비선형 PSS 을 위한 NFL-H$_\infty$/SMC 의 설계 : Part B

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NFL-H$_\infty$/SMC Design for Nonlinear PSS : Part B

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[Abstract] In this paper, the standard Dole, Glover, Khargoneker, and Francis (abbr. : DGKF 1989) H$_\infty$ controller (H$_\infty$C) is extended to the nonlinear feedback linearization-H$_\infty$/sliding mode controller (NFL-H$_\infty$/SMC) to solve the problem associated with the full state feedback for the unmeasurable state variables in the conventional SMC, to obtain the smooth control as the linearized controller for a linear system (or to cancel the nonlinearity for the nonlinear system), and to improve the time-domain performance under worst case.

Keywords : nonlinear feedback linearization-H$_\infty$/sliding mode controller, power system stabilizer

1. Introduction

Under worst situation, the standard Dole, Glover, Khargoneker, and Francis (abbr. : DGKF 1989) H$_\infty$ controller (H$_\infty$C) [1] is extended to the nonlinear feedback linearization-H$_\infty$/sliding mode controller (NFL-H$_\infty$/SMC). The proposed controller is obtained by combining the H$_\infty$ estimator [1] with the nonlinear feedback linearization-sliding mode controller (NFL-SMC) and eliminates the need to measure all the state variables in the conventional SMC [2-18]. The effectiveness of the proposed controller is verified by the simulations in case of 3-cycle line-ground fault and in case of parameter variations.

2. Proposed NFL-H$_\infty$/SMC

The state equations under worst case based on nonlinear feedback linearization (NFL) [20] are

$$z(t) = T(x(t)) \tag{1}$$

$$\dot{z}(t) = Az(t) + B_1 w_{worst}(t) + B_2 u(t) \tag{2}$$

$$p(t) = C_1 z(t) + D_{11} w_{worst}(t) + D_{12} u(t) \tag{3}$$

$$y(t) = C_2 z(t) + D_{21} w_{worst}(t) + D_{22} u(t) \tag{4}$$

where $x \in R^n$, $z \in R^n$, $w_{worst} \in R^{m1}$, $u \in R^{m2}$, $p \in R^{p1}$, $y \in R^{p2}$, A is the $n \times n$ system matrix, B_1 is the $n \times m_1$ exogenous input matrix, B_2 is the $n \times m_2$ control matrix, C_1 is the $p_1 \times n$ regulated output matrix, C_2 is the $p_2 \times n$ output or measurement matrix, D_{11} is the $p_1 \times m_1$ regulated direct feed-forward matrix, D_{12} is the $p_1 \times m_2$ regulated direct feed-forward matrix, D_{21} is the $p_2 \times m_1$ output direct feed-forward matrix, and D_{22} is the $p_2 \times m_2$ output direct feed-forward matrix.

The H$_\infty$ estimator state equation based on NFL is [1]

$$\dot{\hat{z}}(t) = A\hat{z}(t) + B_2 u(t) + B_1 \hat{w}_{worst}(t) + Z_\infty K_e (y(t) - \hat{y}(t)) \tag{5}$$

where $\hat{w}_{worst}(t) = \gamma^{-2} B_1^T X_\infty \hat{z}(t)$ (6)

$$\hat{y}(t) = \left[C_2 + \gamma^{-2} D_{21} B_1^T X_\infty\right]\hat{z}(t) \tag{7}$$

The controller gain K_c is given by

$$K_c = \tilde{D}_{12}\left(B_2^T X_\infty + D_{12}^T C_1\right) \tag{8}$$

where $\tilde{D}_{12} = \left(D_{12}^T D_{12}\right)^{-1}$ (9)

The estimator gain K_e is given by

$$K_e = \left(Y_\infty C_2^T + B_1 D_{21}^T\right)\tilde{D}_{21} \tag{10}$$

where $\tilde{D}_{21} = \left(D_{21} D_{21}^T\right)^{-1}$ (11)

The term Z_∞ is given by

$$Z_\infty = \left(I - \gamma^{-2} Y_\infty X_\infty\right)^{-1} \tag{12}$$

The controller Riccati equation term X_∞ is

$$X_\infty = Ric\begin{bmatrix} A - B_1\tilde{D}_{11}D_{12}^T C_1 & \gamma^{-2}B_1B_1^T - B_2\tilde{D}_{12}B_2^T \\ -\tilde{C}_1^T\tilde{C}_1 & -\left(A - B_1\tilde{D}_{11}D_{12}^T C_1\right)^T \end{bmatrix} \quad (13)$$

where $\tilde{C}_1 = \left(I - D_{12}\tilde{D}_{12}D_{12}^T\right)C_1$ (14)

The estimator Riccati equation term is

$$Y_\infty = Ric\begin{bmatrix} \left(A - B_1\tilde{D}_{21}D_{21}^T C_2\right)^T & \gamma^{-2}C_1C_1^T - C_2^T\tilde{D}_{21}C_2 \\ -\tilde{B}_1\tilde{B}_1^T & -\left(A - B_1\tilde{D}_{21}^T\tilde{D}_{21}C_2\right) \end{bmatrix} \quad (15)$$

where $\tilde{B}_1 = B_1\left(I - D_{21}^T\tilde{D}_{21}D_{21}\right)$ (16)

The estimated control input based on NFL is

$$u_e(t) = -K_e\hat{z}(t) \quad (17)$$

The internally stabilizing control gain is

$$K_{H_\infty C}(s) = \begin{bmatrix} A_1 & Z_\infty K_e \\ -K_c & 0 \end{bmatrix} \quad (18)$$

where $A_1 := A - B_2K_c - Z_\infty K_e C_2$

$$+\gamma^{-2}\left(B_1B_1^T - Z_\infty K_e D_{21}B_1^T\right)X_\infty \quad (19)$$

The closed loop system can be expressed as

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -B_2K_c \\ Z_\infty K_e C_2 & A_2 \end{bmatrix}\begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ Z_\infty K_e D_{21} \end{bmatrix} w_{worst}(t) \quad (20)$$

$$\begin{bmatrix} p(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} C_1 & -D_{12}K_c \\ C_2 & 0 \end{bmatrix}\begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ D_{21} \end{bmatrix} w_{worst}(t) \quad (21)$$

where $A_2 := A - B_2K_c + \gamma^{-2}B_1B_1^T X_\infty$

$$-Z_\infty K_e\left(C_2 + \gamma^{-2}D_{21}B_1^T X_\infty\right) \quad (22)$$

From equations (2) and (6), the state equation based on NFL can be expressed as

$$\dot{z}(t) = Az(t) + B_1w_{worst}(t) + B_2u(t)$$
$$= \left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)z(t) + B_2u(t) \quad (23)$$

The switching surface vector and the differential switching surface vector can be expressed as

$$\sigma(z(t)) = G^T z(t) \quad (24)$$

$$\dot{\sigma}(z(t)) = G^T\dot{z}(t) \quad (25)$$

where G^T is the sliding surface gain [2-5,11].

The Lyapunov's function candidate is chosen by

$$V(z(t)) = \sigma^2(z(t))/2 \quad (26)$$

The time derivative of $V(z(t))$ can be expressed as

$$\dot{V}(z(t)) = \sigma(z(t))\dot{\sigma}(z(t)) \quad (27)$$
$$= G^T z(t)G^T\dot{z}(t) = G^T z(t)G^T$$
$$\left[\left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)z(t) + B_2u_{NFL-W-SMC}(t)\right] \leq 0 \quad (28)$$

The control inputs with switching function are

$$u_{NFL-W-SMC}^{+}(t) \geq -\left(G^T B_2\right)^{-1}\left[G^T\left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)\right]z(t)$$
$$\text{for } G^T z(t) > 0 \quad (29)$$

$$u_{NFL-W-SMC}^{-}(t) \leq -\left(G^T B_2\right)^{-1}\left[G^T\left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)\right]z(t)$$
$$\text{for } G^T z(t) < 0 \quad (30)$$

The control input with sign function is

$$u_{NFL-W-SMC}^{sign}(t) = -\left(G^T B_2\right)^{-1}\left[G^T\left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)\right]z(t)$$
$$sign(\sigma(z(t))) \quad (31)$$

The above equation (31) can be reformed as

$$u_{NFL-W-SMC}^{sign}(t) = -K_{W-SMC}z(t)\ sign(\sigma(z(t))) \quad (32)$$

$$K_{W-SMC} := \left(G^T B_2\right)^{-1}\left[G^T\left(A + B_1\left(\gamma^{-2}B_1^T X_\infty\right)\right)\right] \quad (33)$$

Finally, the estimated control input vector is

$$u_{NFL-H_\infty/SMC}^{sign}(t) = -K_{W-SMC}\hat{z}(t)\ sign(\sigma(\hat{z}(t))) \quad (34)$$

The internally stabilizing control gain is

$$K_{H_\infty/SMC}(s) = \begin{bmatrix} A_1 & Z_\infty K_e \\ -K_{W-SMC}\,sign(\sigma(\hat{z}(t))) & 0 \end{bmatrix} \quad (35)$$

where $A_1 := A - B_2K_{W-SMC}\,sign(\sigma(\hat{z}(t))) - Z_\infty K_e C_2$

$$+\gamma^{-2}\left(B_1B_1^T - Z_\infty K_e D_{21}B_1^T\right)X_\infty \quad (36)$$

The closed loop system can be expressed as

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -B_2K_{W-SMC}\,sign(\sigma(\hat{z}(t))) \\ Z_\infty K_e C_2 & A_2 \end{bmatrix}\begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix}$$
$$+\begin{bmatrix} B_1 \\ Z_\infty K_e D_{21} \end{bmatrix} w_{worst}(t) \quad (37)$$

$$\begin{bmatrix} p(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} C_1 & -D_{12}K_{W-SMC}\,sign(\sigma(\hat{z}(t))) \\ C_2 & 0 \end{bmatrix}\begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ D_{21} \end{bmatrix} w_{worst}(t) \quad (38)$$

where $A_2 := A - B_2K_{W-SMC}\,sign(\sigma(\hat{z}(t))) + \gamma^{-2}B_1B_1^T X_\infty$

$$-Z_\infty K_e\left(C_2 + \gamma^{-2}D_{21}B_1^T X_\infty\right) \quad (39)$$

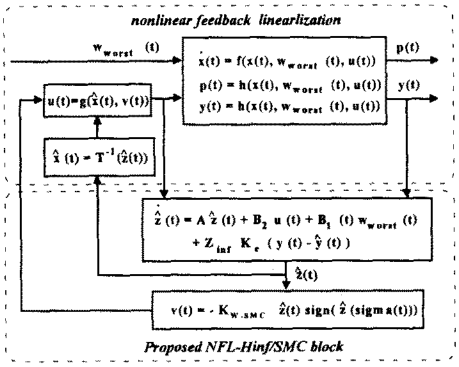


Fig. 1 Proposed NFL-H_∞/SMC.

3. Nonlinear power system model

The d-axis current and the q-axis current are [19]

$$i_d(t) = c_1e_q'(t) - c_2\left(R_2\sin\delta(t) + X_1\cos\delta(t)\right) \quad (40)$$

$$i_q(t) = c_3e_q'(t) - c_4\left(-X_2\sin\delta(t) + R_1\cos\delta(t)\right) \quad (41)$$

$$c_1 = \frac{(C_1X_1 - C_2R_2)}{(R_1R_2 + X_1X_2)}, \quad c_2 = \frac{V_{inf}}{(R_1R_2 + X_1X_2)}$$

$$c_3 = \frac{(C_1R_1 + C_2X_2)}{(R_1R_2 + X_1X_2)}, \quad c_4 = \frac{V_{inf}}{(R_1R_2 + X_1X_2)}$$

$$Z_1 = R_1 + jX_1, \qquad Z_2 = R_2 + jX_2, \quad Y = G + jB$$

$$Z_T = \frac{Z_1 Z_2}{Z_1 + Z_2}, \quad 1 + Z_T Y := C_1 + jC_2, \quad C_1 := 1 + RG - XB$$

$$C_2 := XG + RB, \quad R_1 := R - C_2 x'_d, \quad R_2 := R - C_2 x_q$$

$$X_1 := X + C_1 x_q, \quad X_2 := X + C_1 x'_d$$

$$v_d(t) = x_q i_q(t) \tag{42}$$

$$v_q(t) = e'_q(t) - x'_d i_d(t) \tag{43}$$

$$v_T^2(t) = v_d^2(t) + v_q^2(t) \tag{44}$$

$$\begin{aligned} T_e(t) \approx P_e(t) &= i_d(t) v_d(t) + i_q(t) v_q(t) \\ &= e'_q(t) i_q(t) + (x_q - x'_d) i_d(t) i_q(t) \end{aligned} \tag{45}$$

The nonlinear 4-th order state equations are [19]

$$\dot{\omega}(t) = \frac{1}{M} T_m - \frac{1}{M} T_e(t) \tag{46}$$

$$\dot{\delta}(t) = \omega_o(\omega(t) - 1) \tag{47}$$

$$\dot{e}'_q(t) = -\frac{1}{T'_{do}} e'_q(t) - \frac{(x_d - x'_d)}{T'_{do}} i_d(t) + \frac{1}{T'_{do}} e_{fd}(t) \tag{48}$$

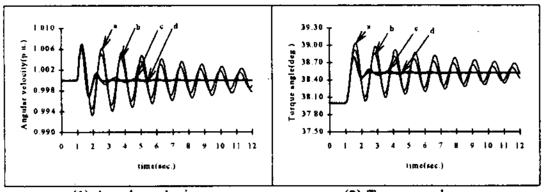
$$\dot{e}_{fd}(t) = -\frac{1}{T_A} e_{fd}(t) + \frac{K_A}{T_A}\left(V_{ref} - v_T(t) + u_E(t)\right) \tag{49}$$

$$e_{fd\min} \le e_{fd} \le e_{fd\max} \text{ and } u_{E\min} \le u_E \le u_{E\max} \tag{50}$$

$e_{fd\max} = 6.0 \quad e_{fd\min} = -6.0$, and $u_{E\min} = +0.2 \quad u_{E\min} = -0.2$

4. Simulation

The proposed NFL-H$_\infty$/SMC-PSS in Fig. 2 exhibits better damping properties.

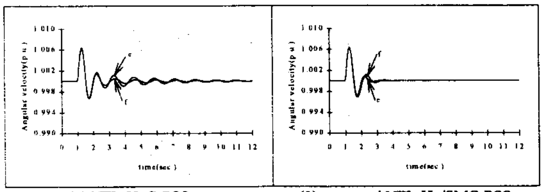


(1) Angular velocity (2) Torque angle

Fig. 2 Normal load operation. *(a : no control b : conventional PSS c :* NFL-H$_\infty$C-PSS *d : proposed* NFL-H$_\infty$/SMC-PSS*)*

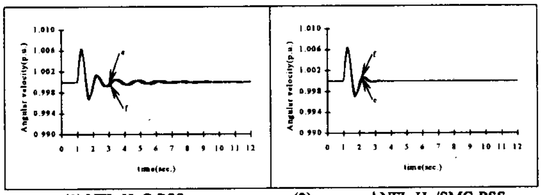
2. Parameter variation test

The proposed NFL-H$_\infty$/SMC-PSS in Fig. 3 (2) and in Fig. 4 (2) exhibits better damping properties and is less sensitive to variations of AVR gain as compared to the NFL-H$_\infty$C-PSS in Fig. 3 (1) and in Fig. 4 (1).



(1) NFL-H$_\infty$C-PSS (2) proposed NFL-H$_\infty$/SMC-PSS

Fig. 3 Angular velocity waveforms for AVR gain. *(e : normal f : parameter variation)*



(1) NFL-H$_\infty$C-PSS (2) proposed NFL-H$_\infty$/SMC-PSS

Fig. 4 Angular velocity waveforms for inertia moment. *(e : normal f : parameter variation)*

5. Conclusion

The effectiveness of the proposed controller has been verified by the nonlinear time-domain simulations in case of 3-cycle line-ground fault and in case of parameter variations for AVR gain K_A and for inertia moment M.

References

[1] J. C. Doyle, K. Glover, P. P. Khargonekar and B. A. Francis, "State-space solutions to standard H_2 and H_∞ control problems", IEEE Trans. on Automatic Control, Vol. 34, No. 8, pp. 831-847, Aug., 1989.

[2] V. I. Utkin, "Variable structure systems with sliding modes", IEEE Trans. on Automatic Control, AC-22, No.2, pp. 212-222, April, 1977.

[3] W. C. Chan and Y. Y. Hsu, "An optimal variable structure stabilizer for power system stabilization", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-102, pp. 1738-1746, Jun., 1983.

[4] J. J. Lee, "Optimal multidimensional variable structure controller for multi-interconnected power system", KIEE Trans., Vol. 38, No. 9, pp. 671-683, Sep., 1989.

[5] M. L. Kothari, J. Nanda and K. Bhattacharya, 'Design of variable structure power system stabilizers with desired eigenvalues in the sliding mode', IEE Proc. C, Vol. 140, No. 4, pp. 263-268, 1993.

[6] S. S. Lee, J. K. Park and J. J. Lee, "Sliding mode-MFAC power system stabilizer", Jour. of KIEE, Vol. 5, No. 1, pp. 1-7, Mar., 1992

[7] S. S. Lee and J. K. Park, "Sliding mode-model following power system stabilizer including closed-loop feedback", Jour. of KIEE, Vol. 9, No. 3, pp. 132-138, Sep., 1996

[8] S. S. Lee, J. K. Park et al., "Multimachine stabilizer using sliding mode-model following including closed-loop feedback", Jour. of KIEE, Vol. 9, No. 4, pp. 191-197, Dec., 1996.

[9] S. S. Lee and J. K. Park, "Sliding mode power system stabilizer based on LQR : Part I", Jour. of EEIS, Vol. 1, No. 3, pp. 32-38, 1996.

[10] S. S. Lee and J. K. Park, "Sliding mode observer power system stabilizer based on linear full-order observer : Part II", Jour. of EEIS, Vol. 1, No. 3, pp. 39-45, 1996.

[11] S. S. Lee and J. K. Park, "Full-order observer-based sliding mode power system stabilizer with desired eigenvalue-assignment for unmeasurable state variables", Jour. of EEIS, Vol. 2, No. 2, pp. 36-42, 1997.

[12] S. S. Lee and J. K. Park, "New sliding mode observer-model following power system stabilizer including CLF for unmeasurable state variables", Jour. of EEIS, Vol. 2, No. 3, pp. 88-94, 1997.

[13] S. S. Lee and J. K. Park, "Multimachine stabilizer using sliding mode observer-model following including CLF for unmeasurable state variables", Jour. of EEIS, Vol. 2, No. 4, pp. 53-58, 1997.

[14] S. S. Lee and J. K. Park, "H_∞ observer-based sliding mode power system stabilizer for unmeasurable state variables", Jour. of EEIS, Vol. 2, No. 1, pp. 70-76, 1997.

[15] S. S. Lee and J. K. Park, "Nonlinear feedback linearization-full order observer/sliding mode controller design for improving transient stability in a power system", Jour. of EEIS, Vol. 3, No. 2, pp. 184-192, 1998.

[16] S. S. Lee and J. K. Park, "Nonlinear feedback linearization-H_∞/sliding mode controller design for improving transient stability in a power system", Jour. of EEIS, Vol. 3, No. 2, pp. 193-201, 1998.

[17] S. S. Lee and J. K. Park, "Design of power system stabilizer using observer/sliding mode, observer/sliding mode-model following and H_∞/sliding mode controllers for small-signal stability study", Inter. Jour. of Electrical Power & Energy Systems, accepted, 1998.

[18] S. S. Lee and J. K. Park, "Design of reduced-order observer-based variable structure power system stabilizer for unmeasurable state variables, IEE PROC.-GEN., TRANS. AND DISTRIB., accepted, 1998.

[19] Y. N. Yu, "Electric power system dynamics", Academic press, 1983.

[20] R. Marino and P. Tomei, "Nonlinear control design", Prentice-Hall Press, 1995.