비선형 PSS을 위한 NFL-FOO/SMC의 설계 : Part A

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NFL-FOO/SMC Design for Nonlinear PSS : Part A

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[Abstract] In this paper, the proposed controller is obtained by combining the nonlinear feedback linearization-sliding mode controller (NFL-SMC) with the full order observer (FOO) and eliminates the need to measure all the state variables in the conventional NFL-SMC.

Keywords : nonlinear feedback linearization-full order observer/sliding mode controller, power system stabilizer

1. Introduction

To solve the problem associated with the unmeasurable state variables in the conventional SMC [1-17] and to obtain the smooth control as the linearized controller for a linear system (or to cancel the nonlinearity for the nonlinear system), the nonlinear feedback linearization-full order observer/sliding mode control (NFL-FOO/SMC) is proposed in this paper. The proposed controller is obtained by combining the nonlinear feedback linearization-based sliding mode control (NFL-SMC) with the full order observer (FOO) [18] and eliminates the need to measure all the state variables in conventional SMC. The effectiveness of the proposed controller is verified by the nonlinear time-domain simulations in case of 3-cycle line-ground fault and in case of parameter variations (20% over-estimations) for AVR gain K_A and for inertia moment M.

2. Nonlinear power system model

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

$$i_d(t)=c_1e'_q(t)-c_2\left(R_2\sin\delta(t)+X_1\cos\delta(t)\right) \quad (1)$$

$$i_q(t)=c_3e'_q(t)-c_4\left(-X_2\sin\delta(t)+R_1\cos\delta(t)\right) \quad (2)$$

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

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

$$Z_1=R_1+jX_1,\qquad Z_2=R_2+jX_2$$

$$Y=G+jB,\qquad Z_T=\frac{Z_1Z_2}{Z_1+Z_2}$$

$$1+Z_TY:=C_1+jC_2,\qquad C_1:=1+RG-XB$$

$$C_2:=XG+RB,\qquad R_1:=R-C_2x'_d$$

$$R_2:=R-C_2x_q,\qquad X_1:=X+C_1x_q$$

$$X_2:=X+C_1x'_d$$

$$v_d(t)=x_qi_q(t) \quad (3)$$

$$v_q(t)=e'_q(t)-x'_di_d(t) \quad (4)$$

$$v_T^2(t)=v_d^2(t)+v_q^2(t) \quad (5)$$

$$T_e(t)\approx P_e(t)=i_d(t)v_d(t)+i_q(t)v_q(t)$$
$$=e'_q(t)i_q(t)+(x_q-x'_d)i_d(t)i_q(t) \quad (6)$$

where $i_d(t)$ is the d-axis current, $i_q(t)$ is the q-axis current, $P_e(t)$ is the electrical power, $e'_q(t)$ is the q-axis transient voltage, $\delta(t)$ is the torque angle, $V_{\inf}$ is the infinite bus voltage, x_d is the d-axis reactance, x_q is the q-axis reactance, and x'_d is the d-axis transient reactance.

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

$$\dot\omega(t)=\frac{1}{M}T_m-\frac{1}{M}T_e(t) \quad (7)$$

$$\dot\delta(t)=\omega_o(\omega(t)-1) \quad (8)$$

$$\dot e'_q(t)=-\frac{1}{T'_{do}}e'_q(t)-\frac{(x_d-x'_d)}{T'_{do}}i_d(t)+\frac{1}{T'_{do}}e_{fd}(t) \quad (9)$$

$$\dot e_{fd}(t)=-\frac{1}{T_A}e_{fd}(t)+\frac{K_A}{T_A}\left(V_{ref}-v_T(t)+u_E(t)\right) \quad (10)$$

$$e_{fd\min}\le e_{fd}\le e_{fd\max}\ \text{and}\ u_{E\min}\le u_E\le u_{E\max} \quad (11)$$

$e_{fd\max} = 6.0$ $e_{fd\min} = -6.0$, and $u_{E\max} = +0.2$ $u_{E\min} = -0.2$
where $\omega(t)$ is the angular velocity, $e_{fd}(t)$ is the exciter output voltage, T_m is the mechanical torque, T_e is the electrical torque, T_A is the voltage regulator time constant, K_A is the voltage regulator gain, T'_{do} is the d-axis transient open circuit time constant, M is the inertia coefficient, ω_o is the synchronous angular velocity, V_{ref} is the regulator reference voltage, v_T is the generator terminal voltage, and u_E is the supplementary excitation control input.

3. NFL-FOO/SMC design

The full-state feedback equation and the output equation based on NFL are

$$z(t) = T(x(t)) \tag{12}$$

$$\dot{z}(t) = Az(t) + Bu(t) \tag{13}$$

$$y(t) = Cz(t) \tag{14}$$

The observer state equation based on NFL is [18]

$$\dot{\hat{z}}(t) = A\hat{z}(t) + Bu(t) + L(y(t) - C\hat{z}(t))$$

$$= (A - LC)\hat{z}(t) + Bu(t) + Ly(t) \tag{15}$$

$$L = PC^T R^{-1} \tag{16}$$

$$AP + PA^T - PC^T R^{-1} CP + Q = 0 \tag{17}$$

where Q and R are positive definite matrices.
The estimated control input vector is

$$u_{NFL-FOO/LQR} = -K_{LQR}\hat{z}(t) \tag{18}$$

$$K_{LQR} = R^{-1} B^T P \tag{19}$$

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{20}$$

The closed loop system can be expressed

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -BK_{LQR} \\ LC & A - BK_{LQR} - LC \end{bmatrix} \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{21}$$

$$[y(t)] = [C \quad 0] \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{22}$$

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

$$\sigma(z(t)) = G^T z(t) \tag{23}$$

$$\dot{\sigma}(z(t)) = G^T \dot{z}(t) \tag{24}$$

where G^T is the sliding surface gain [1-4,10].
The Lyapunov's function is chosen by

$$V(z(t)) = \sigma^2(z(t))/2 \tag{25}$$

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

$$\dot{V}(z(t)) = \sigma(z(t))\dot{\sigma}(z(t)) \tag{26}$$

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

$$= G^T z(t) G^T [Az(t) + Bu_{NFL-SMC}(t)] \le 0 \tag{27}$$

The control inputs with switching function are

$$u^+_{NFL-SMC}(t) \ge -(G^T B)^{-1}(G^T A)z(t) \quad for \; G^T z(t) > 0 \tag{28}$$

$$u^-_{NFL-SMC}(t) \le -(G^T B)^{-1}(G^T A)z(t) \quad for \; G^T z(t) < 0 \tag{29}$$

The control input with sign function is formed as

$$u^{sign}_{NFL-SMC}(t) = -(G^T B)^{-1}[G^T A]z(t) \; sign(\sigma(z(t))) \tag{30}$$

The above equation (30) can be reformed as

$$u^{sign}_{NFL-SMC}(t) = -K_{SMC} z(t) \; sign(\sigma(z(t))) \tag{31}$$

$$K_{SMC} := (G^T B)^{-1}[G^T A] \tag{32}$$

Finally, the *estimated control input vector* is

$$u^{sign}_{NFL-FOO/SMC}(t) = -K_{SMC}\hat{z}(t) \; sign(\sigma(\hat{z}(t))) \tag{33}$$

The closed loop system can be expressed as

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -BK_{SMC} sign(\sigma(\hat{z}(t))) \\ LC & A - LC - BK_{SMC} sign(\sigma(\hat{z}(t))) \end{bmatrix} \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{34}$$

$$[y(t)] = [C \quad 0] \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{35}$$

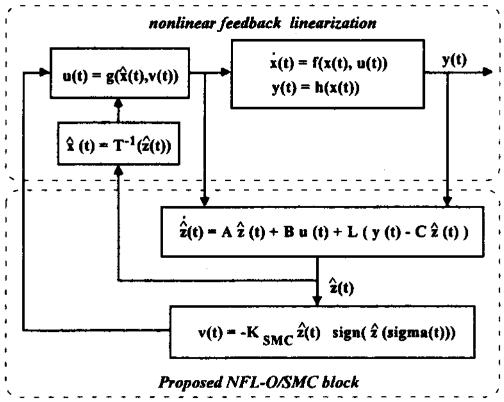
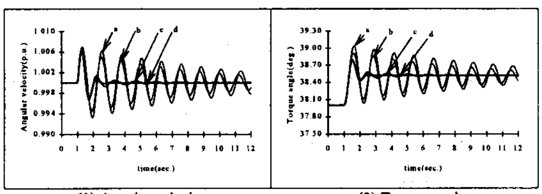


Fig. 1. Proposed NFL-FOO/SMC.

4. Simulation

The proposed NFL-FOO/SMC-PSS in Fig. 2 exhibits better damping properties.

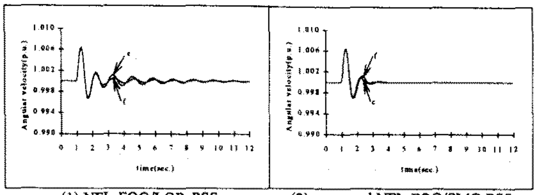


(1) Angular velocity (2) Torque angle

Fig. 2. Normal load operation. *(a:no control b:conventional PSS c:NFL-FOO/LQR-PSS d : proposed NFL-FOO/SMC-PSS)*

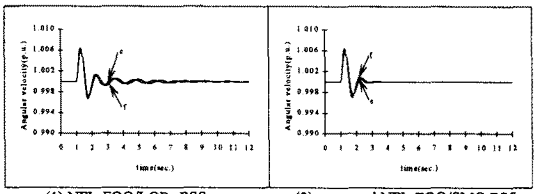
2. *Parameter variation test*

The proposed NFL-FOO/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-FOO/LQR-PSS in Fig. 3 (1) and in Fig. 4 (1).



(1) NFL-FOO/LQR-PSS (2) proposed NFL-FOO/SMC-PSS

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



(1) NFL-FOO/LQR -PSS (2) proposed NFL-FOO/SMC-PSS

Fig. 4. Angular velocity waveforms under parameter variation of 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.

Appendix

A.1 Preliminary for NFLC [20]

Let us consider the general nonlinear system

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t) \quad \text{(A.1)}$$

$$y(t) = h(x(t)) \quad \text{(A.2)}$$

The linearizing diffeomorphism is given by

$$z(t) = T(x(t)) := [h \;\; L_f h \;\; L_f^2 h \;\; L_f^3 h ....]^T$$

$$:= [z_1(t) \;\; z_2(t) \;\; z_3(t) \;\; z_4(t) ....]^T \quad \text{(A.3)}$$

The state space forms based on NFL are

$$\frac{dz(t)}{dt} = Az(t) + Bu(t) \quad \text{(A.4)}$$

$$y(t) = Cz(t) \quad \text{(A.5)}$$

The derivatives of the output are

$$y(t) = L_f^0 h(x(t)), \qquad \frac{dy(t)}{dt} = L_f h(x(t)) + L_g h(x(t))u(t)$$

....

$$\frac{d^r y(t)}{dt^r} = L_f^r h(x(t)) + L_g L_f^{r-1} h(x(t))u(t) \quad \text{(A.6)}$$

Remark : The above equations (A.1) and (A.2) are said to have *relative degree* r at a point x^o if (i) $L_g L_f^k h(x) = 0$ for all x in a neighborhood of x^o and all $k < r-1$ and (ii) $L_g L_f^{r-1} h(x^o) \neq 0$.

The control input vector based on NFL is

$$u(t) = g(x(t), v(t)) := -\frac{L_f^r h}{L_g L_f^{r-1} h} + \frac{1}{L_g L_f^{r-1} h} v(t) \quad \text{(A.7)}$$

where $v(t) = \frac{d^r y(t)}{dt^r}$ has a linear relation.

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