Design method of nonlinear adaptive controller for the main steam valve of turbogenerator set considering state constrain

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Abstract. Aiming at the main steam-valve control of turbine generator unit with amplitude constraint and parameter uncertainty, adaptive backstepping is implemented on the main steam valve controller. The controller not only has an adaptive ability to uncertain parameters of the system and a good transient response performance, but also does not linearize the system. Meanwhile, the problem of state limit in the main steam-valve control of turbogenerator is effectively solved by using the Lyapunov function with constraints. Simulation results are presented to show the performance of the adaptive backstepping control.

1. Introduction
With the rapid development of social economy, electric power has more and more influence on economic growth and people's life. People put forward higher requirements for the quantity and quality of energy transmission. If the power system has problems or cannot operate stably, it will cause great losses to the society. Therefore, the stable operation of the power system is extremely important [1]. In recent years, the steam-valve control of a turbogenerator set has been paid much attention and research because it can restrain and improve the low-frequency oscillation, the large disturbance and the small disturbance in the power system [2]. Considering the amplitude constraint problem of the state variables in the system, how to deal with the internal disturbances in the design process of the controller is a more worthy research subject under the condition that the state quantity does not exceed the constraint value.

At present, many advanced nonlinear control strategies have been applied [3, 4], for instance, optimal control, decentralized nonlinear predictive control, backstepping method, $H_\infty$ control, etc. In reference [5, 6], self-adaptive controllers are designed, which can make the system stable quickly. However, these literature does not consider the amplitude constraints of state variables. Literature [7, 8] solved the problem of limiting the control quantity, but neither of the two references takes into account uncertain parameters. Therefore, it is of major practical significance to study the nonlinear control of steam-valve considering the state constraints and uncertain parameters.

In view of the above-mentioned literature in controller design method exist deficiencies, based on the backstepping and Lyapunov function designed a nonlinear adaptive valve controller. When the initial value of the state variable meets certain conditions, the controller not only has excellent transient response performance and an adaptive ability for uncertain parameters, but also guarantees that the state variable does not exceed its constraint value.
2. Background and related work
The dynamic system model for valve control of turbine-generator is the third order model of a single machine infinite bus system. The system structure diagram is illustrated in figure 1.

\[ \Delta \delta, \Delta \omega, \Delta P_e \]

Robust controller

\[ \begin{align*}
\delta &= \omega - \omega_0 \\
\dot{\omega} &= \frac{\omega_0}{H} \left( P_m + C_{ML} P_w - P_e - P_D \right) \\
\dot{P}_m &= -(1/T_{HR}) \left( P_m - C_H P_w + C_{ML} u \right)
\end{align*} \] (1)

Where the angle and speed of the generator rotor are expressed by \( \delta \) and \( \omega \), respectively. \( C_{ML} \) is the power distribution coefficient of the medium-low pressure cylinder. \( C_H \) and \( P_H \) are the power distribution coefficient and output mechanical power of high-pressure cylinder, respectively. The initial value of mechanical power is \( P_{m0} \). \( P_e \) is the active power and \( P_D \) is the damping power. \( u \) is the valve control voltage. \( H \) is the rotary inertia. \( T_{HR} \) is the equivalent time constant.

A set of equations is constructed, \( x_1 = \delta - \delta_0, \) \( x_2 = \omega - \omega_0, \) \( x_3 = P_m - C_H P_w_0 \). \( a_0 = (\omega_0 / H) P_{m0} \), \( h = \omega_0 / H \), \( b = -(\omega_0 E_q V_q) / H X_{\infty} \), \( T = 1/T_{HR} \), \( n = \sin(\delta_0 + x_1) \), \( \theta = -D / H \) is the unknown parameter.

Where \( \omega_0 \) and \( \delta_0 \) represent the initial values of \( \omega \) and \( \delta \), respectively. \( E_q' \) is the transient potential of the generator q axis. \( D \) is the damping coefficients. The equivalent reactance between the generator and the infinite bus system is \( X_{\infty} \). \( V_\infty \) is infinite bus voltage. Therefore, the equivalent expression of system (1) is

\[ \begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= b x_2 + c_0 + a_0 + b n \\
\dot{x}_3 &= T x_3 + T C_{ML} u
\end{align*} \] (2)

3. Design of nonlinear adaptive controller
This section design a nonlinear adaptive controller which solves the main steam-valve control problem using backstepping method.

**Step 1** According to the first-order expression of the system (2), we define \( z_1 = x_1 \) and take \( x_2 \) as the dummy variable. Where \( c_1 \) is a design constant and \( c_1 > 0 \). The stabilization function is defined as \( x_{2d} = -c_1 \arctan(x_1) \).

It's easy to know that \( x_{2d} \) is constrained and satisfies:

\[ |x_{2d}| < \frac{\pi}{2} c_1 \] (3)

Define the equation

\[ z_2 = x_2 - x_{2d} \] (4)
The derivative of $z_i$ is $\dot{z}_i = z_i - c_i \arctan(x_i)$.

For the first subsystem, we define the Lyapunov function $V_1 = k_i x_i \arctan(x_i)$, where $k_i$ is a design constant and $k_i > 0$. Then, its derivative is

$$V_1 = -k_i c_i \arctan(x_i) (\arctan(x_i) + \frac{x_i}{1 + x_i^2}) + k_i z_i (\arctan(x_i) + \frac{x_i}{1 + x_i^2})$$

$$= -W_1(x_i) + k_i z_i (\arctan(x_i) + \frac{x_i}{1 + x_i^2})$$

(5)

Define the equation $W_1(x_i) = k_i c_i \arctan(x_i) (\arctan(x_i) + \frac{x_i}{1 + x_i^2})$. Obviously, $W_1(x_i)$ is a positive definite function with $x_i$ as its independent variable.

Step 2 According to the former second-order formulas of the system (2), let $x_i$ be the dummy variable and the stabilization function is defined as

$$x_{3d} = (-c_2 z_2 - \theta x_2 - a_0 - b_n - c_1 x_2 \arctan(x_i) + k_i \frac{k_2 - z_2}{k_2^2 - z_2^2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2})) \frac{1}{h}$$

(6)

Where $c_2$ is a design constant and $c_2 > 0$, $\theta = \theta - \hat{\theta}$ ( $\hat{\theta}$ stands for the estimated value of the unknown parameter $\theta$), $|z_2| < k_2$. Define the equation:

$$z_2 = x_2 - x_{3d}$$

(7)

Notice that $\dot{z}_2 = -c_2 z_2 - \frac{k_2^2 - z_2^2}{k_2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2}) + h x_2 + \tilde{\theta} h x_2$. The Lyapunov function of the second subsystem is

$$V_2 = V_1 + \frac{1}{2} k_i \log\left(\frac{k_2^2}{k_2^2 - z_2^2}\right)$$

(8)

Where $k_i$ is a design constant and $k_i > 0$. Then, the derivative of $V_2$ is

$$\dot{V}_2 = \dot{V}_1 + \frac{k_2 z_2 x_2}{k_2^2 - z_2^2} = -W(x_i) - k_i c_i \arctan(x_i) \frac{k_2 - z_2^2}{k_2^2 - z_2^2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2}) + k_i h x_2 + k_i x_2 - \hat{\theta} x_2$$

(9)

Step 3 The derivation of $x_{3d}$ is $\dot{x}_{3d} = \frac{1}{h} (-c_2 - \hat{\theta} - \frac{c_1}{1 + x_i^2} + \frac{2 z_2}{k_2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2})) \hat{\theta} x_2 + \dot{\Phi} x_2$.

Notice that

$$\Phi = \frac{1}{h} (-c_2 - \hat{\theta} - \frac{c_1}{1 + x_i^2} + \frac{2 z_2}{k_2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2})) (\hat{\theta} x_2 + h x_2 + a_0 + b_n)$$

$$+ \frac{1}{h} ((-c_2 + \frac{2 z_2}{k_2} (k_i \arctan(x_i) + \frac{k_i x_i}{1 + x_i^2})) (-x_{3d}) - \frac{1}{(1 + x_i^2)^2} - \frac{2 c_1 x_i^2}{(1 + x_i^2)^2})$$

(10)

The global Lyapunov function of the system (2) is

$$V_3 = V_2 + \frac{1}{2} k_i \log\left(\frac{k_2^2}{k_2^2 - z_2^2}\right) + \frac{1}{2} \hat{\theta}^2$$

(11)

Where $k_i$ is a design constant and $k_i > 0$, $|z_2| < k_4$, $\gamma$ is a given adaptive gain parameter and $\gamma > 0$. $\dot{V}_3$ is the derivative of $V_3$, and there is

$$\dot{V}_3 = -W(x_i) - k_i c_i \frac{z_2 x_2}{k_2^2 - z_2^2} + \hat{\theta} (\frac{k_2}{k_2^2 - z_2^2}) z_2 x_2 + \frac{1}{h} (-c_2 - \hat{\theta} - \frac{c_1}{1 + x_i^2} + \frac{2 z_2}{k_2} (k_i \arctan(x_i)$$

$$+ \frac{k_i x_i}{1 + x_i^2})) + \frac{k_i h x_2}{k_2^2 - z_2^2} (T x_3 + T C u - \dot{\Phi}) + \frac{k_i h}{k_2^2 - z_2^2} z_2 x_2$$

(12)

Selection parameter adaptive law:
\begin{equation}
\dot{\theta} = \gamma \left( \frac{k_2 z_2 x_2}{k_2 - z_2^2} - (c_2 - h) \frac{k_1 x_1}{1 + x_1^2} + \frac{2z_2}{k_3} \left( \frac{k_2 \arctan(x_1)}{1 + x_1^2} \right) \right)
\end{equation}

Selective main steam-valve control law:

\begin{equation}
u = \frac{1}{T_C h} (-T x_3 + \Phi c_j \dot{z}_3)
\end{equation}

Where $c_j$ is a design constant and $c_j > 0$. When $\dot{z}_3 = 0$, we have $\dot{z}_3 = \frac{k_2 c_j z_2}{k_2 - z_2^2} + \frac{k_2 h}{k_2 - z_2^2} \frac{2z_2}{k_3} - \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2}$

\begin{equation}
\dot{V}_3 = -W(x_1) - k_2 c_j z_2^2 \left( z_2 - z_3 \right) - \frac{k_2 c_j z_2}{k_2 - z_2^2} + \frac{k_2 h}{2(k_2 - z_2^2)} z_2^3 - \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2}
\end{equation}

Define the equation. Then, we have

\begin{equation}
Y = \frac{k_2 c_j z_2^2}{k_2 - z_2^2} + \frac{k_2 h}{2(k_2 - z_2^2)} z_2^2 + \frac{k_2 h}{2(k_2 - z_2^2)} z_2^3 - \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2}
\end{equation}

Notice that

\begin{equation}
c_j \geq \frac{k_2 h}{(k_2 c_j)^2} + \frac{h}{2}
\end{equation}

Where $a_i$ is a constant and $a_i \in (0,1)$. Then, we have

\begin{equation}
Y \leq \frac{k_2 c_j z_2^2}{k_2 - z_2^2} \left( \frac{k_2 h}{(k_2 c_j)^2} + \frac{h}{2} \right) + \frac{k_2 h}{2(k_2 - z_2^2)} z_2^3 - \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2} = \frac{k_2 h}{2(k_2 - z_2^2)} z_2^3 - \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2}
\end{equation}

Obviously, the following inequality always holds: $k_2 c_j z_2^2 \leq \frac{k_2 h}{(k_2 c_j)^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2}$. When $z_3 < k_2 a_i$, we obtain

\begin{equation}
\frac{k_2 h}{2(k_2 - z_2^2)} z_2^3 < \frac{k_2 h}{2(k_2 - (k_2 c_j)^2)} z_2^3, \quad \frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2} \geq \frac{k_2 c_j}{k_2 - z_2^2} z_2^2
\end{equation}

Then, it holds that $\frac{k_2 c_j}{k_2 - z_2^2} \frac{z_2}{z_2 - z_3^2} \frac{z_2}{z_2 - z_3^2} \geq \frac{k_2 h}{2(k_2 - (k_2 c_j)^2)}$, $\forall z_3 < k_2 a_i$.

When $\dot{z}_3 > 0$, if the inequality $\dot{V}_3 = \dot{W}(x_1) - k_2 h(z_2 - z_3^2) \leq 0$ holds, we have $\dot{V}_3 \leq 0$. $V_3$ is constrained. When $\dot{z}_3 > 0$, $\dot{V}_3 \leq 0$. $V_3$ is constrained. When $\dot{z}_3 < 0$, $\dot{V}_3 \leq 0$. $V_3$ is constrained.

From equation (3) and (4), we know that $x_2$ is constrained. The equation (6) and (7) show that $x_2$ is constrained. The working range of the system is $D = \{x_1 \in R, x_2 < k_3, x_3 < R, \mid z_2 \mid < k_3, \mid \dot{z}_3 \mid < k_4 \}$, when $\mid x_2 \mid < k_2, \mid x_3 \mid < k_3$. Under the action of main steam-valve control law (14), the dynamics of this system can be expressed by the following nonlinear differential equations:
The stability and controllability of closed-loop adaptive systems are described in the following paragraphs.

**Theorem** When the system satisfies equations (13) and (14), the design parameters of the formula (18) and (20) are known and the initial conditions are \( k_2 z_2(0) < k_2, k_4 z_4(0) < k_4 \), the domain of the closed-loop system (2) is \( D = \{ z_1 \in R, z_2 \in R, z_3 \in R : \| z_1 \| < k_2, \| z_2 \| < k_4 \} \). The following two conclusions can be obtained:

1) In the set \( U \subseteq R^n \), the system has global asymptotic stability.
2) In the interval of \( D \), the control law function \( u \) is continuous.

**Proof** The Lyapunov function for the closed-loop system (21) has positive definiteness and continuity in the domain \( D = \{ z_1 \in R, z_2 \in R, z_3 \in R : \| z_1 \| < k_2, \| z_2 \| < k_4 \} \). In addition, as \( \| z_1 \| \to \infty, \| z_2 \| \to k_2, \| z_3 \| \to k_4 \), \( \| \tilde{v} \| \) goes to infinity, its derivative is negative definite in the region \( D \) when it satisfies formulas (18) and (20). Therefore, any trajectory starting from \( D \) will gradually converge to the origin. It is easy to see that the control rate \( \dot{u} \) is continuous from equation (14).

4. Simulation results

Simulation of transient stability has been performed by MATLAB according to the above design results. The non-zero initial value is at \( P_H = 0.29 \) and \( P_H = 0.33 \) respectively and the state constraint of the system is \( 312.959 \leq \omega \leq 314.359, 0.13 \leq P_M \leq 0.35 \). Parameters for controller and adaptive laws are chosen as \( k_1 = 0.1, k_2 = 0.01, k_3 = 0.3, k_4 = 0.00071, k_5 = 1, \delta_0 = 57.3, \omega_0 = 314.159, H = 8, D = 5, P_w = 1, E = 1.08, r = 1, V_s = 1, \dot{X}_{\text{MC}} = 0.94, C_H = 0.24, C_M = 0.76, T_{\text{MC}} = 0.4, c_1 = 0.38/\pi, c_2 = 20, c_3 = 9 \).

The simulation results are presented in Figure 2~5, where the solid line and the dashed line are the state response curves with initial conditions of \( P_H = 0.33 \) and \( P_H = 0.28 \) respectively. Under different initial conditions, it can be observed from figure 2 that the work angle is smooth and bounded. Figure 3 and figure 4 show that the rotor angular velocity of the generator and the mechanical power generated by the high-pressure cylinder tend to be stable quickly and smoothly after small oscillations,
and the constraints given are never exceeded. It can be seen from figure 5 that the designed controller can make its gain within a reasonable range and the transient response performance is improved.

![Figure 4. Mechanical power transient curve of high-pressure cylinder.](image1)

![Figure 5. Control voltage of high-pressure oil engine.](image2)

5. Conclusion
The valve controller designed in this paper has strong robustness to parameter uncertainties. By using the adaptive backstepping method and the Lyapunov function with constraints, the proposed controller not only ensures that the constraints of the state variables are not exceeded and makes the system tend to stability, but also has a strong adaptive ability to change the system parameters. This design requires that the initial value of the rotor angular velocity and the mechanical power produced by the high-pressure cylinder meets certain conditions, so that the system state quantity does not exceed its constraint range. The new method reduces the requirement of initial conditions and simplifies the design process of the controller. Simulation results demonstrate the validity of the proposed controller.

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