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Nonlinear Adaptive Robust Control Design for Static Synchronous Compensator Based on Improved Dynamic Surface Method

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Abstract: In view of single machine to infinite bus system with static synchronous compensator, which is affected by internal and external disturbances, a nonlinear adaptive robust controller is constructed based on the improved dynamic surface control method (IDSC). Compared with the conventional DSC, the sliding mode control is introduced to the dynamic surface design procedure, and the parameter update laws are designed using the uncertainty equivalence criterions. The IDSC method not only reduces the complexity of the controller but also greatly improves the system robustness, speed and accuracy. The derived controller cannot only attenuate the influences of external disturbances against system output, but also has strong robustness to system parameters variance because the damping coefficient is considered in the internal parameter uncertainty. Simulation result reveals that the designed controller can effectively improve the dynamic performances of the power system.

Keywords: Power systems, robust control, parameter uncertainty, disturbance attenuation, dynamic surface control (DSC).

1 Introduction

The static synchronous compensator (STATCOM) is one of the important flexible alternative current transmission systems (FACTS) devices and can be used for dynamic compensation of power systems to provide voltage support and stability improvement[1−3]. Over the past two decades, various kinds of linear controllers for STATCOM have been studied. The synthesized feedback controller was proposed to improve phase margin in inductive load[4], a linear quadratic regulator (LQR) control was proposed in [5], and the feedforward techniques and high gain full state feedback approach were used based on a linearization of the dq inverter model in [6]. But these linear feedback controllers cannot guarantee the uniform performance at all operating points. It is necessary to analyze the STATCOM system from the nonlinear control standpoint.

So far, some nonlinear controllers have been designed for STATCOM system, such as input-output feedback linearization[7−9]. The input-output feedback linearization method allows the reference tracking or regulating problems to be solved by linear output feedback controllers. However, although the stability and tracking performance of the system are ensured by feedback controller, the stability and transient behavior of internal dynamics cannot be guaranteed. In [10], the semi-global stability using Lyapunov stability method for the modified damping controller was proved. In [11−13], passivity-based control (PBC) was proposed and the effectiveness of the PBC methodology for STATCOM to achieve a robust performance was researched. Based on the adaptive fuzzy sliding mode controller and the Nussbaum gain, a new power system stabilizer which enhances damping and improves transient dynamics of power system stabilizers was introduced in [14]. The Nussbaum gain was used to avoid the positive sign constraint and the problem of controllability of the system.

Although these existing nonlinear control methods are effective in some ways, one of the main problems of them is that the parameter uncertainty, unmodelled dynamic state and external disturbance have not been considered[15]. However, practical power systems are highly nonlinear, of large scale and multivariables, so they are inevitably subjected to the effects of external disturbances in the operation states, such as system faults, different hand operations and load variations. Besides, there are other general disturbances from different sources, for instance, the inaccurate description of system model, and errors of the controlled plant or the noise of measurement components. Therefore, it is a key point to tackle effectively these parameter uncertainties, unmodelled dynamic states and external disturbances in the controller design procedure.

In this paper, we extend the previous control methods for actual systems[16, 17]. Contribution made in this paper consists in an adaptive robust control scheme which incorporates the improved dynamic surface control method with disturbance attenuation techniques. Compared with the conventional backstepping and dynamic surface control (DSC)[18], for the single machine to infinite bus system (SMIB) with STATCOM including parametric uncertainties and exogenous disturbances, the sliding mode control is introduced into the dynamic surface design, and the parameters updated law is based on the uncertainty principle of equivalence[19]. As a result, the computation is reduced and system robustness is improved. In addition, the external disturbances are attenuated based on the Lyapunov

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stability theorem, and the robust stability and uniform ultimate boundedness are ensured for the controlled system. As the entire design process does not use any linearization processing, we can fully make use of the system nonlinearity to ensure the applicability of the proposed control law in the nonlinear systems. Further, simulation results are shown to verify the effectiveness of the proposed control law in an SMIB system.

The rest of the paper is organized as follows. Section 2 is devoted to the modelling of power system. The details of controller design and the main results are described in Section 3. Simulation studies are given in Section 4, and Section 5 concludes the work.

2 System model description

The configuration of an SMIB system equipped with a STATCOM is shown in Fig. 1.

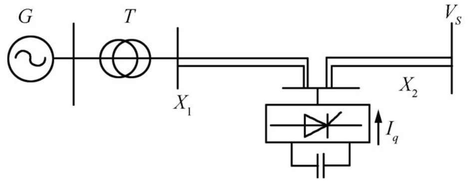

Fig. 1 An SMIB system with STATCOM

In this system, the STATCOM is the parallel control which is based on power converter, and it is supposed that the components in it have no limitations of natural commutation and work as forced commutation. Then the STATCOM could be modeled as a reactive flow resource, which could inject lead or lag current to the power system. If the mechanical input power of the generator is constant, then the generator is represented by the constant voltage source after transient reactance, and the STATCOM is described by a first-order inertial loop. The whole system model is expressed as follows.

$$\left\{\begin{array}{ll}\dot{\delta} & =\omega-\omega_0\\ \dot{\omega} & =\dfrac{\omega_0}{H}\{P_m-\dfrac{D}{\omega_0}(\omega-\omega_0)-\dfrac{E'_qV_S\sin\delta}{X_1+X_2}[1+\\ & \dfrac{X_1X_2I_q}{\sqrt{(X_2E'_q)^2+(X_1V_S)^2+2X_1X_2E'_qV_S\cos\delta}}]\}\\ \dot{I}_q & =\dfrac{1}{T}(-I_q+I_{q0}+u)\end{array}\right. \tag{1}$$

where δ is the rotor angle of the generator, ω is the rotor speed of the generator, P_m is the mechanical power of the prime motor, H is the inertial coefficient of the generator, T is the equivalent time constant of the STATCOM, D and E'_q are damping coefficient and transient EMF of generator q axis, respectively, X_1 is the reactance between the generator's internal bus and STATCOM location bus, X_2 is the equivalent reactance between the middle bus and the infinite bus, V_S is the infinite bus voltage, I_q is the output reactive current of STATCOM, and u is the control input.

For system (1), we redefine the state variables as $x_1=\delta-\delta_0$, $x_2=\omega-\omega_0, x_3=I_q-I_{q0}$, where δ_0, ω_0, I_{q0} are the initial values of corresponding variables. Then system (1) is rewritten as

$$\left[\begin{array}{l}\dot{x}_1=x_2\\ \dot{x}_2=-\dfrac{D}{H}x_2+\dfrac{\omega_0}{H}\{P_m-\dfrac{E'_qV_S\sin\delta}{X_1+X_2}[1+\\ \quad\dfrac{X_1X_2\left(x_3+I_{q0}\right)}{\sqrt{\left(X_2E'_q\right)^2+\left(X_1V_S\right)^2+2X_1X_2E'_qV_S\cos\delta}}]\}\\ \dot{x}_3=\dfrac{1}{T}\left(-x_3+u\right).\end{array}\right. \tag{2}$$

Define $k_1=\frac{\omega_0}{H}$, $k_2=\frac{\omega_0E'_qV_S}{H(X_1+X_2)}$, and assume they are known constants. If D is an unknown constant parameter, then $\theta_2=-\frac{D}{H}$ is also an unknown parameter.

Define a known nonlinear function as

$$f(x_1)=\frac{X_1X_2}{\sqrt{(X_2E'_q)^2+(X_1V_S)^2+2X_1X_2E'_qV_S\cos(x_1+\delta_0)}}. \tag{3}$$

We also consider the external disturbance $w=[w_1\ w_2]^{\mathrm{T}}$, which is unknown bounded. Then system (2) is transformed into

$$\dot{x}_1=x_2 \tag{3a}$$

$$\begin{aligned}\dot{x}_2=\theta x_2+k_1P_m-k_2\sin(\delta_0+x_1)\times\\ [1+f(x_1)(x_3+I_{q0})]+w_1\end{aligned} \tag{3b}$$

$$\dot{x}_3=\frac{1}{T}\left(-x_3+u\right)+w_2. \tag{3c}$$

At the same time, the following assumptions are made for system (3).

Assumption 1. x_i, $(i=1,\cdots,3)$ is both measurable and bounded.

Assumption 2. $w_i\in\mathbf{R}$ and satisfies $w_i\leqslant a_i$, where a_i is a known positive constant, $i=1,2$.

Assumption 3. The reference trajectory x_{1d} and its first- and second-order derivatives are known and bounded.

For system (3) with parameter uncertainty and external disturbances, we can use the IDSC method to design the nonlinear robust controller. The control object is to construct a control law u such that the output $y=x_1$ of the controlled system tracks the reference trajectory x_{1d}, and the tracking error $|x-x_{1d}|$ converges to a small neighborhood of zero.

3 Design of nonlinear adaptive robust controller

For system (3), we first define the surface error as

$$e_i=x_{i-}x_{id} \tag{4}$$

where x_{1d} is the reference trajectory, x_{id} $(i=2,3)$ will be given later on by the first-order filter.

Define the boundary layer errors as

$$y_{i+1}=x_{(i+1)d-}x^*_{i+1} \tag{5}$$

where $x^*_{i+1}(i{=}1,2)$ is the stabilizing function which will also be designed later on.

Now we shall show a new dynamic surface control procedure of the robust adaptive controller for the system defined in (3).

Step 1. For the first subsystem of (3), viewing x_2 as the virtual control, we have

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1d} = x_2 - \dot{x}_{1d} = e_2 + y_2 + x_2^* - \dot{x}_{1d}. \quad (6)$$

We select the first virtual stabilizing function as

$$x_2^* = -c_1 e_1 + \dot{x}_{1d} \quad (7)$$

where c_1 is a positive design constant. Substituting (7) into (6) yields

$$\dot{e}_1 = -c_1 e_1 + e_2 + y_2. \quad (8)$$

Let x_2^* be an input and pass through a first-order filter as

$$\tau_2 \dot{x}_{2d} + x_{2d} = x_2^* \quad (9)$$

where τ_2 is a given time constant, and $x_{2d}(0) = x_2^*(0)$.

Step 2. For the second subsystem of (3), viewing x_3 as the virtual control, we have

$$\begin{aligned}\dot{e}_2 = &\dot{x}_2 - \dot{x}_{2d} = \theta x_2 + k_1 P_m - k_2 \sin(\delta_0 + x_1)\times \\ &[1 + f(x_1)(x_3 + I_{q0})] + w_1 - \dot{x}_{2d} = \\ &k_1 P_m - k_2 \sin(\delta_0 + x_1)\left[1 + f(x_1)(e_3 + y_3 + x_3^* +\right. \\ &\left. I_{q0})\right] + x_2\left(\hat{\theta} + \frac{1}{2}x_2^2 - z\right) + w_1 - \dot{x}_{2d} \quad (10)\end{aligned}$$

where $\hat{\theta}$ is the parameter estimation of θ, and z is the parameter estimation errors which is given by

$$z = \hat{\theta} - \theta + \frac{x_2^2}{2}. \quad (11)$$

Select the second virtual stabilizing function

$$\begin{aligned}x_3^* = &\frac{1}{k_2 \sin(\delta_0 + x_1) f(x_1)}[-c_2 e_2 - k_1 P_m - x_2(\hat{\theta} + \frac{1}{2}x_2^2) - \\ &\frac{e_2}{(2\gamma_2)^2} + \dot{x}_{2d} - k_2 \sin(\delta_0 + x_1)] - I_{q0} \quad (12)\end{aligned}$$

where c_2, γ_2 are positive design constants, and the adaptive law to the uncertain parameter is selected as follows based on the uncertainty equivalence criterion.

$$\begin{aligned}\dot{\hat{\theta}} = &-x_2[k_1 P_m - k_2 \sin(\delta_0 + x_1)[1 + f(x_1)(x_3 + I_{q0})] + \\ &x_2(\hat{\theta} + \frac{1}{2}x_2^2)]. \quad (13)\end{aligned}$$

Therefore, the dynamics of the estimation error is

$$\dot{z} = -x_2^2 z + x_2 w_1. \quad (14)$$

Substituting (11) and (12) into (10) yields

$$\begin{aligned}\dot{e}_2 = &-c_2 e_2 - \frac{e_2}{(2\gamma_2)^2} - x_2 z + k_2 \sin(\delta_0 + x_1) f(x_1)\times \\ &(e_3 + y_3) + w_1. \quad (15)\end{aligned}$$

Let x_3^* be an input and pass through a first-order filter as

$$\tau_3 \dot{x}_{3d} + x_{3d} = x_3^* \quad (16)$$

where τ_3 is a given time constant, and $x_{3d}(0) = x_3^*(0)$.

Step 3. For the third subsystem of (3), in light of (4), we have

$$\dot{e}_3 = \dot{x}_3 - \dot{x}_{3d} = \frac{1}{T}(-x_3 + u) + w_2 - \dot{x}_{3d}. \quad (17)$$

Define the sliding mode $s = d_1 e_1 + d_2 e_2 + e_3 = 0$ which satisfies the asymptotic reaching condition, where d_1 and d_2 are positive design constants, and define the Lyapunov function of the whole system as

$$V = \frac{1}{2}\sum_{i=1}^{2} e_i^2 + \frac{1}{2}\sum_{i=2}^{3} y_i^2 + \frac{1}{2}s^2 + \frac{\varepsilon}{2}z^2 \quad (18)$$

where $\varepsilon > 0$ is a design constant. The time derivative of V is

$$\dot{V} = \sum_{i=1}^{2} e_i \dot{e}_i + \sum_{i=2}^{3} y_i \dot{y}_i + s\dot{s} + \varepsilon z \dot{z}. \quad (19)$$

Noting that (10) and $\dot{x}_{(i+1)d} = \frac{x_{i+1}^* - x_{(i+1)d}}{\tau_{i+1}}$, we can get

$$\begin{aligned}\dot{y}_{i+1} = &\ \dot{x}_{(i+1)d} - \dot{x}_{i+1}^* = \frac{x_{i+1}^* - x_{(i+1)d}}{\tau_{i+1}} - \dot{x}_{i+1}^* = \\ &-\frac{y_{i+1}}{\tau_{i+1}} - \dot{x}_{i+1}^*. \quad (20)\end{aligned}$$

From (7), we have $\dot{x}_2^* = -c_1 \dot{e}_1 + \ddot{x}_{1d}$, based on Assumptions 1−3, we know $\dot{x}_2^*$ is also bounded, i.e., there exists a positive constant D_2 such that sup $|\dot{x}_2^*| \leqslant D_2$.

Besides, we can get from (12)

$$\begin{aligned}\dot{x}_3^* = &\frac{-\cos(\delta_0 + x_1) f(x_1)\dot{x}_1 - \sin(\delta_0 + x_1)\dot{f}(x_1)\dot{x}_1}{k_2[\sin(\delta_0 + x_1) f(x_1)]^2}\times \\ &(-c_2 \dot{e}_2 - \dot{x}_2 \hat{\theta} - x_2 \dot{\hat{\theta}} - \frac{3}{2}x_2^2 \dot{x}_2 - \frac{\dot{e}_2}{(2\gamma_2)^2} + \ddot{x}_{2d} - \\ &k_2 \cos(\delta_0 + x_1)\dot{x}_1).\end{aligned}$$

So $\dot{x}_3^*$ can be written as the function form, i.e., $\dot{x}_3^* = f(x_1, \dot{x}_1, \dot{x}_2, \hat{\theta}, x_{2d})$. By using Assumptions 1−3 and noting the system model (3), we can know that all the variables in $\dot{x}_3^*$ are bounded, and there exists a positive constant D_3 such that sup$|\dot{x}_3^*| \leqslant D_3$.

Then we have

$$\begin{aligned}\dot{V} = &e_1(-c_1 e_1 + e_2 + y_2) + e_2[-c_2 e_2 - \frac{e_2}{(2\gamma_2)^2} - x_2 z + \\ &k_2 \sin(\delta_0 + x_1) f(x_1)(e_3 + y_3) + w_1] + \\ &\sum_{i=2}^{3} y_i(-\frac{y_i}{\tau_i} + D_i) + s[d_1 \dot{e}_1 + d_2 \dot{e}_2 + \\ &\frac{1}{T}(-x_3 + u) + w_2 - \dot{x}_{3d}] - \varepsilon x_2^2 z^2 + \varepsilon x_2 z w_1. \quad (21)\end{aligned}$$

Select the real control input u as

$$u = x_3 + T[-\beta_1 s - \beta_2 \text{sgn}(s) - d_1 \dot{e}_1 - d_2 \dot{e}_2 - \frac{s}{(2\gamma_3)^2} + \dot{x}_{3d}] \quad (22)$$

where β_1, β_2 and γ_3 are positive design constants. Substituting (22) into (17) yields

$$\dot{e}_3 = -\beta_1 s - \beta_2 \text{sgn}(s) - d_1 \dot{e}_1 - d_2 \dot{e}_2 - \frac{s}{(2\gamma_3)^2} + w_2. \quad (23)$$

In the new coordinates defined by (6)–(23), we have an important theorem as follows.

Theorem 1. For the nonlinear systems (3) in the parameter feedback form with parameter uncertainty and external disturbances, the closed-loop error system will be globally and uniformly ultimately bounded if we apply the robust adaptive control law (22), the stabilizing functions (7), (12) and the parameter adaptive laws (13). Furthermore, given any constant μ^*, there exists T such that $e(t) \leqslant \mu^*$ for all $t \geqslant T$.

Proof. The time derivative of V gives

$$\begin{aligned}\dot{V} = & -c_1e_1^2 - c_2e_2^2 - \frac{e_2^2}{(2\gamma_2)^2} - e_2x_2z - \varepsilon x_2^2z^2 + e_2k_2\times \\ & \sin(\delta_0 + x_1)f(x_1)(e_3 + y_3) + e_2w_1 + \varepsilon x_2zw_1 - \\ & \beta_1s^2 - \beta_2\,|s| - \frac{s^2}{(2\gamma_3)^2} + sw_2 + \sum_{i=2}^{3} y_i\left(\frac{-y_i}{\tau_i} + D_i\right) \leqslant \\ & -c_1e_1^2 - c_2e_2^2 - \beta_1s^2 - \beta_2\,|s| + \frac{1}{2}e_2^2 + \frac{1}{2}(x_2z)^2 - \\ & \varepsilon x_2^2z^2 - \left[\frac{e_2^2}{(2\gamma_2)^2} - e_2w_1\right] + \varepsilon x_2zw_1 - \left[\frac{s^2}{(2\gamma_3)^2} - \right. \\ & \left. sw_2\right] + e_2g(x_1)(e_3 + y_3) - \sum_{i=2}^{3}\frac{y_i^2}{\tau_i} + \sum_{i=2}^{3}|y_i|\,|D_i| \leqslant \\ & -c_1e_1^2 - \left(c_2 - \frac{1}{2}\right)e_2^2 - \beta_2\,|s| - (\varepsilon - 1)(x_2z)^2 - \\ & \beta_1[(d_1e_1 + d_2e_2)^2 + e_3^2 + 2(d_1e_1 + d_2e_2)e_3] + \\ & \sum_{i=2}^{3}\gamma_i^2w_i^2 + \frac{\varepsilon^2}{2}w_1^2 + \frac{|g(x_1)|}{2}(2e_2^2 + e_3^2 + y_3^2) - \\ & \sum_{i=2}^{3}\frac{y_i^2}{\tau_i} + \sum_{i=2}^{3}\frac{\sigma y_i^2}{2} + \sum_{i=2}^{3}\frac{D_i^2}{2\sigma}\end{aligned} \tag{24}$$

where $\sigma > 0$ is a design constant, and $g(x_1) = k_2\sin(\delta_0 + x_1)f(x_1)$.

It follows that

$$\begin{aligned}\dot{V} \leqslant & -c_1e_1^2 - \left(c_2 - \frac{1}{2} - |g(x_1)|\right)e_2^2 - \beta_2\,|s| - \\ & (\varepsilon - 1)(x_2z)^2 + m_1e_1^2 + m_2e_2^2 + \\ & m_3e_3^2 + \frac{|g(x_1)|}{2}e_3^2 - \\ & \left(\frac{1}{\tau_2} - \frac{\sigma}{2}\right)y_2^2 - \left[\frac{1}{\tau_3} - \frac{\sigma}{2} - \frac{|g(x_1)|}{2}\right]y_3^2 + \\ & \left(\gamma_2^2 + \frac{\varepsilon}{2}\right)w_1^2 + \gamma_3^2w_2^2 + \frac{D_2^2 + D_3^2}{2\sigma}\end{aligned} \tag{25}$$

where $m_1 = -\beta_1d_1^2 + \beta_1d_1d_2 + \beta_1d_1$, $m_2 = -\beta_1d_1^2 + 2\beta_1d_1d_2 + \beta_1d_1$, and $m_3 = -\beta_1 + \beta_1d_1 + \beta_1d_2$.

In the normal operation of power system, $g(x_1)$ and w_i are bounded, then we can suppose $|g(x_1)| \leqslant G_{\max}$, $|w_i| \leqslant w_{\max}$, and select $\gamma = \max\{\sqrt{\gamma_2^2 + \frac{\varepsilon}{2}}, \gamma_3\}$. Then we get

$$\begin{aligned}\dot{V} \leqslant & -(c_1 - m_1)e_1^2 - \left(c_2 - \frac{1}{2} - m_2 - G_{\max}\right)e_2^2 - \\ & \left(-m_3 - \frac{G_{\max}}{2}\right)e_3^2 - \beta_2\,|s| - (\varepsilon - 1)\times \\ & (x_2z)^2 - \left(\frac{1}{\tau_2} - \frac{\sigma}{2}\right)y_2^2 - \left[\frac{1}{\tau_3} - \frac{\sigma}{2} - \right. \\ & \left.\frac{G_{\max}}{2}\right]y_3^2 + 2\gamma^2w_{\max}^2 + \frac{D_2^2 + D_3^2}{2\sigma}.\end{aligned} \tag{26}$$

Select $c_1 > m_1$, $c_2 > \frac{1}{2} + m_2 + G_{\max}$, $m_3 + \frac{G_{\max}}{2} < 0$, $\beta_2 > 0$, $\varepsilon > 1$, $\frac{1}{\tau_2} > \frac{\sigma}{2}$, $\frac{1}{\tau_3} > \frac{\sigma}{2} + \frac{G_{\max}}{2}$, $a_0 = \min\left\{c_i, \beta_i, \varepsilon, \frac{1}{\tau_{i+1}}\right\}$, and $b_0 = 2\gamma^2d_{\max}^2 + \sum_{i=2}^{n}\frac{D_i^2}{2\sigma}$. Then we have

$$\dot{V} \leqslant -a_0\Big(\sum_{i=1}^{3}e_i^2 + \sum_{i=2}^{3}y_i^2\Big) + b_0. \tag{27}$$

If $\|\boldsymbol{E}\| > \sqrt{\frac{b_0}{a_0}}$ and $\|\boldsymbol{Y}\| > \sqrt{\frac{b_0}{a_0}}$, then $\dot{V} \leqslant 0$, where $\boldsymbol{E} = [e_1, e_2, e_3]^{\mathrm{T}}$ and $\boldsymbol{Y} = [y_2, y_3]^{\mathrm{T}}$. So the system errors are uniformly ultimately bounded. □

Remark 1. The above inequality guarantees that e_i will converge to $\frac{b_0}{a_0}$ in an exponential rate, and when the external disturbances w_i disappear, the whole system will still be globally uniformly ultimately bounded.

Remark 2. For the selection of designed constants, it seems that the value of $G_{\max}$ needs to be decided. But in fact, this is not completely such. When the control gain $g(x_1)$ is constant, we can know the real value of $G_{\max}$ definitely. When $g(x_1)$ is a bounded function, we only set c_i and $\frac{1}{\tau_i}$ large enough to guarantee the stability and some performance of system by trial and error.

4 Simulation results

In this section, we simulate the closed-loop system under the designed controller. The used system parameters are in the following: $H = 8$, $E_q^{'} = 1$, $V_s = 1$, $X_1 = 0.6$, $X_2 = 0.4$, $\delta_0 = \frac{\pi}{3}$, and $\omega_0 = 314.159$ rad/s.

The relevant design parameters are taken as follows: $d_1 = 0.6, d_2 = 0.1, d_3 = 2, \beta_1 = 80, \beta_2 = 2, c_1 = 2, c_2 = 30, \varepsilon = 4, \sigma = 10, \gamma = 0.2$, and $\tau_2 = \tau_3 = 0.01$.

The closed-loop system is simulated in two cases: small-signal stability and large-disturbances stability.

Case 1. Small-signal stability.

The simulation results are shown in Figs. 2–4.

From the responding curves of the system states, we can see that the system has very good convergence performance though it is subjected to the influence of external disturbances and parameter uncertainty. The states of the closed-loop system go into the steady states in no more than 0.5 seconds.

At the same time, the parameter estimation is also convergent to steady state, just like what the response curve depicted in Fig. 4. Thus, all of these do verify the conclusion of Theorem 1.

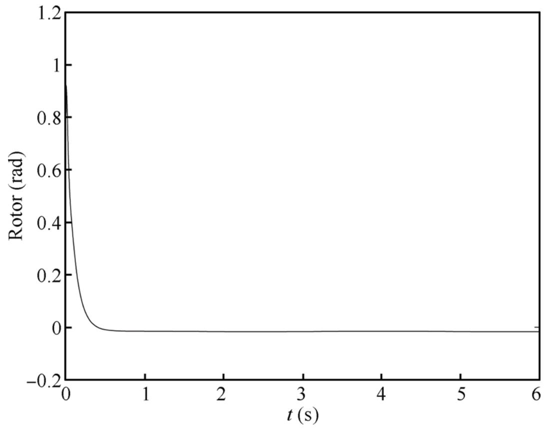

Fig. 2 The time response of rotor in Case 1

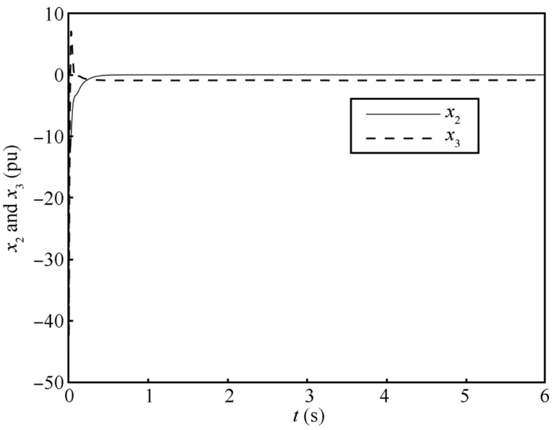

Fig. 3 The response curves of x_2, x_3

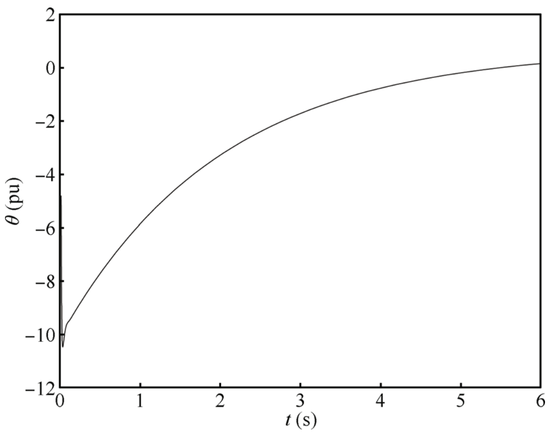

Fig. 4 The time response of parameter estimations

Case 2. Large-disturbances stability.

The system is in a pre-fault steady-state. Suppose that a symmetrical three-phase short-circuit fault occurs at the outlet of the transformer at $t = 0.2$ s. In order to show the effectiveness of the proposed IDSC controller, we compare it with the adaptive backstepping controller under the same initial condition and system parameters.

The corresponding results are shown in Figs. 5 and 6.

One can see that the rotor angle for the proposed IDSC in this paper approaches to the required operation points more quickly than the case of backstepping control, and that the local oscillation amplitudes of power angle and relative bus voltage under the IDSC are smaller. The simulation results show that the IDSC controller enhances the rotor angle and voltage stability in the presence of the fault.

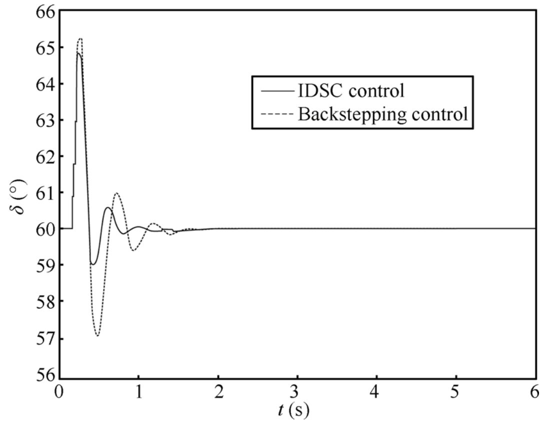

Fig. 5 Rotor angle responding curves

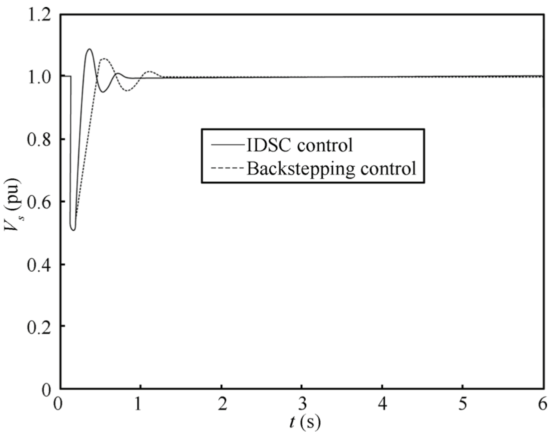

Fig. 6 Bus voltage V_s responding curves of the system

5 Conclusions

A novel adaptive control strategy is presented in this paper based on the perturbed nonlinear mathematic model using the IDSC. The parameter uncertainty and the external disturbances are considered comprehensively, and finally the uniformly ultimately bounded is achieved. Compared with the conventional backstepping methods, this approach reduces the requirements of the controlled systems, such as matching condition and so on, while the robustness to model errors and external disturbances and the adaptability to uncertain parameters are reserved. Based on this approach, the robust adaptive controller has been designed and simulation studies are conducted. Simulation results demonstrate that the suggested controller can effectively improve the dynamic performances of the power systems.

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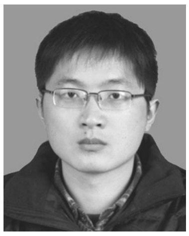

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