p(t) + (B_p + \Delta B_p) \cdot u_p(t)$$
$$= \tilde{A}_p \cdot x_p(t) + \tilde{B}_p \cdot u_p(t) \tag{11}$$
$$y_p(t) = C_p \cdot x_p(t) \tag{12}$$

where $\tilde{A}_p = A_p + \Delta A_p$ is a $n \times n$ system matrix with the parameter variations for plant and $\tilde{B}_p = B_p + \Delta B_p$ a $n \times 1$ control matrix with the parameter variations for plant. And C_p is the $1 \times n$ output matrix for plant.
The following linear full-order observer equation of the controlled plant for unmeasurable state variables can be expressed as

$$\dot{\hat{x}}_p(t) = \tilde{A}_p \cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_p(t) + L_p \cdot (y_p(t) - C_p \cdot \hat{x}_p(t))$$
$$= (\tilde{A}_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_p(t) + L_p \cdot y_p(t) \tag{13}$$

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

$$L_p = P_p \cdot C_p^T \cdot R_p^{-1} \tag{14}$$

is the $n \times 1$ output injection matrix for plant.
P_p is the symmetric positive definite solution of

$$\tilde{A}_p \cdot P_p + P_p \cdot \tilde{A}_p^T - P_p \cdot C_p^T \cdot R_p^{-1} \cdot C_p \cdot P_p + Q_p = 0 \tag{15}$$

Q_p and R_p are positive definite matrices chosen by the designer.
The input control vector with a feedback gain for unmeasurable state is expressed

$$u_p(t) = u_{CLF}(t) + u_{SMO}(t)$$
$$= -K_p \cdot \hat{x}_p(t) + u_{SMO}(t) \tag{16}$$

where $u_{CLF}(t)$ is the closed-loop feedbaqck control input and $u_{SMO}(t)$ the sliding mode obsever control input. And K_p is a $1 \times n$ feedback gain for plant and can be obtained by pole placement.
Substituting eq.(16) into eq.(13), for unmeasurable state, the following full-order observer equation of the controlled plant including CLF can be expressed as

$$\dot{\hat{x}}_p(t) = (\tilde{A}_p - L_p \cdot C_p) \cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_p(t) + L_p \cdot y_p(t)$$
$$= (\tilde{A}_{tp} - L_p \cdot C_p) \cdot \hat{x}_p(t) + \tilde{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t) \tag{17}$$

where $\tilde{A}_{tp} = (\tilde{A}_p - \tilde{B}_p \cdot K_p)$ is a $n \times n$ system matrix with the parameter variations including CLF for plant.
The error vector and the differential error vector can be expressed as

$$e(t) = x_m(t) - \hat{x}_p(t) \tag{18}$$
$$\dot{e}(t) = \dot{x}_m(t) - \dot{\hat{x}}_p(t) \tag{19}$$

By substituting eq.(10) and eq.(17) into eq.(19), we have

$$\dot{e}(t) = \dot{x}_m(t) - \dot{\hat{x}}_p(t)$$
$$= [A_{tm} \cdot x_m(t) + B_m \cdot r_m(t)] - [(\tilde{A}_{tp} - L_p \cdot C_p) \cdot \hat{x}_p(t)$$
$$+ \tilde{B}_p \cdot u_{SMO}(t) + L_p \cdot y_p(t)] \tag{20}$$
$$x_m(t) = e(t) + \hat{x}_p(t) \tag{21}$$

By substituting eq.(21) into eq.(20), we have

$$\dot{e}(t) = A_{tm} \cdot x_m(t) + B_m \cdot r_m(t) - (\tilde{A}_{tp} - L_p \cdot C_p) \cdot \hat{x}_p(t)$$
$$- \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t)$$
$$= A_{tm} \cdot e(t) - (\tilde{A}_{tp} - L_p \cdot C_p - A_{tm}) \cdot \hat{x}_p(t) + B_m \cdot r_m(t)$$
$$- \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t) \tag{22}$$

Suppose the sliding mode exists on all hyperplanes. The sliding surface vector and the differential sliding surface vector can be expressed as

$$s(e(t)) = G^T \cdot e(t) \tag{23}$$
$$\dot{s}(e(t)) = G^T \cdot \dot{e}(t) \tag{24}$$

where G^T is the sliding surface gain.
To determine a control law that keeps the system on $s(e(t)) \Rightarrow 0$, we introduce the Lyapunov's function

$$V(e(t)) = s^2(e(t))/2 \tag{25}$$

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

$$\dot{V}(e(t)) = s(e(t)) \cdot \dot{s}(e(t)) \tag{26}$$
$$= G^T \cdot e(t) \cdot G^T \cdot \dot{e}(t) \tag{27}$$

By substituting eq.(22) into eq.(27), we have

$$\dot{V}(e(t)) = G^T \cdot e(t) \cdot G^T \cdot [A_{tm} \cdot e(t) - (\tilde{A}_{tp} - L_p \cdot C_p - A_{tm}) \cdot \hat{x}_p(t)$$
$$+ B_m \cdot r_m(t) - \tilde{B}_p \cdot u_{SMO}(t) - L_p \cdot y_p(t)]$$
$$= G^T \cdot e(t) \cdot [G^T \cdot A_{tm} \cdot e(t)$$
$$- G^T \cdot (\tilde{A}_{tp} - L_p \cdot C_p - A_{tm}) \cdot \hat{x}_p(t) + G^T \cdot B_m \cdot r_m(t)$$
$$- G^T \cdot \tilde{B}_p \cdot u_{SMO}(t) - G^T \cdot L_p \cdot y_p(t)] \le 0 \tag{28}$$

From eq.(28), the control input vector with switching for the controlled plant can be represented by

$$u_{SMO}^{+}(t) \ge (G^T \cdot \tilde{B}_p)^{-1} \cdot [G^T \cdot A_{tm} \cdot e(t) - G^T \cdot (\tilde{A}_{tp} - L_p \cdot C_p - A_{tm}) \cdot \hat{x}_p(t)$$
$$+ G^T \cdot B_m \cdot r_m(t) - G^T \cdot L_p \cdot y_p(t)] \quad for \quad G^T \cdot e(k) > 0 \tag{29}$$

$$u_{SMO}^{-}(t) \le \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot \left[G^T \cdot A_m \cdot e(t) - G^T \cdot \left(\tilde{A}_p - L_p \cdot C_p - A_m\right) \cdot \hat{x}_p(t) + G^T \cdot B_m \cdot r_m(t) - G^T \cdot L_p \cdot y_p(t)\right] \quad for \quad G^T \cdot e(k) < 0 \tag{30}$$

From eq.(29) and eq.(30), the control input vector with sign function for the controlled plant can be reformed

$$u_{SMO}^{sign}(t) = \left[SE_{gain} \cdot e(t) + SP_{gain} \cdot \hat{x}_p(t) + SU_{gain} \cdot r_m(t) + SO_{gain} \cdot y_p(t)\right] \cdot \mu \cdot sign(s(e(t))) \tag{31}$$

where μ is the bias gain.

$$SE_{gain} := \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot A_{k_m} \tag{32}$$

is a sliding equal error feedback gain.

$$SP_{gain} := -\left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot \left(\tilde{A}_{k_p} - A_{k_m} - L_p \cdot C_p\right) \tag{33}$$

is a sliding equal estimated plant feedback gain.

$$SU_{gain} := \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot B_m \tag{34}$$

is a sliding equal input gain.

$$SO_{gain} := -\left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot L_p \tag{35}$$

is a sliding equal measured output gain.

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

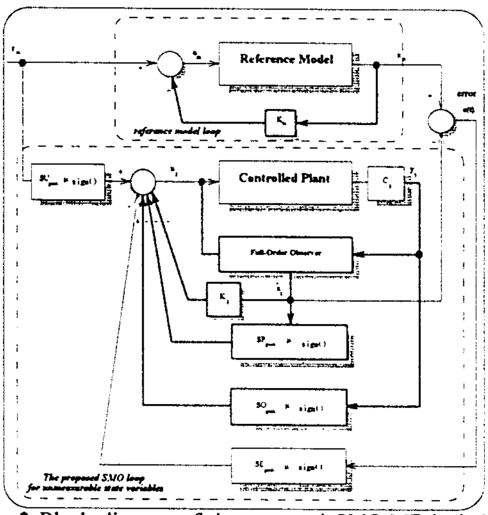

Fig. 2 Block diagram of the proposed SMO-MF including CLF for unmeasurable state variables.

4. Data analysis for SMO-MF PSS

The initial conditions to determine the values of the above A_m and B_m are found in reference[6].

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

$$A_m = \begin{bmatrix} -1.0108 & -33.93 & -0.1305 & 0.1057 & 0 \\ 0 & 0 & -0.108 & 0 & 0 \\ -0.0153 & 207.35 & -0.1846 & 0.1495 & 0 \\ -2600 & 0 & 0 & -20 & -2600 \\ -78 & 0 & 0 & -0.6 & -79 \end{bmatrix}$$

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

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

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

The output injection gain L is

$$L = 1.0e-009 \cdot [0.014 \quad 0.0 \quad 0.005 \quad 0.4284 \quad 0.0122]^T$$

The sliding surface vector is obtained

$$S = [-1.7396 \quad -61.8829 \quad 0.9864 \quad -3.1327 \quad 1.000]^T$$

5. Time domain simulation

The time domain simulation for different initial conditions is carried out for a 10 sec. Fig. 3 shows that the proposed SMO-MF PSS is able to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial condition.

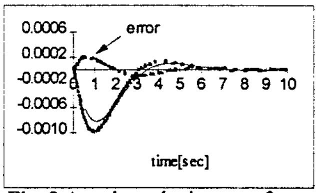

Fig. 3 Angular velocity waveform.

6 . Conclusion

The sliding mode observer-model following(SMO-MF) PSS including closed-loop feedback(CLF) for unmeasurable plant state variables at different initial condition has been presented. Simulation result has been shown that the proposed SMO-MF PSS including CLF is able to achieve asymptotic tracking error between the reference model state and the estimated plant state at different initial conditions.

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