'97 대한전기학회 창립 50주년 하계학술대회 논문집 (PSP78)

전력계통안정기를 위한 이산-모드 폐루우프 피이드백에 기준한 SM-MF 제어기 설계 : Part 2

이 상 성 o 박종근
서울대학교 전기공학부

Design of Discrete-Mode CLF-based SM-MF Controller for Power System Stabilizer : Part 2

Sang-Seung Lee○ and Jong-Keun Park
School of Electrical Engineering
Seoul National University

[Abstract]

In this paper, the continuous sliding mode-model following(SM-MF) power system stabilizer(PSS) including closed-loop feedback(CLF) is extended to discrete-time sliding mode-model following(DSM-MF) PSS including CLF.

Keywords : Discrete-mode Sliding Mode-Model Following, Closed Loop Feedback, Power System Stabilizer

1. Introduction

The sliding mode-model following(SM-MF) by K. K. D. Young[1] has been applied to the PSS for an uncertain synchronous generator system for dealing with the internal parameter variations[2]. And a sliding mode-model following(SM-MF) power system stabilizer(PSS) including closed-loop feedback (CLF) has been proposed[3]. The aim of this SM-MF PSS including CLF is to achieve stable generator system(only with left-hand poles) by using CLF for unstable synchronous generator model and then is to obtain asymptotic tracking error between the reference model state and the controlled plant state for generator system. In this paper, the continuous SM-MF PSS including CLF is extended to DSM-MF PSS including CLF.

2. Synchronous generator model

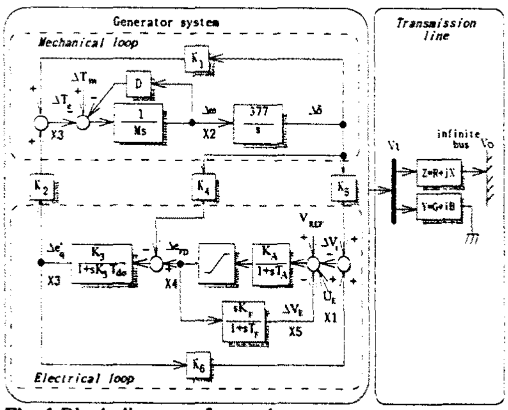


Fig. 1 Block diagram of a synchronous generator system.

The block diagram of the synchronous generator model is shown in Fig. 1[5].

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

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

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

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

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

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

3. A formulation of DSM-MF including CLF

The continuous 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 $x_m \in R^n$, $u_m \in R^1$, A_m is a $n\times n$ system matrix for model and B_m is a $n\times 1$ control vector for model.

The discrete-time state equation for a reference model can be expressed as

$$x_m[(k+1)] = \Phi_m\cdot x_m(k) + \Gamma_m\cdot u_m(k) \tag{7}$$

$x_m \in R^n$, $u_m \in R^1$, Φ_m and Γ_m are the reference model state transition and control transition matrices of appropriate dimensions, evaluated using the following relations:

$$\Phi_m = e^{A_m\cdot T_s} \tag{8}$$

$$\Gamma_m = \left(e^{A_m\cdot T_s} - I\right)\cdot A_m^{-1}\cdot B_m \tag{9}$$

where T_s is the sampling period and I is an identity matrix.
The discrete-time control input[4] of a reference model with reference input vector can be expressed as

$$u_m(k) = -K_m \cdot x_m(k) + r_m(k) \tag{10}$$

where $r_m \in R^1$ is a reference input vector for model.
K_m is a $1 \times n$ feedback gain for model and can be obtained by pole placement.
By substituting eq.(10) into eq.(7), the discrete-time state equation with the CLF for a reference model is

$$x_m[(k+1)] = (\Phi_m - \Gamma_m \cdot K_m) \cdot x_m(k) + \Gamma_m \cdot r_m(k) \tag{11}$$

$$\text{Let} \quad \Phi_{km} = \Phi_m - \Gamma_m \cdot K_m \tag{12}$$

The discrete-time state equation for a reference model including CLF can be reformed as

$$x_m[(k+1)] = \Phi_{km} \cdot x_m(k) + \Gamma_m \cdot r_m(k) \tag{13}$$

where Φ_{km} is a $n \times n$ discrete-time system matrix including feedback gain for model.
The continuous state equation for the controlled plant can be expressed as

$$\dot{x}_p(t) = \tilde{A}_p \cdot x_p(t) + \tilde{B}_p \cdot u_p(t) \tag{14}$$

where $x_p \in R^n$, $u_p \in R^1$; $\tilde{A}_p$ is a $n \times n$ system matrix with the parameter variations for plant, $\tilde{B}_p$ is a $n \times 1$ control input vector with the parameter variations for plant.
The discrete-time state equation for the controlled plant can be expressed as

$$x_p[(k+1)] = \tilde{\Phi}_p \cdot x_p(k) + \tilde{\Gamma}_p \cdot u_p(k) \tag{15}$$

where $x_p \in R^n$ and $u_p \in R^1$; $\tilde{\Phi}_p$ and $\tilde{\Gamma}_p$ are the controlled plant state transition and control transition matrices of appropriate dimensions, evaluated using the following relations:

$$\tilde{\Phi}_p = e^{\tilde{A}_p T_s} \tag{16}$$

$$\tilde{\Gamma}_p = \left(e^{\tilde{A}_p T_s} - I\right) \cdot \tilde{A}_p^{-1} \cdot \tilde{B}_p \tag{17}$$

where T_s is the sampling period and I is an identity matrix.
The discrete-time control input vector[4] for the controlled plant can be expressed as

$$u_p(k) = -K_p \cdot x_p(k) + u_{SM}(k) \tag{18}$$

By substituting eq.(18) into eq.(15), the discrete-time state equation for the controlled plant including CLF can be expressed as

$$x_p[(k+1)] = \left(\tilde{\Phi}_p - \tilde{\Gamma}_p \cdot K_p\right) \cdot x_p(k) + \tilde{\Gamma}_p \cdot u_{SM}(k) \tag{19}$$

$$\text{Let} \quad \tilde{\Phi}_{kp} = \tilde{\Phi}_{kp} - \tilde{\Gamma}_p \cdot K_p \tag{20}$$

The discrete-time state equation for the controlled plant including feedback gain can be reformed as

$$x_p[(k+1)] = \tilde{\Phi}_{kp} \cdot x_p(k) + \tilde{\Gamma}_p \cdot u_{SM}(k) \tag{21}$$

where $\tilde{\Phi}_{kp}$ is a $n \times n$ discrete-time system matrix including CLF with the parameter variations for plant.
The error vector and the differential error vector are given

$$e(k) = x_m(k) - x_p(k) \;\; and \;\; e(k+1) = x_m(k+1) - x_p(k+1) \tag{22}$$

The limits of the error vector and the differential error vector for discrete-time are given

$$\lim_{t\to\infty} e(k) = 0 \;\text{ and }\; \lim_{t\to\infty} e(k+1) = 0 \tag{23}$$

From eq.(13), eq.(21) and eq.(23), we get

$$\begin{aligned} e(k+1) &= x_m(k+1) - x_p(k+1) \\ &= \Phi_{km} \cdot x_m(k) + \Gamma_m \cdot r_m(k) - \tilde{\Phi}_{kp} \cdot x_p(k) - \tilde{\Gamma}_p \cdot u_{SM}(k) \end{aligned} \tag{24}$$

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

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

$$\begin{aligned} e(k+1) &= \Phi_{km} \cdot e(k) + \Phi_{km} \cdot x_p(k) + \Gamma_m \cdot r_m(k) \\ &\quad - \tilde{\Phi}_{kp} \cdot x_p(k) - \tilde{\Gamma}_p \cdot u_{SM}(k) \\ &= \Phi_{km} \cdot e(k) + \left[\Phi_{km} - \tilde{\Phi}_{kp}\right] \cdot x_p(k) \\ &\quad + \Gamma_m \cdot r_m(k) - \tilde{\Gamma}_p \cdot u_{SM}(k) \end{aligned} \tag{26}$$

Suppose the sliding mode exists on all hyperplanes.
The sliding surface vector in the error state space can be expressed as

$$s(e(k)) = G^T \cdot e(k) \Rightarrow 0 \;\; or \;\; s(e(k+1)) = G^T \cdot e(k+1) \Rightarrow 0 \tag{27}$$

where G^T is the sliding surface gain.
In contrast to continuous case, the discrete-time Lyapunov function[4] can be represented by

$$V(s(e(k))) = s(e(k))^T \cdot s(e(k))/2 \tag{28}$$

The discrete-time derivative of $V(s(e(k)))$ is given by

$$\begin{aligned} \dot{V}(s(e(k))) &= V(s(e(k))) \cdot \dot{V}(s(e(k))) \\ &= V(s(e(k))) \cdot \left[V(s(e(k+1))) - V(s(e(k)))\right] \end{aligned} \tag{29}$$

$$\begin{aligned} &= G^T \cdot e(k) \cdot \Big[\left[\Phi_{Km} - I\right] \cdot e(k) + \left[\Phi_{Km} - \tilde{\Phi}_p\right] \cdot x_p(k) \\ &\quad + \Gamma_m \cdot r_m(k) - \tilde{\Gamma}_p \cdot u_{SM}(k)\Big] \le 0 \end{aligned} \tag{30}$$

where I is an identity matrix.
From eq.(30), the control input vector with switching for the

controlled plant can be derived

$$u^{+}(k) \le \left(G^T \cdot \tilde{\Gamma}_p\right)^{-1} \cdot G^T \cdot \left[\left[\Phi_{K_m} - I\right] \cdot e(k) + \left[\Phi_{K_m} - \tilde{\Phi}_{K_p}\right] \cdot x_p(k) + \Gamma_m \cdot r_m(k)\right]$$
$$for \quad G^T \cdot e(k) > 0 \qquad (31)$$

$$u^{-}(k) \ge \left(G^T \cdot \tilde{\Gamma}_p\right)^{-1} \cdot G^T \cdot \left[\left[\Phi_{K_m} - I\right] \cdot e(k) + \left[\Phi_{K_m} - \tilde{\Phi}_{K_p}\right] \cdot x_p(k) + \Gamma_m \cdot r_m(k)\right]$$
$$for \quad G^T \cdot e(k) < 0 \qquad (32)$$

From eq.(31)-(32), the control input vector with sign function for the controlled plant can be reformed

$$u_{SU}^{sign}(k) = \left[DSE_{gain} \cdot e(k) + DSP_{gain} \cdot x_p(k) + DSU_{gain} \cdot r_m(k)\right] \cdot \mu \cdot sign\left(s\left(e(k)\right)\right) \qquad (33)$$

where μ is a bias gain.

$$DSE_{gain} = \left(G^T \cdot \tilde{\Gamma}_p\right)^{-1} \cdot G^T \cdot \left(\Phi_{K_m} - I\right) \qquad (34)$$

is a discrete-time sliding error feedback gain.

$$DSP_{gain} = \left(G^T \cdot \tilde{\Gamma}_p\right)^{-1} \cdot G^T \cdot \left(\Phi_{K_m} - \tilde{\Phi}_{K_p}\right) \qquad (35)$$

is a discrete-time sliding plant feedback gain.

$$DSU_{gain} = \left(G^T \cdot \tilde{\Gamma}_p\right)^{-1} \cdot G^T \cdot \Gamma_m \qquad (36)$$

is a discrete-time sliding input gain.

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

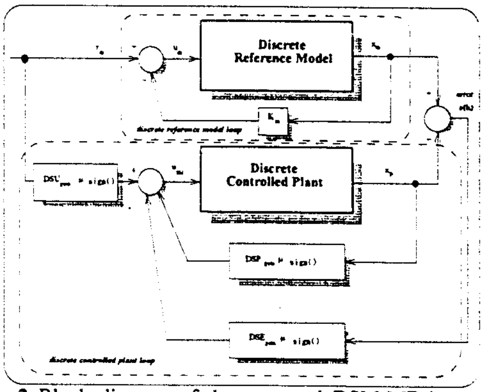


Fig. 2 Block diagram of the proposed DSM-MF including CLF.

4. Data analysis for DSM-MF PSS

The values of the system matrix A_m and the control vector B_m for a continuous reference model under normal load operating 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 values of the system matrix Φ_m and the control vector Γ_m for a discrete-time reference model at sampling period $T_s = .05$ are given as

$$\Phi_m = \begin{bmatrix} -0.8909 & -1.6345 & -0.0017 & 0.0042 & -0.1063 \\ 0.0004 & 0.9720 & -0.0053 & 0.0000 & 0.0003 \\ -0.1529 & 10.3362 & 0.9634 & 0.0059 & -0.1490 \\ -24.7451 & 35.2746 & 0.0527 & 0.7010 & -23.7483 \\ -0.7121 & 1.0360 & 0.0015 & -0.0087 & 0.2684 \end{bmatrix}$$

$$\Gamma_m = \begin{bmatrix} 0.1085 & -0.0004 & 0.1522 & 24.7562 & 0.7125 \end{bmatrix}^T$$

By the pole placement, the values of the feedback gain K_m for the discrete-time reference model can be obtainded

$$K_m = \begin{bmatrix} -0.0062 & -47.3148 & 2.3158 & 0.0200 & -0.4503 \end{bmatrix}$$

The eigenvalues including CLF for discrete-time are stable with poles at

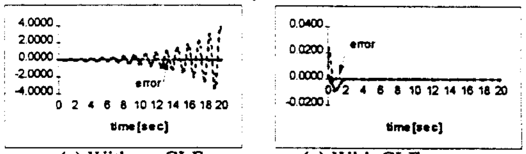
$$eig(\Phi_m - \Gamma_m \cdot K_m) = -0.1232, 0.7419, 0.8585, 0.8483, 0.9800$$

The discrete-time sliding surface vector G can be obtained as

$$G = \begin{bmatrix} -0.1 & -0.2 & -0.3 & 1.0 & 1.0 \end{bmatrix}^T$$

5. Simulation

The simulations are carried out for a 20 sec and electrical torque. The proposed DSM-MF PSS including CLF in Fig. 3 (b) is compared the DSM-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 continuous sliding mode-model following(SM-MF) power system stabilizer(PSS) including CLF is extended to discrete-time sliding mode-model following(DSM-MF) including CLF. Simulation results show that the proposed DSM-MF PSS including CLF is able to achieve asymptotic tracking error between the discrete-time reference model state and the discrete-time controlled plant state.

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