전력계통안정기를 위한 H_∞ 관측기에 기준한 슬라이딩 모드 제어기 설계 : Part II

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Design of H_∞ Observer-Based Sliding Mode Controller for Power System Stabilizer : Part II

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[Abstract]
This paper presents a power system stabilizer(PSS) using the H_∞ observer-based sliding mode controller(H_∞ observer-based SMC) for unmeasurable state variables. The effectiveness of the proposed H_∞ observer-based SMPSS for unmeasurable state variables is shown by the simulation result.

Keywords : H_∞ Observer-based Sliding Mode Controller, Lyapunov's Second Method, Power System Stabilizer

1. Introduction

To design the PSS with better performance, many control strategies have been proposed since 1970s. Among these methods, the H_∞ optimization theory theories[1-3] have been developed as a controller which offers an effective way of the design of transient stability controllers for power system[4-8]. The above H_∞ optimization theories have been applied for designing power system stabilizers as follows : Ohtsuka et al[4] have been designed to deal with a state feedback H_∞ optimal control theory-based generator control system algorithm on single machine infite bus system. Asgharian[5] has been designed to deal with a robust H_∞ power system stabilizer with no adverse effect on shaft torsional modes and to enhance the performance not only the nominal plant but also a clearly defined set of plants inside which the actual system lies. Chen and Malik[6] have been designed to deal with a systematic method to formulate the H_∞ optimal PSS design problem into a general H_∞ control design framework and have been tested on a singlemachine infinite bus system. Ahmed, Chen and Petroianu[7] have been designed to deal with a sub-optimal H_∞ excitation controllers for multimachine system for damping low frequency oscillations. Folly, Yorino and Sasaki[8] have been designed to deal with a H_∞-PSS using numerator-denominator uncertainty representation. In this paper, we present the power system stabilizer(PSS) using the proposed H_∞ observer-based sliding mode controller(SMC) to solve the problem of the full state feedback for unmeasurable state variables and to improve the time domain performance.

2. Power system generator model

The small perturbation transfer-function block diagram of generator system for a single machine to the infinite bus system is shown in Fig. 1[9].

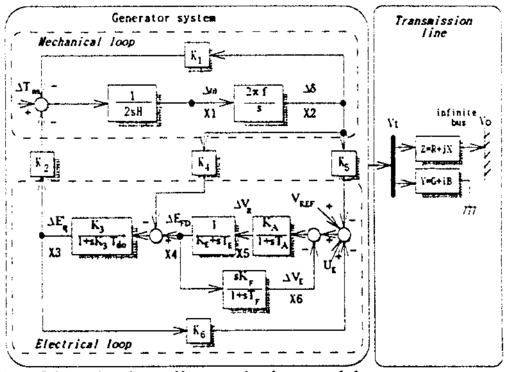

Fig. 1 Linearized small perturbation model.

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

$$\Delta\dot{\omega}(t) = -\frac{K_1}{2H}\cdot\Delta\delta(t) + \frac{K_2}{2H}\cdot\Delta e_q'(t) \tag{1}$$

$$\Delta\dot{\delta}(t) = 2\pi f\cdot\Delta\omega(t) \tag{2}$$

$$\Delta\dot{E}_q'(t) = -\frac{K_4}{T_{do}'}\cdot\Delta\delta(t) - \frac{1}{T_{do}'\cdot K_3}\cdot\Delta E_q'(t) + \frac{1}{T_{do}'}\cdot\Delta E_{fd}(t) \tag{3}$$

$$\Delta\dot{E}_{fd}(t) = -\frac{K_E}{T_E}\cdot\Delta E_{fd}(t) + \frac{1}{T_E}\cdot\Delta V_R(t) \tag{4}$$

$$\Delta\dot{V}_R(t) = -\frac{K_A\cdot K_5}{T_A}\cdot\Delta\delta(t) - \frac{K_A\cdot K_6}{T_A}\cdot\Delta E_q'(t) - \frac{1}{T_A}\cdot\Delta V_R(t) - \frac{K_A}{T_A}\cdot\Delta V_E(t) + \frac{K_A}{T_A}\cdot u_E(t) \tag{5}$$

$$\Delta\dot{V}_E(t) = -\frac{K_E\cdot K_F}{T_E\cdot T_F}\cdot\Delta E_{fd}(t) - \frac{K_F}{T_E\cdot T_F}\cdot\Delta V_R(t) - \frac{1}{T_F}\cdot\Delta V_E(t) \tag{6}$$

The 6-th order state variables can be expressed as

$$x(t) = \left[\Delta\omega(t)\quad \Delta\delta(t)\quad \Delta E_q'(t)\quad \Delta E_{fd}(t)\quad \Delta V_R(t)\quad \Delta V_E(t)\right]^T \tag{7}$$

where $\Delta\omega(t)$ is the angular velocity, $\Delta\delta(t)$ the torque angle, $\Delta E_q'(t)$ the quadratic-axis transient voltage, $\Delta E_{fd}(t)$ the exciter output voltage, $\Delta V_R(t)$ the voltage regulator output voltage and $\Delta V_E(t)$ the output voltage.

3. A H_∞ observer-based sliding mode controller

The state equation and the output equation[1-3] can be expressed as

$$\dot{x}(t) = A \cdot x(t) + B_1 \cdot w(t) + B_2 \cdot u(t) \quad (8)$$

$$z(t) = C_1 \cdot x(t) + D_{11} \cdot w(t) + D_{12} \cdot u(t) \quad (9)$$

$$y(t) = C_2 \cdot x(t) + D_{21} \cdot w(t) + D_{22} \cdot u(t) \quad (10)$$

where $x \in R^n$ is the state vector, $u \in R^m$ the control input vector, $w \in R^q$ the exogenous input vector, $z \in R^p$ the regulated output vector and $y \in R^r$ the measured output vector.

The H_∞ observer-based state equation for unmeasurable state variables can be expressed as

$$\dot{\hat{x}}(t) = A \cdot \hat{x}(t) + B_2 \cdot u(t) + B_1 \cdot \hat{w}(t) + Z_\infty \cdot K_e \cdot (y(t) - \hat{y}(t)) \quad (11)$$

where $\hat{w}(t) = \gamma^{-2} \cdot B_1^T \cdot X_\infty \cdot \hat{x}(t)$ (12)

$$\hat{y}(t) = [C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] \cdot \hat{x}(t) \quad (13)$$

The controller gain K_c is given by

$$K_c = \tilde{D}_{12} \cdot (B_2^T \cdot X_\infty + D_{12}^T \cdot C_1) \quad (14)$$

where $\tilde{D}_{12} = (D_{12}^T \cdot D_{12})^{-1}$ (15)

The estimator gain K_e is given by

$$K_e = (Y_\infty \cdot C_2^T + B_1 \cdot D_{21}^T) \cdot \tilde{D}_{21} \quad (16)$$

where $\tilde{D}_{21} = (D_{21} \cdot D_{21}^T)^{-1}$ (17)

The term Z_∞ is given by

$$Z_\infty = (I - \gamma^{-2} \cdot Y_\infty \cdot X_\infty)^{-1} \quad (18)$$

The controller Riccati equation term X_∞ is given by

$$X_\infty = Ric\begin{bmatrix} A - B_2 \cdot \tilde{D}_{12} \cdot D_{12}^T \cdot C_1 & \gamma^{-2} \cdot B_1 \cdot B_1^T - B_2 \cdot \tilde{D}_{12} \cdot B_2^T \\ -\tilde{C}_1^T \cdot \tilde{C}_1 & -(A - B_2 \cdot \tilde{D}_{12} \cdot D_{12}^T \cdot C_1)^T \end{bmatrix} \quad (19)$$

where $\tilde{C}_1 = (I - D_{12} \cdot \tilde{D}_{12} \cdot D_{12}^T) \cdot C_1$ (20)

And the estimator Riccati equation term Y_∞ is given by

$$Y_\infty = Ric\begin{bmatrix} (A - B_1 \cdot \tilde{D}_{21} \cdot D_{21}^T \cdot C_2)^T & \gamma^{-2} \cdot C_1 \cdot C_1^T - C_2^T \cdot \tilde{D}_{21} \cdot C_2 \\ -\tilde{B}_1 \cdot \tilde{B}_1^T & -(A - B_1 \cdot \tilde{D}_{21}^T \cdot \tilde{D}_{21} \cdot C_2) \end{bmatrix} \quad (21)$$

where $\tilde{B}_1 = B_1 \cdot (I - D_{21}^T \cdot \tilde{D}_{21} \cdot D_{21})$ (22)

In the design of H_∞ observer-based controller for unmeasurable state variables, the control input vector is given by

$$u(t) = -K_c \cdot \hat{x}(t) \quad (23)$$

where $\hat{x} \in R^n$ is the estimated state variables and K_c the H_∞ control input gain.

From eq. (11), eq. (12), eq. (13) and eq. (16), we have

$$\begin{aligned}\dot{\hat{x}}(t) &= A \cdot \hat{x}(t) + B_2 \cdot u(t) + B_1 \cdot \hat{w}(t) + Z_\infty \cdot K_e \cdot (y(t) - \hat{y}(t)) \\ &= [A - Z_\infty \cdot K_e \cdot [C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] \\ &\quad + B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty] \cdot \hat{x}(t) + B_2 \cdot u(t) + Z_\infty \cdot K_e \cdot y(t)\end{aligned} \quad (24)$$

Suppose the sliding mode exists on all hyperplanes. Then, during sliding, the switching surface vector for unmeasurable state variables can be expressed as

$$\sigma(\hat{x}(t)) = G^T \cdot \hat{x}(t) \quad (25)$$

$$\dot{\sigma}(\hat{x}(t)) = G^T \cdot \dot{\hat{x}}(t) \quad (26)$$

where $\hat{x} \in R^n$ is the estimated state variables and G^T the sliding surface gain.

To determine a control law that keeps the system on $\sigma(\hat{x}(t)) = 0$, we introduce the Lyapunov's second method

$$V(\hat{x}(t)) = \sigma^2(\hat{x}(t))/2 \quad (27)$$

The time derivative of $V(\hat{x}(t))$ can be expressed as

$$\dot{V}(\hat{x}(t)) = \sigma(\hat{x}(t)) \cdot \dot{\sigma}(\hat{x}(t)) \quad (28)$$

$$\begin{aligned}&= G^T \cdot \hat{x}(t) \cdot G^T \cdot \dot{\hat{x}}(t) \\ &= G^T \cdot \hat{x}(t) \cdot [G^T \cdot [A - Z_\infty \cdot K_e \cdot [C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] \\ &\quad + B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty] \cdot \hat{x}(t) + G^T \cdot B_2 \cdot u_{SMC}(t) \\ &\quad + G^T \cdot Z_\infty \cdot K_e \cdot y(t)] \le 0\end{aligned} \quad (29)$$

From eq. (29), the control input of the H_∞ observer-based SMC for unmeasurable state variables with switching can be reduced

$$\begin{aligned}u_{SMC}^+(t) \ge &-(G^T \cdot B_2)^{-1} \cdot [G^T \cdot [A - Z_\infty \cdot K_e \\ &[C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] + B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty]] \\ &\cdot \hat{x}(t) + G^T \cdot Z_\infty \cdot K_e \cdot y(t) \quad for \ G^T \cdot \hat{x}(t) > 0\end{aligned} \quad (30)$$

$$\begin{aligned}u_{SMC}^-(t) \le &-(G^T \cdot B_2)^{-1} \cdot [G^T \cdot [A - Z_\infty \cdot K_e \\ &[C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] + B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty]] \\ &\cdot \hat{x}(t) + G^T \cdot Z_\infty \cdot K_e \cdot y(t) \quad for \ G^T \cdot \hat{x}(t) < 0\end{aligned} \quad (31)$$

Finally, from eq. (30) and eq. (31), the control input of the proposed H_∞ observer-based SMC for unmeasurable state variables with sign function can be reformed

$$\begin{aligned}u_{SMC}^{sign}(t) = &-(G^T \cdot B_2)^{-1} [G^T \cdot [A - Z_\infty \cdot K_e \cdot [C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty] \\ &+ B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty] \cdot \hat{x}(t) + G^T \cdot Z_\infty \cdot K_e \cdot y(t)] \cdot sign(\sigma(\hat{x}(t)))\end{aligned}$$

(32)

To simplfy the eq.(32), the following equation can be formed

$$u^{new}_{SMC}(t) = \left[GK_1 \cdot \hat{x}(t) + GK_2 \cdot y(t)\right] \cdot sign\left(\sigma\left(\hat{x}(t)\right)\right) \quad (33)$$

where $GK_1 := -\left(G^T \cdot B_2\right)^{-1} \cdot G^T \cdot \left[A - Z_\infty \cdot K_c\right.$

$$\left.\left\{C_2 + \gamma^{-2} \cdot D_{21} \cdot B_1^T \cdot X_\infty\right\} + B_1 \cdot \gamma^{-2} \cdot B_1^T \cdot X_\infty\right] \quad (34)$$

$$GK_2 := -\left(G^T \cdot B_2\right)^{-1} \cdot G^T \cdot Z_\infty \cdot K_c \quad (35)$$

Fig. 2 is the block diagram of the proposed H_∞ observer-based SMC for unmeasurable state variables.

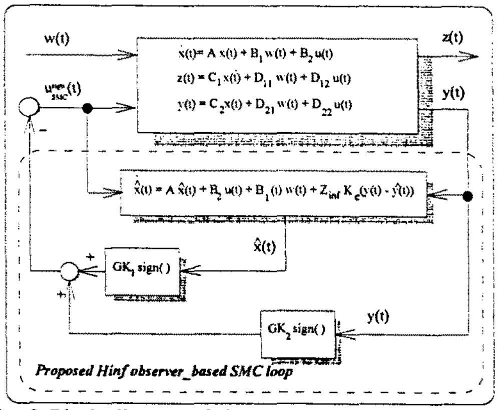

Fig. 2 Block diagram of the proposed H_∞ observer-based SMC for unmeasurable state variables.

4. Data analysis

To determine the values of the A and the B_2, the $K_1 \sim K_6$ values under normal load operation are given as

$K1 = 1.1584 \quad K2 = 1.4347 \quad K3 = 0.3600$

$K4 = 1.8364 \quad K5 = -0.1113 \quad K6 = 0.3171$

And the values of the A and the B_2 under normal load operation are given by

$$A = \begin{bmatrix} 0 & -0.1158 & -0.1435 & 0 & 0 & 0 \\ 314.159 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.3061 & -0.4630 & 0.1667 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 2 & 0 \\ 0 & 111.33 & -317.11 & 0 & -20 & -1000 \\ 0 & 0 & 0 & 0.01 & 0.2 & -2 \end{bmatrix}$$

$$B_1 = \left[\frac{1}{2H} \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\right]^T \quad B_2 = \left[0 \quad 0 \quad 0 \quad 0 \quad 1000 \quad 0\right]^T$$

$$C_1 = diag(100,\ 0,\ 0,\ 0,\ 0,\ 0,) \quad C_2 = \left[1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\right]$$

The sliding surface vector can be obtained

$$G = \left[-82146.276 \quad 188.818 \quad 2647.961 \quad -32.674 \quad 1.0 \quad 539.925\right]^T$$

5 Simulation studies

Simulation study is carried out to evaluate the performance of the proposed H_∞ observer-based SMPSS for a 5[sec]. Fig. 3 is the angular velocity waveforms of the H_∞ observer-based PSS and the proposed H_∞ observer-based SMPSS under normal load operation.

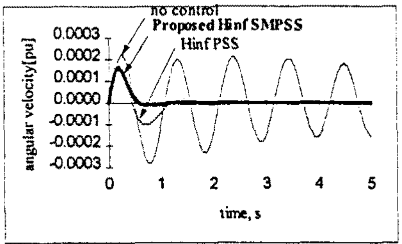

Fig. 3 Waveforms for angular velocity under normal load.

6. Conclusion

The power system stabilizer(PSS) using the proposed H_∞ observer-based sliding mode controller(SMC) has been presented. The proposed H_∞ observer-based SMPSS has been demonstrated good performance under normal load operation.

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