전력계통안정기를 위한 전-차수 관측기에 기준한 슬라이딩 모드 제어기 설계 : Part I

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Design of Full-Order Observer-based Sliding Mode Controller for Power System Stabilizer : Part I

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[Abstract]

This paper presents the proposed full-order observer-based sliding mode power system stabilizer(FOOSMPSS) for finding unmeasurable state variables(torque angle, quadratic-axis transient voltage, exciter output voltage, voltage regulator output voltage and output voltage) by measuring angular velocity. The simulation results is shown by the comparision of the FOOPSS with the proposed FOOSMPSS.
Keywords : Full-Order Observer-based Sliding Mode Controller, Power System Stabilizer

1. Introduction

The power system stabilizer(PSSs) has been designed to damp out the low frequency oscillations of the power system[1-5]. Among these methods, sliding mode control[6] theories have been developed as a controller which offers an effective way of the design of transient stability controllers for power system[7-11]. In sliding mode control(SMC) (or VSC), the most distinct feature is existence of a sliding mode which occurs on predetermined sliding heperplane. Once in sliding mode, the system will be forced to slide along, or at the vicinity of, the sliding hyperplane and hence is robust to plant parameter variations and plant external disturbances. This SMC theory has been applied for designing power system stabilizers as follows : Chan and Hsu[7] have been developed for the selection of the sliding hyperplane of SMC based on the linear optimal control theory and applied to PSSs for single-machine & for multi-machine. Wang, Mohlre, Spee and Mittelstadt[8] have been applied to VSS facts controller for power system transient stability. Kothari, Nanda and Bhattacharya[9] have been applied for the design of SMCPSS with desired eigenvalues in sliding mode. However, these sliding mode controllers[6-10] applied to the power system stabilizer(PSS) are all based on assumption that the complete state is available for implementation of the control law. To solve these problems of the full state feedback mentioned above, a composite sliding mode observer(CSMO) based on full-order observer(FOO) for unmeasurable state variables has been developed[11]. The aim of this CSMO based on FOO is to achieve the stable system(only with left-hand poles) by using FOO and then is to apply the SMC. In contrast to the CSMO, this paper presents the proposed full-order observer-based sliding mode power system stabilizer(FOOSMPSS) for finding unmeasurable state variables(torque angle, quadratic-axis transient voltage, exciter output voltage, voltage regulator output voltage and output voltage) by measuring angular velocity. This FOOSMPSS can be obtained by combining the sliding mode control(SMC) with the full-order observer(FOO)[12-14]. The control input of the proposed FOOSMPSS for unmeasurable state variables is derived by Lyapunov's second method to determine a control input that keeps the system stable.

2. Power system 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[4,9]. An IEEE type-1 excitation system model has been considered which neglects saturation of the exciter and voltage limits of amplifier output.

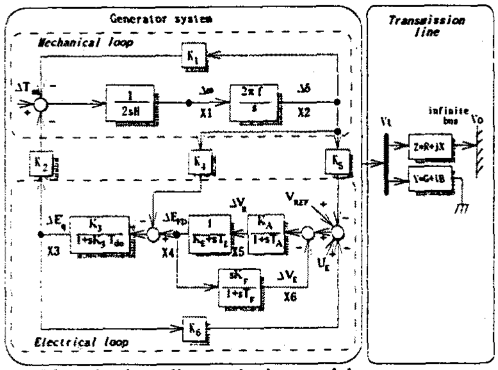

Fig. 1 Linearized small perturbation model.

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

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

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

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

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

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

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

where

K_1 *and* K_2 are the constants derived from electrical torque, K_3 *and* K_4 the constants derived from field voltage equation and K_5 *and* K_6 the constants derived from terminal voltage magnitude. And T_A is the voltage regulator time constant, K_A the voltage regulator gain, T_E the exciter time constant, K_E the exciter constant related to self excited field, T_F the regulator stabilizing circuit time constant, T_{do}' the d-axis transient open circuit time constant and H the inertia moment coefficient. And u_E is the supplementary excitation control input.
The 6-th order state variables can be expressed as

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

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 FOOSM controller

The state equation for full-state feedback and the output equation can be expressed as

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

$$y(t) = C \cdot x(t) \quad (9)$$

where A is the system matrix with the parameter variations, B the control matrix with the parameter variations and C the $m \times n$ output matrix. And $x \in R^n$ the state vector, $u \in R^m$ the control input vector and $y \in R^p$ the output state vector.
The full-order observer state equation for unmeasurable state variables[12,13,14] can be expressed as

$$\begin{aligned} \dot{\hat{x}}(t) &= A \cdot \hat{x}(t) + B \cdot u(t) + L \cdot \left(y(t) - C \cdot \hat{x}(t)\right) \\ &= (A - L \cdot C) \cdot \hat{x}(t) + B \cdot u(t) + L \cdot y(t) \end{aligned} \quad (10)$$

where $L = P \cdot C^T \cdot R^{-1}$ (11)
is the $n \times m$ output injection matrix.
P is the symmetric positive definite solution of

$$A \cdot P + P \cdot A^T - P \cdot C^T \cdot R^{-1} \cdot C \cdot P + Q = 0 \quad (12)$$

Q and R are positive definite matrices chosen by the designer. And $\hat{x} \in R^n$ is the estimated state. From eq.(10), the following assumptions are made :

(A,B) *is controllable and* (A,C) *is observable.*

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

$$\sigma(\hat{x}(t)) = G^T \cdot \hat{x}(t) \quad (13)$$

$$\dot{\sigma}(\hat{x}(t)) = G^T \cdot \dot{\hat{x}}(t) \quad (14)$$

where G^T is the sliding surface gain.
To determine a control law that keeps the system stable, we introduce the Lyapunov's function

$$V(\hat{x}(t)) = \sigma^2(\hat{x}(t))/2 \quad (15)$$

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

$$\begin{aligned} \dot{V}(\hat{x}(t)) &= \sigma(\hat{x}(t)) \cdot \dot{\sigma}(\hat{x}(t)) \quad (16) \\ &= G^T \cdot \hat{x}(t) \cdot G^T \cdot \dot{\hat{x}}(t) \\ &= G^T \cdot \hat{x}(t) \cdot G^T \cdot \left[(A - L \cdot C) \cdot \hat{x}(t) + B \cdot u_{SMC}(t) + L \cdot y(t)\right] \\ &\le 0 \quad (17) \end{aligned}$$

where u_{SMC} is the sliding mode control input vector.
From eq. (17), the control input for unmeasurable state variables with switching can be derived as follow:

$$u_{SMC}^{-}(t) \ge -(G^T \cdot B)^{-1} \cdot \left[G^T \cdot [A - L \cdot C] \cdot \hat{x}(t) + G^T \cdot L \cdot y(t)\right] \quad \text{for } G^T \cdot \hat{x}(t) > 0 \quad (18)$$

$$u_{SMC}^{-}(t) \le -(G^T \cdot B)^{-1} \cdot \left[G^T \cdot [A - L \cdot C] \cdot \hat{x}(t) + G^T \cdot L \cdot y(t)\right] \quad \text{for } G^T \cdot \hat{x}(t) < 0 \quad (19)$$

Finally, from eq.(18) and eq.(19), the control input of the proposed FOOSMC for unmeasurable state variables with sign function can be reformed

$$u_{SMC}^{sign}(t) = -(G^T \cdot B)^{-1} \cdot \left[G^T \cdot [A - L \cdot C] \cdot \hat{x}(t) + G^T \cdot L \cdot y(t)\right] \cdot sign\left(\sigma(\hat{x}(t))\right) \quad (20)$$

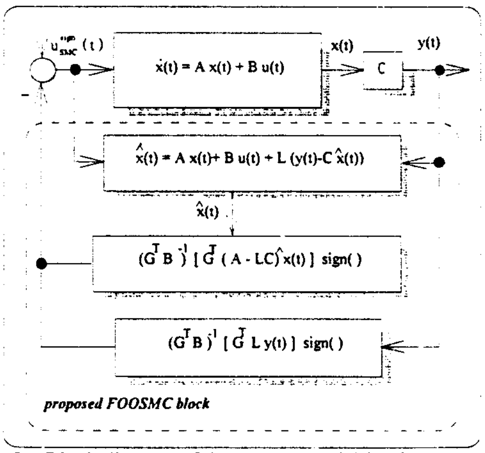

Fig. 2 Block diagram of the proposed FOOSMC.

The overall block diagram in Fig. 2 represents the proposed full-order observer-based sliding mode controller(FOOSMC) for unmeasurable state variables.

The algorithm for realization of FOOSMC can be summarized as follows:

(1) Choose the equation of hyperplane to be of the form $\sigma(\hat{x}(t)) = 0$.

(2) Compute the estimated control input with the sign function for a sliding mode.

(3) Apply the controlled plant.

4. Data analysis of the FOOSMPSS

Norminal parameters of the system for the initial d-q axis current and voltage components and torque angle needed for evaluating the K constants are as follows :

$V_{do} = 0.8211 \ p.u \quad I_{do} = 0.8496 \ p.u$

$E'_{qo} = 0.8427 \ p.u \quad V_{qo} = 0.5708 \ p.u$

$I_{qo} = 0.5297 \ p.u \quad V_{o} = 1.0585 \ p.u$

$\delta_{o} = 77.40^{\circ}$

The $K_1 - K_6$ 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 A, B and C under normal load operation condition are given by

$$A = \begin{bmatrix} 0 & -0.1158 & -0.1435 & 0 & 0 & 0 \\ 314.159 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.3061 & -0.4630 & 0.1667 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 2 & 0 \\ 0 & 1113.3 & -317.11 & 0 & -20 & -1000 \\ 0 & 0 & 0 & 0.01 & 0.2 & -2 \end{bmatrix}$$

$$B = [0 \ 0 \ 0 \ 0 \ 1000 \ 0]^T \qquad C = [1 \ 0 \ 0 \ 0 \ 0 \ 0]$$

If the desired pole locations are set to $-8.0, \ -8.5, \ -9.0, \ -9.5, \ -10.0$, the sliding surface vector can be obtained

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

The output injection vector L can be obtained

$$L = 1.0e-008 \cdot [.0000 \ \ -.0058 \ \ .0020 \ \ -.0694 \ \ -.9504 \ \ -.0100]^T$$

5. Simulation studies

Simulation study is carried out to evaluate the performance of the proposed FOOSMPSS for a 5 sec.

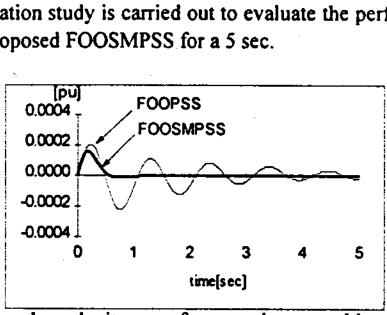

Fig. 3 Angular velocity waveforms under normal load.

Under normal load condition, a 0.02[p.u] initial condition of input torque reference is applied. The dynamic simulation results in Fig. 3 are shown by the comparision of the FOOPSS with the proposed FOOSMPSS under normal load operation. It can be clearly seen that the responses obtained with FOOSMPSS under normal load operation are well damped.

6. Conclusion

A full-order observer-based sliding mode power system stabilizer(FOOSMPSS) for unmeasurable state variables has been proposed. The simulation result has been shown by the comparision of the FOOPSS with the proposed FOOSMPSS under normal load operation.

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