Coordinated Excitation and Speed Robust Control Based on the State Extend and Filtering Estimation

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Abstract—For the nonlinear robust control difficulty in the MIMO system, which has many uncertain parameters, the state extending and filtering robust control (SEFERC) is proposed. The uncertain nonlinear part of the MIMO is extend to the new state parameter and can be estimated. With the estimated value, combined with the direct feedback linearization (DFL), the nonlinear system can convert to the linear system. According H_∞ control method, the robust control of the linear system is realized. Taking the certain excitation and speed coordinated control system for example, simulation results show that the SEFERC can accelerate the convergence speed of the state variables and can improve the excitation and speed coordinated control speed as illustrated by the portions given in this document.

Keywords- MIMO system; multi uncertain parameters; state extend; filtering estimation; nonlinear robust control; state parameter estimation

I. INTRODUCTION

Multi-machine power system has many characters, such as the complex structure, the nonlinearity and the parametric uncertainty. When there are many uncertain parameters, the control law design of the power system will be difficult. The multi-machine power system is one kind of the MIMO systems. It is very significant to study the design of the control law for the multi-uncertain-parameters nonlinear MIMO system^{[1]-[2]}.

In the nonlinear control, the exact feedback linearization (EFL) and the nonlinear control based on the objective holographic feedbacks (NCOHF) are proposed and can realize the linearization and the global asymptotic stability. But the realization of the EFL and the NCOHF need know the accurate model of the MIMO system^{[3]-[4]}. The coordinated passivity control method, which based on the passivity theory and the back-stepping design technique, has the special requirement for the structure of the control system^[5]. The method based on the Hamilton energy theory resolve the designing difficulty of the Lyapunov function, but at the same time the design of the Hamilton energy function is complicated^{[6]-[7]}.

The uncertainty includes the inside uncertainty and the outside uncertainty. The inside uncertainties result from the variation in the structure and the parameter of the system. The outside uncertainties result from the extant disturbance. In order to overcome the influence from the uncertainties, the H_∞ control, the sliding model control, the ESO control is proposed. These methods based on the stability theory and have some shortcomings, such as difficulties in the sliding model face

selection, the chattering of the sliding model control, the complexity of the robust adaptive deduction and so on^{[8]-[10]}. In recent years, many filtering estimation methods, such as EKF, UKF, CDKF, STF and so on^{[11]-[13]}, develop rapidly and are used to estimate the values of the state parameters in the state equations. These methods are based on the filtering theory and the statistic theory and can overcome the uncertainty of the nonlinear system.

In this paper, combining the state extending technology, direct feedback linearization (DFL) and nonlinear state estimation, the state extend and filtering estimation robust control (SEFERC) method is proposed. In the SEFERC, the nonlinear uncertain parts of the state equation are extended to the new variables and estimated by nonlinear filtering method. The SEFERC is one kind of new method for the robust control. In the end of this paper, taking the certain excitation and speed coordinated control system for example, simulation results show that in comparison with PID-PSS control the SEFERC can accelerate the convergent speed of the state variables and can improve the excitation and speed coordinated control speed.

II. EXCITATION AND SPEED COORDINATED SEFERC

Mathematical model of the excitation and speed control system, which is of uncertainty, is shown as following equ.1.

$$\begin{aligned} \dot{x}_1 &= x_3 \\ \dot{x}_2 &= -\beta_1 x_2 + \beta_2 u_1 \\ \dot{x}_3 &= \beta_3 x_2 - \beta_4 x_3 - \beta_5 \sin(\delta_0 + x_1) x_4 - \beta_5 x_{40} [\sin(\delta_0 + x_1) - \sin(\delta_0)] \\ \dot{x}_4 &= -\beta_6 x_4 - \beta_7 [\cos(\delta_0) - \cos(\delta_0 + x_1)] + \frac{1}{T_{d0}} u_2 \\ y &= CX = x_1 + x_3 \end{aligned} \quad (1)$$

where $\beta_1 = 1/T_H$; $\beta_2 = C/T_H$; $\beta_3 = \omega_0/H$; $\beta_4 = D/H$; $\beta_5 = \frac{\omega_0}{H} \frac{V_s}{x_d' \Sigma}$; $\beta_6 = \frac{x_d \Sigma}{T_{d0} x_d' \Sigma}$; $\beta_7 = \frac{x_d - x_d'}{T_{d0}} \frac{V_s}{x_d' \Sigma}$; $X = [x_1, x_2, x_3, x_4]^T = [\delta - \delta_0, P_m - P_{m0}, \omega - \omega_0, E_q - E_{q0}]^T$; δ represent power angle; ω represent angular velocity; P_m represent mechanical

power; E'_q represent the transient potential; $T_H \Sigma$ represent the control constant of the valve; C represent power constant; T_{d0} represent the time constant of the excitation winding; x_d represent d-axis reactance; x'_d represent d-axis transient reactance; $x'_{d\Sigma} = x'_d + x_T + x_L$, x_T represent the reactance of the transformer, x_L represent the reactance of the transmission line; H represent the moment of the inertia; $u_1 = \mu - \mu_0$, μ represent the valve control, μ_0 represent the initial valve control; $u_2 = V_f - V_{f0}$, V_f represent the excitation control, V_{f0} represent the initial excitation control.

Under the transient and accident condition, such as the grounding of the transmission line, the values of x_d , x'_d , $x'_{d\Sigma}$ will apparent change. The value of D can't be measured at the same time. So in the equ.1, β_4 , β_5 , β_6 , β_7 are the uncertain parameters.

Because there are too many uncertain parameters in the equ.1, it's difficult to calculate the values of u_1 and u_2 by the traditional robust methods, so the SEFERC will be adopting to realize the excitation and speed coordinate control.

Equ.21 can be translated into following equ.2, which is composed of "equivalent inner system" and "equivalent outer system".

$$\begin{aligned}
 \dot{x}_1 &= x_3 \\
 \dot{x}_2 &= -\beta_1 x_2 + \beta_2 u_1 \\
 \dot{x}_{3,o} &= -\beta_5 \cos(\delta_0 + x_1) x_3 (x_4 + x_{40}) - \beta_1 \beta_3 x_2 - \beta_4 x_{3,o} + \\
 &\quad \beta_5 \beta_6 x_4 \sin(\delta_0 + x_1) + \beta_5 \beta_7 \sin(\delta_0 + x_1) [\cos(\delta_0) - \cos(\delta_0 + x_1)] + \\
 &\quad \beta_1 (\beta_3 - \beta_{30}) u_1 - \frac{(\beta_5 - \beta_{50}) \sin(\delta_0 + x_1)}{T_{d0}} u_2 + \beta_{30} u_1 - \frac{\beta_{30} \sin(\delta_0 + x_1)}{T_{d0}} u_2 \\
 &= f(\cdot) + \beta_{30} u_1 - \frac{\beta_{30} \sin(\delta_0 + x_1)}{T_{d0}} u_2 \\
 y &= CX = x_1 + x_3
 \end{aligned} \tag{2}$$

According to the DFL and linear H_∞ control theory, the equ.2 can be expressed by the following equ.3 or equ.4. and the values of u_1 , v can be calculated.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_{3,o} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_{3,o} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \beta_2 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ v \end{bmatrix} \tag{3}$$

$$y = CX = x_1 + x_3$$

OR:

$$\begin{aligned}
 \dot{X} &= AX + BU \\
 y &= CX = x_1 + x_3
 \end{aligned} \tag{4}$$

In the optimal control theory, the value of U is $U = R^{-1} B^T P Z$. When the value of v is confirmed, u_2 can be calculated by the following equ.5:

$$u_2 = (v - f(\cdot) - \beta_{30} u_1) T_{d0} / \beta_{30} \sin(\delta_0 + x_1) \tag{5}$$

Because there are uncertain parameters, such as β_4 , β_5 , β_6 , β_7 in $f(\cdot)$, it is necessary to estimate the value of $f(\cdot)$. In order to estimate the value of $f(\cdot)$, $f(\cdot)$ can be extended to the new variable $x_{3,oo}$. $x_{3,oo}$ can be expressed by following equ.6.

$$\begin{aligned}
 \dot{x}_{3,oo} &= \beta_5 \sin(\delta_0 + x_1) x_3^2 (x_4 + x_{40}) + \beta_1^2 \beta_3 x_2 + \beta_5 \{ \beta_6 x_4 + \\
 &\quad \beta_7 [\cos(\delta_0) - \cos(\delta_0 + x_1)] \} [\beta_6 \sin(\delta_0 + x_1) + 2x_3 \cos(\delta_0 + x_1)] - \\
 &\quad \beta_5 \cos(\delta_0 + x_1) (x_4 + x_{40}) x_{3,o} - \beta_5 x_{3,oo} + \beta_5 \sin^2(\delta_0 + x_1) - \\
 &\quad \beta_1 \beta_2 \beta_3 u_1 + \frac{\beta_5}{T_{d0}} [(\beta_7 - 1) x_3 \cos(\delta_0 + x_1) + \beta_6 \sin(\delta_0 + x_1)] u_2 \\
 &= f_1(\cdot) - \beta_1 \beta_2 \beta_3 u_1 + \frac{\beta_5}{T_{d0}} [(\beta_7 - 1) x_3 \cos(\delta_0 + x_1) + \beta_6 \sin(\delta_0 + x_1)] u_2 \\
 &= f_1(\cdot) - a u_1 + b(x_3) u_2
 \end{aligned} \tag{6}$$

The equation, used to estimate the values of the $f(\cdot)$, can be expressed by following equ.7.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_{3,o} \\ \dot{x}_{3,oo} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ f_1(\cdot) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_{3,o} \\ x_{3,oo} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \beta_2 & 0 \\ 0 & 0 \\ 0 & 0 \\ -a & b(x_3) \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{7}$$

$$y = CX = x_1 + x_3$$

In the equ.7, u_1 , u_2 , x_1 , x_2 is the present values, which should be measured by detecting hardware circuit. When the value $x_{3,oo}$ (namely $f(\cdot)$) is estimated, according the equ.7, the value of u_2 can be calculated.

III. SIMULATION AND ANALYSIS

In order to validate the effect of the SEFERC, the simulation of the excitation and speed coordinated control is performed. The parameters of the excitation and speed control mathematical model are as follows:

$X_d=1.2, H=11.6s, T_d=1.15s, T_H=0.35, C=1, x_L=1.46, P_m0=0.32, D=3p.u.$

Simulation 1: when the three phases short-circuit grounding appears at 1.1 second and disappears at 1.2 second, the comparison between the estimation value by STF and the real values of the state parameters and the extend state parameter $x_{3,0,0}$ are shown as Figure 1.

FIGURE 1. THE COMPARISON BETWEEN THE REAL VALUE AND THE ESTIMATED VALUE OF THE STATE PARAMETER

As the shown of the fig1.a to Figure 1.d, on the dynamic condition, the values of the state parameters in the ex-system can be estimated accurately by STF, which is the basis of the SEFERC.

Simulation 2: when the load is increased by 60% at 0.5 second and the SEFERC and the PID-PSS is adopting respectively, the change curves of the state and the control variables can be shown as Figure 2.a to Figure 2.d.

FIGURE 2. CHANGE CURVE OF THE STATE AND THE CONTROL VARIABLES, WHEN THE SEFERC AND THE PID-PSS IS ADOPTING RESPECTIVELY

As Figure 2.a to Figure 2.d shown, because the nonlinearity and uncertainty of the excitation and speed coordinated control system isn't considered in the PID-PSS control, the convergent speed of the state variables and the control speed are slow. On the contrary, because the values of the uncertain and disturbance part of the control system are estimated in the SEFERC, the excitation and speed coordinated control is accurate and the convergent speed is rapid. The SEFERC provides a new method for the nonlinear robust control.

IV. CONCLUSION

In this paper, the state extending and filtering robust control (SEFERC) is proposed for the nonlinear MIMO system with many uncertain parameters. Compared with traditional robust control methods, which is based on the Lyapunov stability theory, the SEFERC is based on the statistical principle and combine the DFL, H_∞ control method. In the SEFERC, the nonlinear uncertain parts of the state equation are extended to the new variables and estimated by nonlinear filtering method. When the values of the nonlinear parts of the system are known, combining the DFL, the nonlinear system can be changed into linear system. According to the H_∞ control theory, the robust control of the linear system can be realized. Taking the excitation and speed coordinated control for example, results of the SEFERC simulation show that the values of the nonlinear uncertain parts of the system can be estimated accurately and the SEFERC can realize the robust control of the nonlinear uncertain system. Comparing with the PID-PSS control, the SEFERC can accelerate the convergence speed of the state variables and improve the control speed.

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