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전력계통안정기를 위한 폐-루우프 피이드백에 기준한 SM-MF 제어기 설계 : Part 1

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Design of Closed-Loop Feedback-based SM-MF Controller for Power System Stabilizer : Part 1

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[Abstract]
This paper presents a power system stabilizer(PSS) using sliding mode-model following(SM-MF) including closed-loop feedback(CLF) and compares the SM-MF PSS without CLF with that including CLF. The aim of this SM-MF PSS including CLF is to damp the low-frequency oscillation by using CLF and then is to obtain asymptotic tracking error between the reference model state and the plant state.
Keywords : Sliding Mode-Model Following, Closed Loop Feedback, Power System Stabilizer

1. Introduction

Since the 1970's, with the development of modern control theory, various new control schemes have been introduced for PSS design and many useful results have been published[1,2]. Among these PSSs design methods, the sliding mode-model following(SM-MF) control method for full state feedback[3] has been applied for an uncertain generator system with voltage regulator and exciter for a single machine to the infinite bus system[4]. In this paper, we present the power system stabilizer(or synchronous generator stabilizer) using a SM-MF including CLF[5].

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[1].

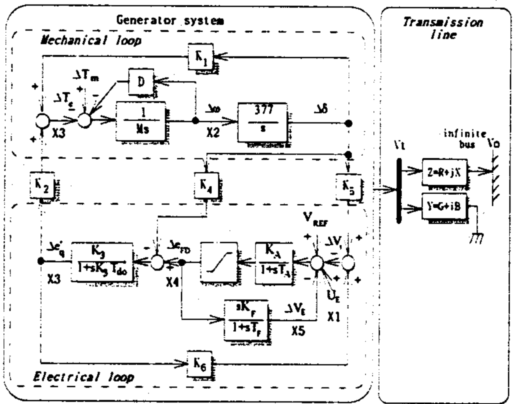


Fig. 1 Block diagram of a synchronous generator system.

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

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

$$\Delta\dot{\omega}(t) = -\frac{1}{M} \cdot \Delta T_{em}(t) \tag{2}$$

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

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

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

where

$$\lambda_1 = \frac{K_1 - K_2 K_3 K_4}{K_3 T'_{do}(K_5 K_2 - K_1 K_6)} \quad \text{and} \quad \lambda_2 = \frac{K_3 K_4 K_6 - K_5}{K_3 T'_{do}(K_5 K_2 - K_1 K_6)}$$

3. A SM-MF controller including CLF

The state equation for a reference model can be expressed as

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

where A_m is a $n \times n$ system matrix for model, B_m a $n \times 1$ control vector for model, $x_m \in R^n$ a state vector for model and $u_m \in R^1$ a control input for model.
The control input[5] of a reference model with reference input vector $r_m(t)$ can be expressed as

$$u_m(t) = -K_m \cdot x_m(t) + r_m(t) \tag{7}$$

where $K_m = R_m^{-1} \cdot B_m^T \cdot P_m$ (8)
is a $1 \times n$ feedback gain vector for model.
P_m is the symmetric positive definite solution of

$$P_m \cdot A_m + A_m^T \cdot P_m - P_m \cdot B_m \cdot R_m^{-1} \cdot B_m^T \cdot P_m + Q_m = 0 \tag{9}$$

Q_m and R_m are positive definite matrices chosen by the designer for model. And $r_m \in R^1$ is a reference input vector for model.
By substituting eq.(7) into eq.(6), the closed-loop feedback system for a reference model is

$$\dot{x}_m(t) = (A_m - B_m \cdot K_m) \cdot x_m(t) + B_m \cdot r_m(t) \tag{10}$$

Let $A_{km} = A_m - B_m \cdot K_m$ (11)

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

$$\dot{x}_m(t) = A_{km} \cdot x_m(t) + B_m \cdot r_m(t) \tag{12}$$

where A_{km} is a $n \times n$ system matrix including CLF for model.
The state equation for the controlled plant with internal parameter variations can be formed as

$$\begin{aligned}\dot{x}_p(t) &= (A_p + \Delta A_p) \cdot x_p(t) + (B_p + \Delta B_p) \cdot u_p(t) \\ &= \tilde{A}_p \cdot x_p(t) + \tilde{B}_p \cdot u_p(t)\end{aligned} \tag{13}$$

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 vector with the parameter variations for plant. And $x_p \in R^n$ is a state vector for plant and $u_p \in R^1$ a control input vector for plant.
The control input[5] of the controlled plant with sliding mode control input can be expressed as

$$u_p(t) = -K_p \cdot x_p(t) + u_{SMI}(t) \tag{14}$$

where $K_p = R_p^{-1} \cdot \tilde{B}_p^T \cdot P_p$ (15)
is a $1 \times n$ feedback gain vector for plant.
P_p is the symmetric positive definite solution of

$$P_p \cdot \tilde{A}_p + \tilde{A}_p^T \cdot P_p - P_p \cdot \tilde{B}_p \cdot R_p^{-1} \cdot \tilde{B}_p^T \cdot P_p + Q_p = 0 \tag{16}$$

Q_p and R_p are positive definite matrices chosen by the designer for plant. And $u_{SMI} \in R^1$ is a sliding mode control input vector for plant.
By substituting eq.(14) into eq.(13), the proposed state equation for the controlled plant including CLF can be expressed as

$$\dot{x}_p(t) = (\tilde{A}_p - \tilde{B}_p \cdot K_p) \cdot x_p(t) + \tilde{B}_p \cdot u_{SMI}(t) \tag{17}$$

Let $\tilde{A}_{kp} = \tilde{A}_p - \tilde{B}_p \cdot K_p$ (18)

The proposed state equation for the controlled plant including CLF can be reformed as

$$\dot{x}_p(t) = \tilde{A}_{kp} \cdot x_p(t) + \tilde{B}_p \cdot u_{SMI}(t) \tag{19}$$

where $\tilde{A}_{kp}$ is a $n \times n$ system matrix including feedback gain with the parameter variations for plant.
The error vector and the differential error vector between the model state and the plant state are

$$e(t) = x_m(t) - x_p(t) \tag{20}$$

$$\dot{e}(t) = \dot{x}_m(t) - \dot{x}_p(t) \tag{21}$$

The limits of the error vector and the differential error vector are

$$\lim_{t \to \infty} e(t) = 0 \tag{22}$$

$$\lim_{t \to \infty} \dot{e}(t) = 0 \tag{23}$$

The model following control method is based on subtracting the state of a model from that of a plant to minimise the error between the plant state and the model state.

$$\begin{aligned}\dot{e}(t) &= \dot{x}_m(t) - \dot{x}_p(t) \\ &= A_{km} \cdot x_m(t) + B_m \cdot r_m(t) - \tilde{A}_{kp} \cdot x_p(t) - \tilde{B}_p \cdot u_{SMI}(t)\end{aligned} \tag{24}$$

$$x_m(t) = e(t) + x_p(t) \tag{25}$$

By substituting (25) into (24), we get

$$\begin{aligned}\dot{e}(t) &= A_{km} \cdot e(t) + A_{km} \cdot x_p(t) + B_m \cdot r_m(t) \\ &\quad - \tilde{A}_{kp} \cdot x_p(t) - \tilde{B}_p \cdot u_{SMI}(t) \\ &= A_{km} \cdot e(t) + \left[A_{km} - \tilde{A}_{kp}\right] \cdot x_p(t) \\ &\quad + B_m \cdot r_m(t) - \tilde{B}_p \cdot u_{SMI}(t)\end{aligned} \tag{26}$$

Suppose the sliding mode exists on all hyperplanes. Then, during sliding, the switching surfaces in the error state space are given

$$s(e(t)) = G^T \cdot e(t) \Rightarrow 0 \tag{27}$$

$$\dot{s}(e(t)) = G^T \cdot \dot{e}(t) \Rightarrow 0 \tag{28}$$

In the above eq.(27), the algorithm of the sliding surface gain G^T is found in references[1,3]. To determine a control law that keeps the system on $s(e(t)) \Rightarrow 0$, we introduce the Lyapunov function

$$V(e(t)) = s^2(e(t))/2 \tag{29}$$

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

$$\dot{V}(e(t)) = s(e(t)) \cdot \dot{s}(e(t)) \tag{30}$$

$$= G^T \cdot e(t) \cdot G^T \cdot \dot{e}(t) \tag{31}$$

$$\begin{aligned}&= G^T \cdot e(t) \cdot G^T \cdot \left\{A_{km} \cdot e(t) + \left[A_{km} - \tilde{A}_{kp}\right] \cdot x_p(t) \right. \\ &\quad \left. + B_m \cdot r_m(t) - \tilde{B}_p \cdot u_{SMI}(t)\right\} \le 0\end{aligned} \tag{32}$$

From eq. (32), the control input vector with switching for the controlled plant can be represented by

$$u_{SMI}^{+}(t) \ge (G^T \cdot \tilde{B}_p)^{-1} \cdot G^T \cdot \left[A_{km} \cdot e(t) + \left[A_{km} - \tilde{A}_{kp}\right] \cdot x_p(t) + B_m \cdot r_m(t)\right]$$

$$\text{for } G^T \cdot e(t) > 0 \tag{33}$$

$$u_{SM}^{-}(t) \le \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot \left[A_{km} \cdot e(t) + \left[A_{km} - \tilde{A}_{kp}\right] \cdot x_p(t) + B_m \cdot r_m(t)\right]$$
$$for \ \ G^T \cdot e(t) < 0 \qquad (34)$$

From eq.(33) and eq.(34), the following control input with sign function for the controlled plant can be reformed

$$u_{SM}^{sign}(t) = \left[SE_{gain} \cdot e(t) + SP_{gain} \cdot x_p(t) + SU_{gain} \cdot r_m(t)\right] \cdot \mu \cdot sign\left(s(e(t))\right) \qquad (35)$$

where μ is a bias gain.

$$SE_{gain} := \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot A_{Km} \qquad (36)$$

is an equal error feedback gain.

$$SP_{gain} := \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot \left(A_{Km} - \tilde{A}_{kp}\right) \qquad (37)$$

is an equal plant feedback gain.

$$SU_{gain} := \left(G^T \cdot \tilde{B}_p\right)^{-1} \cdot G^T \cdot B_m \qquad (38)$$

is an equal input gain.

The detailed block diagram of the proposed SM-MF including CLF in Fig. 2 can be shown as

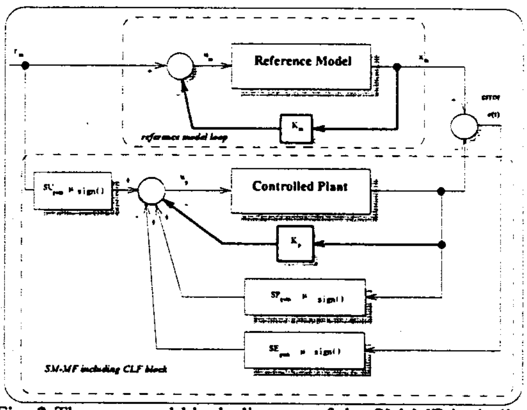


Fig. 2 The proposed block diagram of the SM-MF including CLF.

4. Data analysis

The values of the system matrix A_m and the control vector B_m for a reference model are given as

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

$$B_m = \begin{bmatrix} 0 & 0 & 0 & 2600 & 78 \end{bmatrix}^T$$

The eigenvalues of the A_m matrix are unstable with two poles(right-half) at $-95.9498, 0.1991 \pm 4.8114i, -1.2818 \pm 0.376i$. The values of Q and R are given by $Q = diag(.001, 1, 10e-10, 10e-10)$ and $R = .1$

The values of the feedback gain K_m for the reference model are

$$K_m = \begin{bmatrix} .0036 & -49.4245 & 3.0744 & .0133 & -.2932 \end{bmatrix}.$$

The eigenvalues including CLF are stable with poles at $-95.0788, -11.1131, -1.6048 \pm 1.4637i, -1.5291$.

The values of K_p for the controlled plant are the same as the above K_m. Then for simulations, the controlled plant system matrix and the plant input vector are given by adding the plant parameter uncertainties with reference model.

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

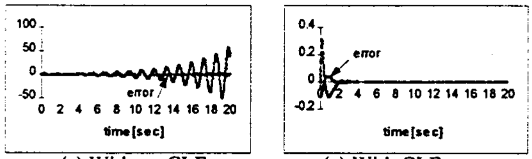
$$\tilde{B}_p = B_m + \Delta B_m = B_m + 10\% \ \ of \ \ B_m$$

The sliding surface vectors is obtained as

$$G = \begin{bmatrix} -2.0093 & 13.6333 & -7.3660 & -3.1548 & 1.000 \end{bmatrix}^T$$

5. Simulation

The simulations are carried out for a 20 sec and electrical torque. The proposed SM-MF PSS including CLF in Fig. 3 (b) is compared the SM-MF without CLF in Fig. 3 (a) and is able to achieve asymptotic tracking error between the reference model state and the plant state.



(a) Without CLF. (a) With CLF.

Fig. 3 Electrical torque waveforms.

6. Conclusion

The sliding mode-model following(SM-MF) power system stabilizer(PSS) including closed-loop feedback(CLF) has been applied. Simulation results has been shown that the proposed SM-MF including CLF is compared the SM-MF without CLF and is able to achieve asymptotic tracking error between the reference model state and the plant state for reference voltage at different initial conditions.

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