Augmented Automatic Choosing Control of Modified Filter Type for Nonlinear Noisy Measurement Systems

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Abstract This paper is concerned with single nonlinear feedback control for nonlinear systems with noisy measurement. A given nonlinear system is linearized piecewise to design the linear optimal controllers, which are then smoothly united into a single nonlinear feedback controller by an automatic choosing function. The state estimation is carried out with a modified nonlinear filter, which includes the 1st- and 2nd-order filters. This is called an augmented automatic choosing control of modified filter type (AACC MF). Simulation results show that the new controller improves the stability of electric power systems well.

Keywords: nonlinear control, augmented automatic choosing control, modified nonlinear filter

1. Introduction

The estimation and control problem of nonlinear systems has been studied for many years [1-8]. Most controllers are synthesized by linearizing a given nonlinear system to which the linear estimation and control theories are applied. One of such control theory is based on a truncation at the first order of the Taylor expansion [1,2]. This control law is easy to be implemented in many practical nonlinear systems, but is only useful in a small region or in essentially linear ones. Controllers based on a change of coordinates in differential geometry [4] are effective in a wider region, but not easy to be implemented in many practical systems. Controllers based on fuzzy reasoning [5] are more practical, but usually require numerous divisions. In the previous work [7], the authors presented an augmented automatic choosing control using a linear filter.

This paper is concerned with a nonlinear feedback controller with the automatic choosing function [6,7], a modified nonlinear filter, and the linear optimal control theory [2,8] for nonlinear systems with noisy measurement. This modified filter includes the 1st-order filter and the 2nd-order filter as special cases. Considering the nonlinearity, the given region of the system is divided into some subdomains. On each subdomain, the system equation is linearized by the Taylor expansion to enable the application of the LQ control theory [2,8]. Constant terms in this linearization are treated as coefficients of stable zero dynamics [7]. The resulting linear controls are smoothly united by the automatic choosing function to yield a single nonlinear feedback control. This controller is called an augmented automatic choosing control of modified filter type (AACC MF).

Experimental results indicate that the stability of electric power systems with AACC MF is more improved than those with the ordinary linear optimal controller (LOC).

2. Statement of the Problem

The plant is assumed to be described by nonlinear dynamic and noisy measurement equations

\[ \dot{x} = f(x) + Bu, \quad x \in D \subset R^n \]  
\[ y = h(x) + v \]  

where \( \cdot = \frac{d}{dt} \), \( x = [x_1, \ldots, x_n]^T \) is an \( n \)-dimensional state vector, \( u = [u_1, \ldots, u_r]^T \) is an \( r \)-dimensional control vector, \( y = [y_1, \ldots, y_m]^T \) is an \( m \)-dimensional measurement vector, \( f \) and \( h \) are nonlinear vector-valued functions with \( f(0) = 0 \) and are continuously differentiable, \( B \) is an \( n \times r \) driving
matrix, \( v \) is white Gaussian noise of \( \mathcal{N}(v; 0, V) \), \( V \) is an \( m \times m \) covariance matrix, and \( T \) denotes transpose.

Considering the nonlinearity of system (1), we introduce a vector-valued function \( \mathbf{C} : \mathbf{D} \rightarrow \mathbb{R}^k \) that defines the separative variables \( \{C_j(x)\} \), where \( \mathbf{C} = \begin{bmatrix} C_1 & \cdots & C_M & \cdots & C_L \end{bmatrix}^T \) is continuously differentiable. Let \( \mathbf{D} \) be a domain of \( \mathbf{C}^{-1} \). For example, if \( \mathbf{x}_{[2]} \) is the element that has the highest nonlinearity of system (1) (see Eq. (19)), then

\[
\mathbf{C}(\mathbf{x}) = \mathbf{x}_{[2]} \in \mathbf{D} \subset \mathbb{R} \quad (L = 1)
\]

The domain \( \mathbf{D} \) is divided into some subdomains: \( \mathbf{D} = \bigcup_{i=0}^{M-1} \mathbf{D}_i \), where \( \mathbf{D}_M = \mathbf{D} - \sum_{i=0}^{M-1} \mathbf{D}_i \) and \( \mathbf{C}^{-1}(\mathbf{D}_0) \ni \mathbf{0} \). \( \mathbf{D}_i \) \((0 \leq i \leq M)\) endowed with a lexicographic order is the Cartesian product \( \mathbf{D}_i = \prod_{j=1}^{N} [a_{ij}, b_{ij}] \), where \( a_{ij} < b_{ij} \).

We here introduce an automatic choosing function of sigmoid type:

\[
I_i(\mathbf{x}) = \frac{1}{1 + \exp\left(2N\left(C_j(x) - a_{ij}\right)\right)} - \frac{1}{1 + \exp\left(-2N\left(C_j(x) - b_{ij}\right)\right)} \quad (3)
\]

where \( N \) is a positive real value and \(-\infty \leq a_{ij} < b_{ij} \leq \infty \). \( I_i(\mathbf{x}) \) is analytic and almost unity on \( \mathbf{C}^{-1}(\mathbf{D}_i) \), otherwise, almost zero (see Fig. 1).

The aim of this study is to design a nonlinear feedback control AACCMF by smoothly uniting the sectionwise controls and by using a modified nonlinear filter.

### 3. Design of Control

The nonlinear function \( \mathbf{f} \) of system (1) is linearized by the Taylor expansion truncated at the first order about the point \( \hat{x}_i \) in \( \mathbf{C}^{-1}(\mathbf{D}_i) \) and \( \hat{x}_0 = 0 \) on each subdomain \( \mathbf{D}_i \) (see Fig. 2):

\[
f(x) \approx f(\hat{x}_i) + A_i(x - \hat{x}_i) = A_i x + w_i
\]

where

\[
A_i = \frac{\partial f(x)}{\partial x} |_{x=\hat{x}_i}, \quad w_i = f(\hat{x}_i) - A_i \hat{x}_i
\]

We introduce stable zero dynamics:

\[
\dot{\hat{x}}_{[n+1]} = -\sigma \hat{x}_{[n+1]} \quad (4)
\]

\[
(\hat{x}_{[n+1]})(0) \approx 1, \quad 0 < \sigma < 1
\]

where the value of \( \sigma \) shall be selected so that \( \sigma = -\hat{x}_{[n+1]}/\hat{x}_{[n]} \leq -\hat{x}_{[k]}/\hat{x}_{[k]} \) holds for all \( k = 1, 2, \ldots, n \). This tries to keep \( \hat{x}_{[n+1]} \approx 1 \) for a good while, when system (1) is not on \( \mathbf{C}^{-1}(\mathbf{D}_0) \). We approximate \( f \) as

\[
f(x) \approx A_i x + w_i \approx A_i \hat{x} + w_i \hat{x}_{[n+1]} \quad (5)
\]

Assume that the control is designed by using Eq. (3) as

\[
u = \sum_{i=0}^{M} u_i I_i(\hat{x}) \quad (6)
\]

where \( \hat{x} \) is an estimate of \( x \).

Note that \( \sum_{i=0}^{M} I_i(\hat{x}) = 1 \) for Eq. (3). Substituting Eqs. (5) and (6) into system (1), the dynamic equation becomes

\[
\dot{x} = f(x) + B u
\]

\[
= \sum_{i=0}^{M} f(x) I_i(\hat{x}) + \sum_{i=0}^{M} B u_i I_i(\hat{x})
\]

\[
\approx \sum_{i=0}^{M} (A_i x + w_i \hat{x}_{[n+1]} + B u_i I_i(\hat{x})) \quad (7)
\]

Consider a special case of \( I_i(\hat{x}) = 1 \) in which \( N = -a_{ij} = b_{ij} \rightarrow \infty \) in Eq. (3).

Set \( X = [x^T, \hat{x}_{[n+1]}]^T \), then Eqs. (4) and (7) yield an approximated linear equation:

\[
\dot{X} = A_i X + \tilde{B} u_i
\]

where

\[
\tilde{A}_i = \begin{bmatrix} A_i & w_i \\ 0 & -\sigma \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}
\]

Therefore, we apply the LQ control theory to obtain the control formula as follows.

Consider that the system and cost function

\[
\Sigma : \{ \dot{X} = \tilde{A}_i X + \tilde{B} u_i, \quad J_i = \frac{1}{2} \int_0^T (X^T Q X + u_i^T R u_i) dt \}
\]

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are given. Then an application of the linear optimal control theory [2] yields
\[ u_i(X) = -F_i X \]
(9)
\[ F_i = R^{-1} B_t^T P_i \]
(10)
where the \((n+1) \times (n+1)\) matrix \(P_i\) satisfies the Riccati equation:
\[ P_i A_i + A_i^T P_i + Q - P_i B R^{-1} B_t^T P_i = 0 \]
(11)
Here, \(Q = Q^T > 0\) and \(R = R^T > 0\) and denote positive symmetric matrices. Values of \(Q\) and \(R\) are properly determined on the basis of engineering experience [8].

4. Design of Filter

We here design a modified nonlinear filter for state estimation by the method of maximum likelihood (see Ref. [3]). Equations (1) and (2) are expanded by the Taylor expansion about an assumed known optimal estimate \(\hat{x}(t)\):
\[ \dot{x}(t) \approx f(\hat{x}(t)) + F(t) e(t) + \frac{1}{2} \lambda \sum_{i=1}^{n} \varphi_i tr(\Pi_i(t)e(t)e(t)^T) + Bu \]
(12)
\[ y(t) \approx h(\hat{x}(t)) + H(t) e(t) + \frac{1}{2} \lambda \sum_{i=1}^{m} \varphi_i tr(\Omega_i(t)e(t)e(t)^T) + v(t) \]
(13)
These are truncated at the 1st order if \(\lambda = 0\) and the 2nd order if \(\lambda = 1\). Here, \(e(t) = x(t) - \hat{x}(t)\), \(F(t) = \partial f(x)/\partial x\mid_{x=\hat{x}(t)}\), \(\Pi_i(t) = \partial^2 f_i(x)/\partial x \partial x^T \mid_{x=\hat{x}(t)}\), \(H(t) = \partial h(x)/\partial x\mid_{x=\hat{x}(t)}\), \(\Omega_i(t) = \partial^2 h_i(x)/\partial x \partial x^T \mid_{x=\hat{x}(t)}\), and \(\varphi_i = [0 \cdots 1(0) \cdots 0]^T\) which is the appropriate dimensional vector. Let the optimal estimate \(\hat{x}(t)\) be the conditional expectation \(\hat{x}(t) = E(x(t) \mid y(\tau), t_0 \leq \tau \leq t)\) of \(x(t)\) at time \(t\).

Let \(S(t)\) be the conditional covariance \(S(t) = E(e(t)e(t)^T) \mid y(\tau), t_0 \leq \tau \leq t\) because of \(E(e(t) \mid y(\tau), t_0 \leq \tau \leq t) = 0\). Then, the filter and covariance equations are approximately derived as [3]
\[ \dot{x}(t) = f(\hat{x}(t)) + \frac{1}{2} \lambda \sum_{i=1}^{n} \varphi_i tr(\Pi_i(t)S(t)) + Bu \]
\[ + K(t) \{ y(t) - h(\hat{x}(t)) \} \]
\[ - \frac{1}{2} \lambda \sum_{i=1}^{m} \varphi_i tr(\Omega_i(t)S(t)) \]
(14)
\[ \dot{S}(t) = F(t)S(t) + S(t)F(t)^T - S(t)H(t)H(t)^T S(t) \]
\[ - \frac{1}{2} \lambda \sum_{i=1}^{m} \varphi_i tr(\Omega_i(t)S(t)) |S(t)|^2 + \{ y(t) - h(\hat{x}(t))\} \]
\[ - \frac{1}{2} \lambda \sum_{i=1}^{m} \varphi_i tr(\Omega_i(t)S(t)) |S(t)| \]
(15)
where
\[ K(t) = S(t)H(t)H(t)^T S(t)^{-1} \]
(16)
with initial values \(\hat{x}(0) = \hat{x}_0\) and \(S(0) = S_0\).

The above Eqs. (14) and (15) become the 1st-order filter or Extended Kalman filter if \(\lambda = 0\), and the 2nd-order filter if \(\lambda = 1\).

In this filter, \(\lambda\) is considered as a weighting variable \(\lambda = \lambda(t) (0 \leq \lambda(t) \leq 1)\).

Therefore, \(\lambda\) can be a constant such as \(\lambda = 0, \gamma, \) and 1, or may be a function such as
\[ \lambda = \frac{1}{2} (1 - sgn(\hat{x}(z)(t))) \]
(17)
when considering \(\hat{x}(z)\). Here, \(sgn(z) = 1\) if \(z > 0\), \(sgn(z) = 0\) if \(z = 0\), and \(sgn(z) = -1\) if \(z < 0\).

5. Synthesis of AACC MF

On the basis of the formulations in the above sections 3 and 4, we have the AACC MF formula as follows.

[AACC MF formula]
\[ \dot{x}(t) = f(\hat{x}(t)) + \frac{1}{2} \lambda \sum_{i=1}^{n} \varphi_i tr(\Pi_i(t)S(t)) + Bu \]
\[ + K(t) \{ y(t) - h(\hat{x}(t)) \} - \frac{1}{2} \lambda \sum_{i=1}^{m} \varphi_i tr(\Omega_i(t)S(t)) \]
\[ \hat{x}_{[n+1]}(t) = -\sigma \hat{x}_{[n+1]}(t) \quad (\hat{x}_{[n+1]}(0) \simeq 1) \]
\[ u(t) = \sum_{i=0}^{M} u_i(t) L_i(\hat{x}(t)) \]
\[ K(t) = S(t)H(t)^T S(t)^{-1} \]
where
\[ A_i = \partial f(x)/\partial x \mid_{x=\hat{x}_i}, \quad w_i = f(\hat{x}_i) - A_i \hat{x}_i, \]
\[ F(t) = \partial f(x)/\partial x \mid_{x=\hat{x}(t)}, \quad H(t) = \partial h(x)/\partial x \mid_{x=\hat{x}(t)} \]
\[ \Pi_i(t) = \partial^2 f_i(x)/\partial x \partial x^T \mid_{x=\hat{x}(t)} \]
\[ \Omega_i(t) = \partial^2 h_i(x)/\partial x \partial x^T \mid_{x=\hat{x}(t)} \]
\[ A_i = \begin{bmatrix} A_i & w_i \\ 0 & -\sigma \end{bmatrix}, \quad B = \begin{bmatrix} B \\ 0 \end{bmatrix} \]
\[ u(t) = -R^{-1} B_t^T P_i \hat{x}(t), \quad \hat{x}(t) = [\hat{x}(t), \hat{x}_{[n+1]}(t)]^T \]
\[ P_i A_i + A_i^T P_i + Q - P_i B R^{-1} B_t^T P_i = 0 \]
\( \dot{S}(t) = F(t)S(t) + S(t)F^T(t) - S(t)H(t)^T V^{-1} H(t) S(t) \)

\[
-\frac{1}{2} \sum_{i=1}^{m} \varphi_i \text{tr}(\Omega_i(t) S(t))^T V^{-1} [\varphi_i(t) - h(\dot{x}(t))]
- \frac{1}{2} \sum_{i=1}^{m} \varphi_i \text{tr}(\Omega_i(t) S(t))^T S(t)
\]

\[ I_{1}(\dot{x}) = \prod_{j=1}^{n} \left\{ 1 - \frac{1}{1 + \exp(2N(C_j \dot{x} - a_j))} \right\} \]

Since this formula is of a structure-specified type, each parameter included in the above equations must be properly selected so that the feedback control system (1) with AACC-MF could stabilize globally.

6. Numerical Example

Consider a field excitation control problem of a single machine power system, which is the Ozeaki-Power-Plant of Kyushu Electric Power Company in Japan. This system is assumed to be described [6,7] by

\[
\begin{align*}
\dot{M} \delta + \tilde{D}(\delta) \dot{\delta} + P_e(\delta) &= P_m \\
P_e(\delta) &= E_f^2 Y_{11} \cos \theta_{11} + E_f \tilde{V} Y_{12} \cos \theta_{12} - \delta \\
E_f + T_d \dot{E}_q^* &= E_{fd} \\
E_f &= E_f^* + (X_d - X_d') T_d(\delta) \\
I_d(\delta) &= -E_f Y_{11} \sin \theta_{11} - \tilde{V} Y_{12} \sin \theta_{12} - \delta
\end{align*}
\]

\[
\tilde{D}(\delta) = \tilde{V}^2 \left\{ T_d''(X_d - X_d'') \sin^2 \delta \\
+ T_d''(X_q - X_q'') \cos^2 \delta \right\}
\]

The output is supposed to be given by \(P_e(\delta)\) and \(\dot{\delta}\), which are easily measurable. \(E_{fd}\) is a control variable. Here, \(\delta\) is the phase angle, \(\dot{\delta}\) the rotor speed, \(M\) the inertia coefficient, \(\tilde{D}(\delta)\) the damping coefficient, \(P_m\) the mechanical input power, \(P_e(\delta)\) the generator output power, \(\tilde{V}\) the reference bus voltage, \(E_f\) the open circuit voltage, \(E_{fd}\) the field excitation voltage, \(X_d\) the direct axis synchronous reactance, \(X_d'\) the direct axis transient reactance, \(X_e\) the external impedance, \(Y_{11}/\theta_{11}\) the self-admittance of the network, \(Y_{12}/\theta_{12}\) the mutual admittance of the network, and \(I_d(\delta)\) the direct axis current of the machine.

Set \(x = [x_{[1]}, x_{[2]}, x_{[3]}]^T = [E_f - \dot{E}_f, \delta - \delta_0, \dot{\delta}]^T\) and \(u = E_{fd} - \dot{E}_{fd}\), so that

\[
\dot{x} = \begin{bmatrix} \dot{x}_{[1]} \\ \dot{x}_{[2]} \\ \dot{x}_{[3]} \end{bmatrix} = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \\ 0 \end{bmatrix} u
\]

\[
y = \begin{bmatrix} y_{[1]} \\ y_{[2]} \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} + v
\]

where

\[
n = 3, \ r = 1, \ m = 2
\]

\[
f_1(x) = -\frac{1}{k_{d0}} \left( x_{[1]} + \dot{E}_f - \dot{E}_f \right) \\
+ \frac{(X_d - \dot{X}_d') \tilde{V} Y_{12}}{\tilde{M}} \cos \left( \theta_{12} - x_{[2]} - \dot{\delta}_0 \right)
\]

\[
f_2(x) = x_{[3]}
\]

\[
f_3(x) = -\frac{\tilde{V} Y_{12}}{M} \left( x_{[1]} + \dot{E}_f \right) \cos \left( \theta_{12} - x_{[2]} - \dot{\delta}_0 \right) \\
- \frac{Y_{11} \cos \theta_{11}}{M} \left( x_{[1]} + \dot{E}_f \right)^2 - \frac{\tilde{D}(x)}{M} x_{[3]} + \frac{P_m}{\tilde{M}}
\]

\[
h_1(x) = Y_{11} \cos \theta_{11} (x_{[1]} + \dot{E}_f)^2 \\
+ \frac{\tilde{V} Y_{12}}{M} (x_{[1]} + \dot{E}_f) \cos \left( \theta_{12} - x_{[2]} - \dot{\delta}_0 \right)
\]

\[
h_2(x) = x_{[2]}
\]

\[
\tilde{D}(x) = \tilde{V}^2 \left\{ T_d''(X_d - X_d'') \sin^2 \left( x_{[2]} + \dot{\delta}_0 \right) \\
+ T_d''(X_d - X_d'') \cos^2 \left( x_{[2]} + \dot{\delta}_0 \right) \right\}
\]

\[
b_1 = \frac{1}{k_{d0}}, \ k = 1 + (X_d - X_d') Y_{11} \sin \theta_{11}
\]

Parameters are given as follows.

\[
\tilde{M} = 0.016095[pu] \quad T_{d0} = 5.09007[sec] \\
\tilde{V} = 1.00[pu] \quad P_m = 1.2[pu] \\
X_d = 0.875[pu] \quad X'_d = 0.422[pu] \\
Y_{11} = 1.04297[pu] \quad Y_{12} = 1.0384[pu] \\
\theta_{11} = -1.56199[rad] \quad \theta_{12} = -1.56199[rad] \\
X_0 = 1.15[pu] \quad X''_d = 0.238[pu] \\
X_a = 0.9[pu] \quad X''_a = 0.3[pu] \\
T''_{d0} = 0.0299[pu] \quad T''_{d0} = 0.02616[pu]
\]

Steady state values are

\[
\dot{E}_f = 1.52243[pu] \quad \dot{\delta}_0 = 48.57^o \\
\dot{\delta}_0 = 0.00[deg/sec] \quad \dot{E}_{fd} = 1.52243[pu]
\]

Set \(X = [x_{[1]}, x_{[2]}, x_{[3]}]^T = [x_{[1]}, x_{[2]}, x_{[3]}, \dot{x}_{[2]}]^T, C(x) = x_{[2]}, L = 1, M = 1, N = 14.1, a_1 = 1.07, \chi_0 = 0, \chi_{11} = [0, 0.88, 0, 0, 0]^T, \sigma = 0.1, R = 1, Q = diag(1, 1, 1, 1), V = diag(1, 1), X(0) = [0, x_{[2]}(0), x_{[3]}(0), 1]^T, \dot{x}(0) = [0, \dot{x}_{[2]}(0), 0]^T, \dot{X}(0) = [\dot{x}_{[2]}(0), 1]^T, \gamma = 0.01. \)

Then

\[
S_A = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 5 & 10 \\ 0 & 10 & 50 \end{bmatrix}, \quad S_A = \begin{bmatrix} 0 & 0 & 0 \gamma & 4 & 0 \\ 0 & 4 & \gamma & -1 \end{bmatrix}
\]

The following experiments are carried out for the new control (AACC-MF) and the ordinary linear optimal control (LOC).

< Case 1 > \(\lambda\) is constant and \(\dot{x}(0)\) is the origin:
Set \(\lambda = \gamma, \dot{x}_{[2]}(0) = 0, \) and \(S(0) = S_A.\)

< Case 2 > \(\lambda\) is variable and \(\dot{x}(0)\) is the origin:
Set \(\lambda\) of Eq. (17), \(\dot{x}_{[2]}(0) = 0, \) and \(S(0) = S_A + S_A.\)
Fig. 3 Stable region in Case 1

Fig. 4 Stable region in Case 2

Fig. 5 Stable regions in Case 3

Fig. 6 Stable region in Case 4

< Case 3 > λ is variable and \( \dot{x}(0) \) is reasonable:
Set λ of Eq. (17), \( \dot{x}_{[2]}(0) = 0.4 \), and \( S(0) = S_A + S_γ \).

< Case 4 > λ is variable and \( \dot{x}(0) \) is larger:
Set λ of Eq. (17), \( \dot{x}_{[2]}(0) = 0.5 \), and \( S(0) = S_A + S_γ \).

Figures 3, 4, 5, and 6 depict the cross section \( x_{[2]}(0) \) - \( x_{[3]}(0) \) of the stable regions for AACCMBF and LOC in the above cases 1, 2, 3, and 4, respectively. Figure 7 shows, for AACCMBF and LOC, the time responses of \( x_{[1]}, x_{[2]}, x_{[3]} \), and \( u \) when \( X(0) = [0, 1, 2, 1]^T \) in case 2. In Fig. 7, the following index

\[
PI = \int_0^{20} (x_{[1]}^2 + x_{[2]}^2 + x_{[3]}^2 + u^2)dt \tag{21}
\]

has the optimal value of 5.75 at \( N = 14.1 \). When parameter \( N \) of Eq. (3) is changed, \( PI \) becomes worse, as shown in Table 1. Thus it is fixed at \( N = 14.1 \) for case 1 through case 4.

<table>
<thead>
<tr>
<th>Table 1 PI</th>
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<td>( N )</td>
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Figures 3 to 6 indicate the following.
The results in Fig. 3 are similar to those for the AACC with the linear filter [7], because \( λ \) is small and the values of \( \dot{x}(0) \) and \( S(0) \) are set the same as in the simulation described in [7].

The stable regions in Fig. 4 are drawn by selecting \( λ \) and \( S(0) \) so as to maximize length \( J \),

\[
J = \max \{ \max(x_{[2]}(0)) - \min(x_{[2]}(0)) : \dot{x}_{[1]}(0) = x_{[3]}(0) = 0 \} \text{ by trial-and-error. The values of } J \text{ of AACCMBF are 3.10 in case 1 and 3.31 in case 2, and those of LOC are 2.24 in case 1 and 3.18 in case 2.}

The results in Figs. 4 and 5 are similar to each
AACC MF are much better than when using LOC.

7. Conclusions

We studied an augmented automatic choosing control of modified filter type (AACC MF) for nonlinear systems with noisy measurement. This controller was applied to a control problem of a power system. Simulation results showed that the new controller is able to improve the stability considerably. The following is left for future work: the problem of optimum selection of the parameters \( \{ M, N, \mu, \beta, \gamma, \omega, \theta \} \) and the initial values \( \{ x(0), y(0) \} \) of AACC MF, which greatly depend on the stable region and trajectory of systems, and the application to other nonlinear systems with higher nonlinearity.

References


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Fig. 7 Time responses of \( x \) and \( u \)

other when the initial value \( \bar{x}(0) \) is selected reasonably. However, when \( \bar{x}(0) \) is too large, the stable region of LOC decreases to almost zero, as in Fig. 6.

As a result, experimental results indicate that the stable region and trajectories when using the new
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