Nonlinear Feedback Linearization-Full Order Observer/Sliding Mode Controller Design for Improving Transient Stability in a Power System

Sang-Seung Lee and Jong-Keun Park

Abstract

In this paper, we present a nonlinear feedback linearization-full order observer/sliding mode controller (NFL-FOO/SMC), to obtain smooth control as a linearized controller in a linear system (or to cancel the nonlinearity in a nonlinear system), and to solve the problem of the unmeasurable state variables as in the conventional SMC. The proposed controller is obtained by combining the nonlinear feedback linearization-sliding mode control (NFL-SMC) with the full order observer (FOO) and eliminates the need to measure all the state variables in the traditional SMC. The proposed controller is applied to the nonlinear power system stabilizer (PSS) for damping oscillations in a power system. The effectiveness of the proposed controller is verified by the nonlinear time-domain simulations in case of a 3-cycle line-to-ground fault and in case of the parameter variation for the AVR gain K_A and for the inertia moment M.

I. Introduction

Sliding mode control theories [1] have been applied as an effective way of the design of small-signal stability controller [2-13] and transient stability controller [14,15] for damping oscillations in a power system.

Recently, nonlinear feedback linearization controller (NFLC) has been attracting great deal of research interest [16-19]. The central idea of the NFLC algebraically transforms a nonlinear dynamics into a fully linear one by differentiating the output equation only until the input term appears, so that the traditional linear controller can be applied [14-21].

However, these nonlinear feedback linearization-sliding mode controllers (NFL-SMC) applied to the power system stabilizer (PSS) [14,15] are based on the assumption that the complete state is avaliable for implementation of the control law.

In this paper, to obtain smooth control as the linearized controller in a linear system, and to tackle the problem of the unmeasurable state variables as in the conventional SMC, the nonlinear feedback linearization-full order observer/sliding mode controller (NFL-FOO/SMC) is presented and applied as the nonlinear power system stabilizer (PSS) [22].

The proposed controller is obtained by combining the nonlinear feedback linearization-sliding mode control (NFL-SMC) [14,15] with the full order observer (FOO) [24] and it does not need to measure all the state variables as in the conventional SMC.

The organization of this paper is as follows: In section II we briefly review the nonlinear power system model. In section III the preliminary for the NFLC is presented. In section IV the proposed NFL-FOO/SMC is presented. In section V the nonlinear power system linearization is presented. In section VI we present the data analysis. In section VII the nonlinear time-domain simulation is shown.

Manuscript received December 10, 1997; accepted March 26, 1998.

The authors are with the School of Electrical Engineering, Seoul National University, Seoul, 151-742, Korea.

II. Nonlinear Power System Model

In this section, we brifly review the nonlinear 4-th order power system equations, the linearized power system equations and the conventional Lead-Lag PSS equations.

1. Nonlinear power system model [22]

The d-axis current and q-axis current equations including the stator algebraic equations and network equations can be represented as

$$i_d(t) = con_1 e_q'(t) - con_2(R_2 \sin\delta(t) + X_1 \cos\delta(t)) \quad (1)$$

$$i_q(t) = con_3 e_q'(t) - con_4(-X_2 \sin\delta(t) + R_1 \cos\delta(t)) \quad (2)$$

where

$$con_1 := \frac{(C_1X_1 - C_2R_2)}{(R_1R_2 + X_1X_2)}, \quad con_2 := \frac{V_\infty}{(R_1R_2 + X_1X_2)}$$

$$con_3 := \frac{(C_1R_1 + C_2X_2)}{(R_1R_2 + X_1X_2)}, \quad con_4 := \frac{V_\infty}{(R_1R_2 + X_1X_2)}$$

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

$$Z_T := \frac{Z_1Z_2}{Z_1 + Z_2}, \quad 1 + Z_TY := C_1 + jC_2$$

$$C_1 := RG - XB, \quad C_2 := XG + RB$$

$$R_1 := R - C_2x_d', \quad R_2 := R - C_2x_q$$

$$X_1 := X + C_1x_q, \quad X_2 := X + C_1x_d'$$

The expressions for $v_d(t)$, $v_q(t)$, $v_T(t)$, and $T_e(t)$ are

$$v_d(t) = x_q i_q(t) \quad (3)$$

$$v_q(t) = e_q'(t) - x_d' i_d(t) \quad (4)$$

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

$$\begin{aligned} T_e(t) \cong P_e(t) &= i_d(t)v_d(t) + i_q(t)v_q(t) \\ &= e_q'(t)i_q(t) + (x_q - x_d')i_d(t)i_q(t) \end{aligned} \quad (6)$$

where $i_d(t)$ is the d-axis current, $i_q(t)$ is the q-axis current, $T_e(t)$ is the electric torque, $P_e(t)$ is the electric power, $e_q'(t)$ is the q-axis transient voltage, $\delta(t)$ is the torque angle, V_∞ 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.

Remark 1: In eq. 6, the electric torque T_e of a synchronous machine near the synchronous speed can be approximated by the electric power P_e.

The nonlinear 4-th order state equations including the limits imposed on AVR output, i.e. field voltage e_{fd}, and on the stabilizing signal u_E are represented as

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

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

$$\dot{e}_q'(t) = -\frac{1}{T_{do}'}e_q'(t) + \frac{(x_d - x_d')}{T_{do}'}i_d(t) + \frac{1}{T_{do}'}e_{fd}(t) \quad (9)$$

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

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

$e_{fd\,\max} = 6.0$ $e_{fd\,\min} = -6.0$ and $u_{E\,\max} = 2.0$ $u_{E\,\min} = -0.2$

where $\omega(t)$ is the angular velocity, $e_{fd}(t)$ is the exciter output voltage, T_m is the mechanical torque, T_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 reference voltage, v_T is the terminal voltage, and u_E is the supplementary excitation control input.

The 4-th order state variables is represented by

$$\begin{aligned} x(t) &= [x_1(t)\ x_2(t)\ x_2(t)\ x_4(t)]^T \\ &:= [\omega(t)\ \delta(t)\ e_q'(t)\ e_{fd}(t)]^T \end{aligned} \quad (12)$$

The nonlinear 4-th order state equations in eq. (7)-(10) are written in the state space form as

$$\dot{x}(t) = f + gu_E(t) \quad (13)$$

$$y(t) = h \quad (14)$$

where $f := (f_1\ f_2\ f_3\ f_4)^T$

$$= \begin{pmatrix} \frac{1}{M}T_m - \frac{1}{M}T_e(t) \\ \omega_o(\omega(t) - 1) \\ -\frac{1}{T_{do}'}e_q'(t) + \frac{(x_d - x_d')}{T_{do}'}i_d(t) + \frac{1}{T_{do}'}e_{fd}(t) \\ -\frac{1}{T_A}e_{fd}(t) + \frac{K_A}{T_A}(V_{ref} - v_T(t)) \end{pmatrix}$$

$$g := \left(0\ 0\ 0\ \frac{K_A}{T_A}\right)^T$$

$$h := \omega \quad (15)$$

2. Linearized power system model [22]

The differential equations are

$$\Delta\dot{\omega}(t) = -\frac{K_1}{M}\Delta\delta(t) - \frac{K_2}{M}\Delta e_q'(t) \quad (16)$$

$$\Delta\dot{\delta}(t) = \omega_o\Delta\omega(t) \quad (17)$$

$$\Delta\dot{e}_q'(t) = -\frac{K_4}{T_{do}'}\Delta\delta(t) - \frac{1}{T_{do}'K_3}\Delta e_q'(t) + \frac{1}{T_{do}'}e_{fd}(t) \quad (18)$$

$$\begin{aligned} \Delta\dot{e}_{fd}(t) = &-\frac{K_AK_5}{T_A}\Delta\delta(t) - \frac{K_AK_6}{T_A}\Delta e_q'(t) - \frac{1}{T_A}e_{fd}(t) \\ &+ \frac{K_A}{T_A}u_E(t) \end{aligned} \quad (19)$$

The 4-th order state variables can be expressed as

$$x(t)=[\Delta\omega(t)\ \ \Delta\delta(t)\ \ \Delta e_q'(t)\ \ \Delta e_{fd}(t)] \tag{20}$$

3. Conventional Lead-Lag PSS [23]

The state equations of the conventional Lead-Lag PSS are

$$\dot{x}_{p1}(t)=-K\frac{(T_2-T_1)}{T_2T_1}\Delta\omega(t)-\frac{1}{T_2}x_{p1}(t) \tag{21}$$

$$\dot{x}_{p2}(t)=K\frac{T_1(T_4-T_3)}{T_4T_1T_4}\Delta\omega(t)+\frac{(T_4-T_3)}{T_4T_4}x_{p1}(t)-\frac{1}{T_4}x_{p2}(t) \tag{22}$$

$$u_E(t)=x_{p2}(t)+\frac{T_3}{T_4}x_{p1}(t)+K\frac{(T_3T_1)}{T_4T_2}\Delta\omega(t) \tag{23}$$

where x_{p1} and x_{p2} are the state variables of the PSS.

III. The Nonlinear Feedback Linearization Controller (NFLC)

In this section, a nonlinear feedback linearization controller (NFCL) is presented [16-19].

Let us consider the general nonlinear system

$$\dot{x}(t)=f(x(t))+g(x(t))u(t) \tag{24}$$

$$y(t)=h(x(t)) \tag{25}$$

in which $f(x)$ and $g(x)$ are smooth vector fields, and $h(x)$ is a smooth function, defined on R^n.

The linearizing diffeomorphism using Lie derivative is given by

$$z(t)=T(x(t)) := [h\ \ L_fh\ \ L_f^2h\ \ L_f^3h.........]^T = [z_1(t)\ \ z_2(t)\ \ z_3(t)\ \ z_4(t)......]^T \tag{26}$$

where the Lie derivative L_fh is simply the directional derivative of h along the direction of the vector f.

Remark 2: $L_fh=\frac{\partial h}{\partial x}f$, ..., $L_f^rh=\frac{\partial(L_f^{r-1}h)}{\partial x}f$.

The state space form based on NFL can be expressed as

$$\dot{z}(t)=Az(t)+Bu(t) \tag{27}$$

$$y(t)=Cz(t) \tag{28}$$

where

$$A=\begin{bmatrix}0&1&0&\dots&0\\ \cdot&\cdot&\cdot&\dots&\cdot\\ \cdot&\cdot&\cdot&\dots&\cdot\\ 0&0&0&\dots&1\\ 0&0&0&\dots&0\end{bmatrix}_{ki\times ki} \qquad B=[0\ 0\ 0.....\ 0\ 1]_{1\times ki}$$

$$C=[0\ 0\ 0......0\ 1]_{1\times ki} \tag{29}$$

The derivatives of the output are

$$y(t)=L_f^0h(x(t))$$

$$\frac{dy(t)}{dt}=L_fh(x(t))+L_gh(x(t))u(t)$$

$$\frac{d^2y(t)}{dt^2}=L_f^2h(x(t))+L_gL_fh(x(t))u(t)$$

....

$$\frac{d^ry(t)}{dt^r}=L_f^rh(x(t))+L_gL_f^{r-1}h(x(t))u(t) \tag{30}$$

Remark 3: The eq. (24) and eq. (25) are said to have a relative degree r at a point x^o, if (i) $L_gL_f^kh(x)=0$ for all x in a neighborhood of x^o, and, for all $k < r-1$ and (ii) if $L_gL_f^{r-1}h(x^o)\neq 0$.

The block digram of the nonlinear feedback linearization controller (NFCL) is shown in Fig. 1

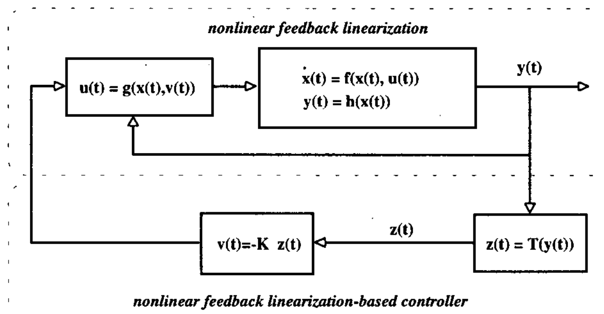


Fig. 1. Nonlinear feedback linearization controller (NFCL).

The control input vector based on NFL is

$$u(t)=g(x(t)),v(t)) := -\frac{L_f^rh}{L_gL_f^{r-1}h}+\frac{1}{L_gL_f^{r-1}h}v(t) \tag{31}$$

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

IV. The Proposed Controller Design

In this section, the nonlinear feedback linearization-full order observer/sliding mode controller (NFL-FOO/SMC) is presented.

The state equation based on NFL can be expressed as

$$z(t)=T(x(t)) \tag{32}$$

$$\dot{z}(t)=Az(t)+Bu(t) \tag{33}$$

$$y(t) = Cz(t) \tag{34}$$

where $x \in R^n$, $z \in R^n$, $u \in R^m$, $y \in R^p$, A is the system matrix, B is the control matrix, and C is the output matrix.

The full-order observer state equation based on NFL for unmeasurable state variables can be expressed as

$$\begin{aligned}\dot{\hat{z}}(t) &= A\hat{z}(t) + Bu(t) + L(y(t) - C\hat{z}(t)) \\ &= (A - LC)\hat{z}(t) + Bu(t) + Ly(t)\end{aligned} \tag{35}$$

$$L = PC^T R^{-1} \tag{36}$$

$$AP + PA^T - PC^T R^{-1} CP + Q = 0 \tag{37}$$

where $\hat{z} \in R^n$ is the estimated state, L is the $n \times m$ output injection matrix, P is the symmetric positive definite solution, and Q and R are positive definite matrices chosen by the designer. From eq. (35), the following assumptions are made :
(A,B) is controllable and (A,C) is observable.

The estimated control input vector based on NFL is given by

$$u_{NFL-FOO/LQR}(t) = -K_{LQR}\hat{z}(t) \tag{38}$$

$$K_{LQR} = R^{-1} B^T P \tag{39}$$

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{40}$$

where K_{LQR} is an optimal feedback gain.

The closed loop system can be expressed as

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -BK_{LQR} \\ LC & A - BK_{LQR} - LC \end{bmatrix} \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{41}$$

$$[y(t)] = [\, C \;\; 0\,] \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{42}$$

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

$$\sigma(z(t)) = G^T z(t) \tag{43}$$

$$\dot{\sigma}(z(t)) = G^T \dot{z}(t) \tag{44}$$

where G^T is the sliding surface gain.

The design procedure for obtaining sliding surface gain G^T with DEA in the eq. (43) can be expressed as follows:
By coordinate transformation, we have

$$p(t) = Mz(t) \tag{45}$$

$$z(t) = M^{-1} p(t) \tag{46}$$

$$MB = \begin{bmatrix} 0 \\ \cdots \\ B_2 \end{bmatrix} \tag{47}$$

where M is the $n \times n$ nonsingular matrix, and B_2 is the $m \times m$ matrix.

By differentiating eq. (45), we get

$$\dot{p}(t) = M\dot{z}(t) \tag{48}$$

Substituting eq. (42) and eq. (46) into eq. (48), we get

$$\dot{p}(t) = MAM^{-1} p(t) + MBu(t) \tag{49}$$

By partitioning p such that $p = [p_1 \; p_2]^T$ where p_1 is a $(n-m) \times 1$ column vector, and p_2 is a $m \times 1$ column vector, eq. (49) reduces to

$$\begin{bmatrix} \dot{p}_1(t) \\ \cdots \\ \dot{p}_2(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ \cdots & \cdots \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} p_1(t) \\ \cdots \\ p_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \cdots \\ B_2 \end{bmatrix} u(t) \tag{50}$$

where A_{11} is the $(n-m) \times (n-m)$, A_{12} is the $(n-m) \times m$, A_{21} is the $m \times (n-m)$, and A_{22} is the $m \times m$.

From the first part of eq. (50), we get

$$\dot{p}_1(t) = A_{11} p_1(t) + A_{12} p_2(t) \tag{51}$$

From eq. (43) and eq. (45), we have

$$\sigma(p(t)) = [\, G_{11} \;\; G_{12}\,] p(t) \tag{52}$$

$$= G_{11} p_1(t) + G_{12} p_2(t) = 0 \tag{53}$$

Substituting eq. (46) into eq. (43), we get

$$\sigma(z(t)) = G^T M^{-1} p(t) = 0 \tag{54}$$

Comparing eq. (52) with eq. (54), we get

$$[\, G_{11} \;\; G_{12}\,] = G^T M^{-1} \tag{55}$$

From eq. (53), $p_2(t)$ is obtained by

$$p_2(t) = -G_{12}^{-1} G_{11} p_1(t) \tag{56}$$

$$\dot{p}_1 = [A_{11} - A_{12} G_{11}] p_1 \tag{57}$$

$$= A_c p_1 \tag{58}$$

If the pair (A_{11}, A_{12}) is controllable by a suitable choice of the vector G_{11}, the eigenvalues of matrix A_c may be placed arbituarily in the complex plane.

From eq. (56), let $G_{12} = I$, we get

$$G^T = [\, G_{11} \;\; I\,] M \tag{59}$$

Thus, the sliding surface gain G^T in eq. (43) is obtained.

To determine a control law that keeps the system stable, we introduce the Lyapunov's function based on NFL

$$V(z(t)) = \sigma^2(z(t))/2 \tag{60}$$

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

$$\dot{V}(z(t)) = \sigma(z(t))\,\dot{\sigma}(z(t)) \tag{61}$$

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

$$= G^T z(t)\, G^T [Az(t) + Bu_{NFL-SMC}(t)] \ \leq\ 0 \tag{62}$$

where $u_{NFL-SMC}$ is the input vector of the nonlinear feedback linearization-sliding mode control (NFL-SMC).

The eq. (62) can be reduced as the control input with switching function

$$u^{+}_{NFL-SMC}(t) \geq -(G^TB)^{-1}\,[G^TA]z(t) \quad \text{for} \quad G^Tz(t) > 0 \tag{63}$$

$$u^{-}_{NFL-SMC}(t) \leq -(G^TB)^{-1}\,[G^TA]z(t) \quad \text{for} \quad G^Tz(t) < 0 \tag{64}$$

The eq. (63) and eq. (64) can be formed as the control input with sign function

$$u^{sign}_{NFL-SMC}(t) \geq -(G^TB)^{-1}\,[G^TA]z(t)\ sign(\sigma(z(t))) \tag{65}$$

The eq. (65) can be simplified as

$$u^{sign}_{NFL-SMC}(t) = -K_{SMC}z(t)\ sign(\sigma(z(t))) \tag{66}$$

where $\quad K_{SMC} := (G^TB)^{-1}\,[G^TA]$ (67)

Finally, the estimated control input vector of the proposed NFL-FOO/SMC for unmeasurable state variables is expressed as

$$u^{sign}_{NFL-FOO/SMC}(t) = -K_{SMC}\hat{z}(t)\ sign(\sigma(\hat{z}(t))) \tag{68}$$

where $\hat{z}(t) \in R^n$ is the estimated state variables, and K_{SMC} is the control input gain of the sliding mode control.

Remark 4: The estimated state $\hat{z}(t)$ in eq. (68) is obtained from eq. (35).

The closed loop system can be expressed as

$$\begin{bmatrix} \dot{z}(t) \\ \dot{\hat{z}}(t) \end{bmatrix} = \begin{bmatrix} A & -BK_{SMC}sign(\delta(\hat{z}(t))) \\ LC & A - LC - BK_{SMC}sign(\delta(\hat{z}(t))) \end{bmatrix} \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{69}$$

$$[y(t)] = [\,C \quad 0\,] \begin{bmatrix} z(t) \\ \hat{z}(t) \end{bmatrix} \tag{70}$$

The overall block diagram in Fig. 2 represents the proposed NFL-FOO/SMC.

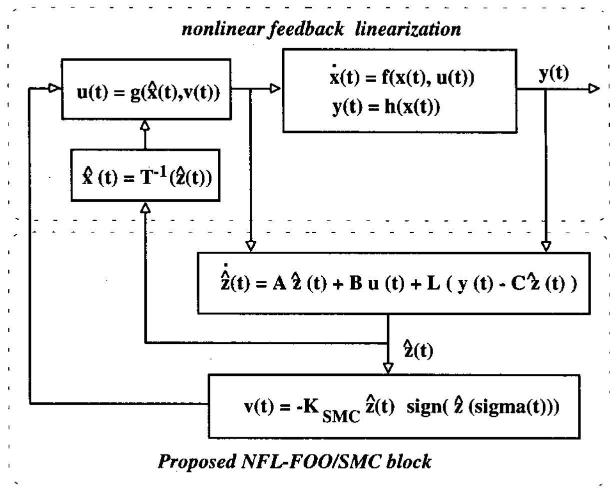


Fig. 2. Block diagram of the proposed NFL-FOO/SMC.

V. Nonlinear Feedback Linearization in a Power System

In this section, the nonlinear feedback linearization to cancel the nonlinearities in a power system is presented.

The nonlinear feedback linearization in a power system from eq. (1)-(10) is obtained by differentiating the angular velocity until the input term appears

$$z_1 := L^o_f = h = \omega \tag{71}$$

$$z_2 := L_f h = \frac{\partial h}{\partial x} f = \frac{\partial \omega}{\partial x} f = \frac{1}{M}(T_m - T_e) \tag{72}$$

$$L_g h = \frac{\partial h}{\partial x} g = \frac{\partial \omega}{\partial x} g = 0 \tag{73}$$

$$z_3 := L^2_f h = \frac{\partial (L_f h)}{\partial x} f = \frac{\partial}{\partial x}\left(\frac{1}{M}(T_m - T_e)\right)$$

$$= -\frac{1}{M}(pd_9 f_2 + pd_{10} f_3) \tag{74}$$

$$L_g L_f h = \frac{\partial (L_f h)}{\partial x} g = \frac{\partial}{\partial x}\left(\frac{1}{M}(T_m - T_e)\right) g = 0 \tag{75}$$

$$z_4 := L^3_f h = \frac{\partial}{\partial x}(L^2_f h) f = \frac{\partial}{\partial x}\left(-\frac{1}{M}(pd_9 f_2 + pd_{10} f_3)\right) f$$

$$= [pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}] f \tag{76}$$

$$L_g L^2_f h = \frac{\partial}{\partial x}(L^2_f h) g = \frac{\partial}{\partial x}\left(-\frac{1}{M}(pd_9 f_2 pd_{10} f_3)\right) g$$

$$= [pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}] g \tag{77}$$

where

$$pd_1 := -\frac{V_\infty}{Z^2_e}(R_2\cos(\delta) - X_1\sin(\delta)) \tag{78}$$

$$pd_2 := \frac{V_\infty}{Z_e^2}(X_2\cos(\delta)+R_1\sin(\delta)) \tag{79}$$

$$pd_3 := x_q\frac{V_\infty}{Z_e^2}(X_2\cos(\delta)+R_1\sin(\delta)) \tag{80}$$

$$pd_4 := x_d'\frac{V_\infty}{Z_e^2}(R_2\cos(\delta)-X_1\sin(\delta)) \tag{81}$$

$$pd_5 := Y_d \tag{82}$$

$$pd_6 := Y_q \tag{83}$$

$$pd_7 := x_qY_q \tag{84}$$

$$pd_8 := 1-x_d'Y_d \tag{85}$$

$$pd_9 := (v_d-x_d'i_q)pd_1+(v_q+x_q'i_d)pd_2 \tag{86}$$

$$pd_{10} := Y_d(v_d-x_d'i_q)+Y_q(v_qx_qi_d)+i_q \tag{87}$$

$$pd_{11} := -\frac{1}{T_{do}'}(x_d-x_d')pd_1 \tag{88}$$

$$pd_{12} := -\frac{1}{T_{do}'} \tag{89}$$

$$pd_{13} := \frac{1}{T_{do}'} \tag{90}$$

$$pd_{14} := -\frac{1}{M}\omega_o pd_9 \tag{91}$$

$$pd_{15} := -\frac{1}{M}(pd_{15}f_1+pd_{17}f_3+pd_{10}pd_{19}) \tag{92}$$

$$pd_{16} := -\frac{1}{M}(pd_{16}f_1+pd_{18}f_3+pd_{10}pd_{20}) \tag{93}$$

$$pd_{17} := -\frac{1}{M}(pd_{10}pd_{21}) \tag{94}$$

$$pd_{18} := \frac{V_\infty}{Z_e^2}(R_2\cos(\delta)+X_1\sin(\delta)) \tag{95}$$

$$pd_{19} := \frac{V_\infty}{Z_e^2}(-X_2\sin(\delta)+R_1\cos(\delta)) \tag{96}$$

$$pd_{20} := (v_d-x_d'i_q)pd_{22}+2(x_q-x_d')\ pd_1pd_2+(v_q+x_qi_d)pd_{23} \tag{97}$$

$$pd_{21} := Y_q(x_q-x_d')pd_1+Y_d(x_q-x_d')pd_2+pd_2 \tag{98}$$

$$pd_{22} := Y_q(x_q-x_d')pd_1+pd_2+Y_d(x_q-x_d')pd_2 \tag{99}$$

$$pd_{23} := 2Y_q(1+(x_q-x_d')Y_d) \tag{100}$$

The pd in above equations represents partial derivatives.

The control input based on NFL is

$$u(t)=g(x(t),v(t)) := -\frac{L_f^3h}{L_gL_f^2h}+\frac{1}{L_gL_f^2h}v(t) \tag{101}$$

$$=\frac{-[[\ pd_{11}\ \ pd_{12}\ \ pd_{13}\ \ pd_{14}]f-v(t)]}{[\ pd_{11}\ \ pd_{12}\ \ pd_{13}\ \ pd_{14}]\,g} \tag{102}$$

Ⅵ. Data Analysis

In this section, the data analysis is presented.
The nominal data of the system, the operating conditions and the conventional PSS are listed in Appendix.

The values of A and B under normal load operation are

$$A=\begin{bmatrix} 0 & -0.0763 & -0.1101 & 0 \\ 376.99 & 0 & 0 & 0 \\ 0 & -0.0327 & -0.1967 & 0.1289 \\ 0 & -80.424 & -845.87 & -20.0 \end{bmatrix} \quad B=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \end{bmatrix}$$

The values of Q and R for LQR are given by

$Q=diag(1e+6,\ 1,\ 1,\ 1e-2)$ and $R=1$

The controller gain is

$K_{LQR}=[-809.4244\ 7.3246\ 12.2734\ 0.0965]$

The observer gain is

$L=1.0e+005[0.001\ -0.0065\ 0.0317\ -7.2984]^T$

The sliding surface gain is

$G=1e+005[-1.9004\ -0.0176\ 0.0333\ 0.0000]^T$

Ⅶ. Nonlinear Time-domain Simulation Test

In this section, the nonlinear time-domain simulation to show the performance for the proposed controller is presented.

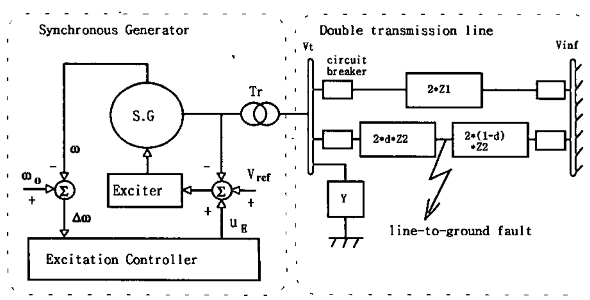
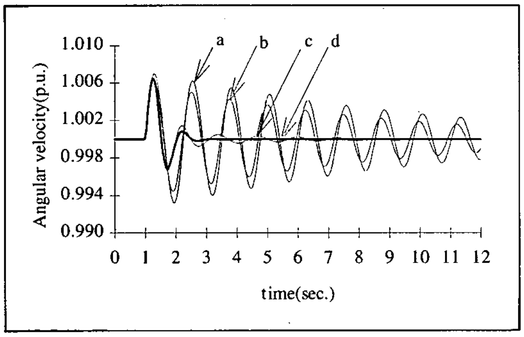


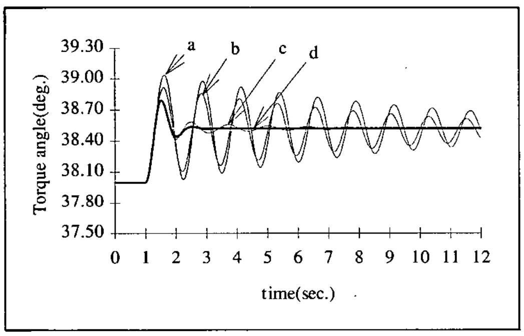
Fig. 3. Block diagram of a power system under line-ground fault at the midpoint of the double transmission line.

A fault is applied to verify the performance of the proposed controller under transient condition. The fault at about 1.0 sec is assumed to occur at the midpoint of the simple system in Fig. 3 and then is cleared after 0.05 sec and the line is reclosed. In Fig. 3, Z2 is the total impedance of faulted line and $d=0.5$ puts the fault in the middle of the line.

1. A 3-cycle line-to-ground fault simulation test



(1) Angual velocity



(2) Torque angle

Fig. 4. Normal load operation. *(a: no control b: conventional PSS c: NFL-FOO/LQR-PSS d: proposed NFL-FOO/SMC-PSS)*

Fig. 4 shows the angular velocity waveform and the torque angle waveform without any control, with the conventional Lead-Lag PSS, with the NFL-FOO/LQR-PSS and with the proposed NFL-FOO/SMC-PSS for a 3-cycle line-to-ground fault under normal load operation.

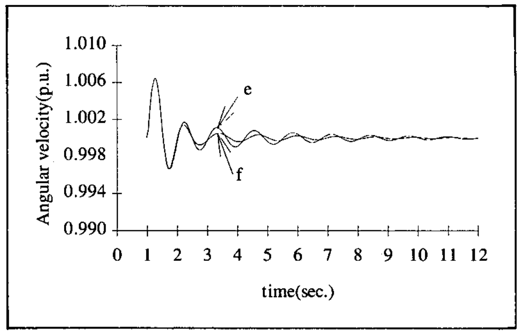
Although the NFL-FOO/LQR-PSS can stabilize the system it is shown that the proposed NFL-FOO/SMC-PSS, exhibits better damping properties.

Because the conventional PSS in Fig. 4 gives poorly damped response, the conventional PSS will not consider again in the following discussions.

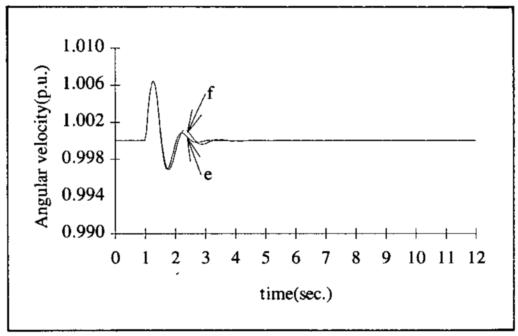
2. Parameter variation test

Case I : A parameter variations of AVR gain K_A

Fig. 5 shows the angular velocity waveform in case of the parameter variations (20% over-estimation) of the AVR gain K_A of the generating unit in the system.



(1) NFL-FOO/LQR-PSS

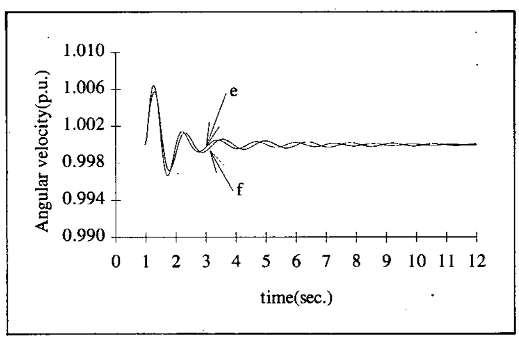


(2) proposed NFL-FOO/SMC-PSS

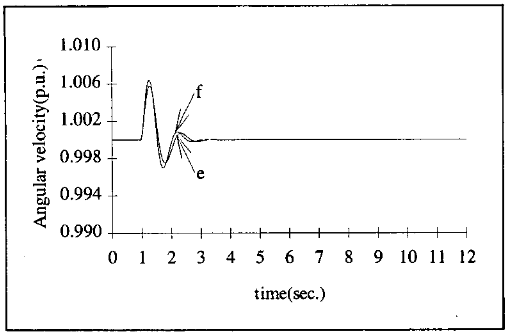
Fig. 5. Angular velocity waveforms for parameter variation of the AVR gain KA.*(e : normal f : parameter variation)*

It is shown that the proposed NFL-FOO/SMC-PSS in Fig. 5 (2) exhibits better damping properties and is less sensitive to variations of the AVR gain K_A as compared to the NFL-FOO/LQR-PSS in Fig. 5 (1).

Case II : A parameter variations of the inertia moment M.



(1) NFL-FOO/LQR-PSS



(2) proposed NFL-FOO/SMC-PSS

Fig. 6. Angular velocity waveforms for parameter variation of the inertia moment M. (*e : normal f : parameter variation*)

Fig. 6 shows the angular velocity waveform in case of the parameter variations (20% over-estimation) of the inertia moment M of the generating unit in the system.

Also, it is shown that the proposed NFL-FOO/SMC-PSS in Fig. 6 (2) exhibits better damping properties and is less sensitive to variations of the inertia moment M as compared to the NFL-FOO/LQR-PSS in Fig. 6 (1).

VIII. Conclusions

A nonlinear feedback linearization-full order observer/ sliding mode controller (NFL-FOO/SMC) has been proposed in this paper.

The proposed controller has been applied to the nonlinear power system stabilizer (PSS) for improving transient stability in a nonlinear power system.

The main results are as follows :

1. Combining the full-order observer (FOO) with the nonlinear feedback linearization-sliding mode controller (NFL-SMC).
2. Obtaining a NFL-FOO/SMC, to tackle the problem of the unmeasurable state variables in the conventional SMC, and to obtain smooth control as the linearized controller in a linear system.
3. Improving in the sense of time-domain dynamic performance and robustness in case of a 3-circle line-to-ground fault, and in case of the parameter variations (20% over-estimations) for the AVR gain K_A and for the inertia moment M.

References

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

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

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

[4] 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.

[5] 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.

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

[7] 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, 1996.

[8] S. S. Lee and J. K. Park, "Sliding mode power system stabilizer based on LQR : Part I", Journal of Electrical Engineering and Information Science (Jour. of EEIS), Vol. 1, No. 3, pp. 32-38, 1996.

[9] 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.

[10] 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, 1997.

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

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

[13] 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.

[14] Y. Kao, L. Jiang, S. Cheng, O. P. Malik and G. S. Hope, "Nonlinear variable structure stabilizer for power system stability", IEEE Trans. on Energy Conversion, Vol. 9, No. 3, pp. 489-494, 1994.

[15] V. G. D. C, Samarasinghe and N. C. Pahalawaththa, "Design of robust variable structure controller for

improving power system dynamic stability", Int. Jour. of Electric Power & Energy Systems, Vol. 18, No. 8, pp. 519-515, 1996
[16] A. Isodori, A. J. Krener, C. G. Giorgi and S. Monaco, "Nonlinear decoupling via feedback : A differential geometric approach", IEEE Trans. on Automatic Control, Vol. AC-26, No. pp. 331-345, April, 1981.
[17] J. -J. E. Slotine and W. Li, "Applied nonlinear control", Prentice-Hall Press, 1991.
[18] A. Isidori, "Nonlinear control system", Springer-Verlag Press, 1995.
[19] R. Marino and P. Tomei, "Nonlinear control design", Prentice-Hall Press, 1995.
[20] Q. Lu and Y. Z. Sun, "Nonlinear stabilizing control of machine system", IEEE Trans. on Power Systems, Vol. 4, No. 1. pp. 236-241, 1989.
[21] M. Nambu and Y. Ohsaw, "Development of an advanced power system stabilizer using a strict linearization approach", IEEE Trans. on Power Systems, Vol. 11, No. 2, pp. 813-818, 1996.
[22] Y. N. Yu, "Electric power system dynamics", Academic Press, 1983.
[23] M. A. Pai, C. D. Vournas, A. N. Micheal and H. Ye, "Applications of interval matrices in power system stabilizer design", Int. Jour. of Electric Power & Energy Systems, Vol. 19, No. 3, pp. 179-184, 1997.
[24] F. L. Lewis, "Applied optimal control and estimation," Prentice-Hall Press, 1992.

Appendix

The nominal data of the system, the operating conditions and the conventional PSS are listed in Tables A.1-A.3.

Table A.1 Generator data and initial condition data

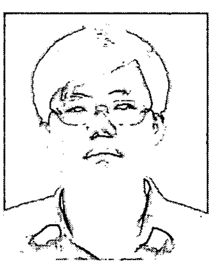
M	T'_{do}	D	x_d	x'_d	x_q	ω_o	P	Q	V_t
9.26	7.76	3.0	0.973	0.19	0.55	377	0.75	0.025	1.05

Table A.2 Excitation system data and line data

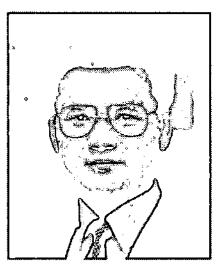
K_A	T_A	R	X	G	B
50.0	0.05	0.034	0.997	0.249	0.262

Table A.3 Conventional Lead-Lag PSS data

K	T_1	T_2	T_3	T_4
0.009	0.6851	0.1	0.06851	0.01



Sang-Seung Lee was born in Kyung-Nam, Korea on April 2, 1960. He is currently working toward the Ph. D. degree in the School of Electrical Engineering at the Seoul National University. His interesting areas are sliding mode control, H_∞ control, feed-back linearization control and PSS.



Jong-Keun Park was born in Taejeon, Korea on Oct. 21, 1952. He received B. S. degree in Electrical Engineering from Seoul National University, Seoul, Korea in 1973, and the M. S. and Ph. D. degrees in Electrical Engineering from University of Tokyo, Japan, 1979 and 1982, respectively. Since 1983, he has been with the Department of Electrical Engineering of the Seoul National University as a professor. His present research interests are power system stability, application of intelligent systems to power systems and power system economics.