Control Engineering Practice 17 (2009) 766–772

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Adaptive coordinated passivation control for generator excitation and thyristor controlled series compensation system

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ARTICLE INFO

Article history:
Received 14 September 2007
Accepted 29 December 2008
Available online 11 February 2009

Keywords:
Coordinated passivation
Adaptive control
Generator excitation
Thyristor controlled series compensation
Power systems

ABSTRACT

The problem of transient stability for a single machine infinite bus system with the generator excitation and thyristor controlled series compensation (TCSC) is addressed via the coordinated passivation method. The system does not need to be linearized. Two types of uncertainties, namely, the damping coefficient uncertainty and the modeling error of TCSC, are considered. First, an excitation control input and a parameter updating law are obtained simultaneously via adaptive back-stepping and Lyapunov methods to achieve stability of the zero dynamics subsystem. Then, a reactance modulated input is derived to ensure the feedback passivity of the whole system, based on which a stabilizing controller for the closed-loop system is designed. Simulation results show that the proposed controller produces better transient performance than the conventional direct feedback linearization controller.

1. Introduction

The past decade has witnessed a rapid increase in the size and complexity of power systems. Maintaining power system stability is thus one of the main concerns (Sadeghzadeh, Ehsan, Hadj Said, & Feuillet, 1999). The design of an advanced control system to enhance the power system stability margin so as to achieve higher transfer limits is one of the major problems in power systems, which has attracted a great deal of research attention in recent years (Bevrani, Hiyama, & Mitani, 2008; Chaudhuri & Pal, 2004; Elshafei, El-Metwally, & Shaltout, 2005).

Synchronous generator excitation control is one of the most important, effective and economic methods to enhance the stability of power systems (Lu & Sun, 1993). Generator excitation control can not only enhance the power system static stability limit, but also attenuate low-frequency electromechanical oscillations inherent to power systems, during transient conditions (Bazanella & Conceição, 2004; Damm, Marino, & Lamnabhi-Lagarrigue, 2004; Maya-Ortiz & Espinosa-Pérez, 2004; Sae-Kok, Yokoyama, Verma, & Ogawa, 2006). Since excitation control is restrained by excitation current ceiling, the requirement of generator possessing excess of excitation current ceiling will increase its manufacturing cost (Lu & Sun, 1993). Also, the rise speed of generator excitation current is restrained by the time constant of excitation windings. Therefore, the improvement of power systems stability limits depends heavily on excitation control. Wang, Hill, Middleton, and Gao (1993) showed that a power system may not maintain the synchronism when a large fault occurs in the power system with a high transfer level and with generator excitation control only.

Improvements in the power electronics technology and in the new area of flexible AC transmission systems (FACTS) have considerable potential to enhance a power system's transient stability (Farsangi, Song, & Lee, 2004). Thyristor controlled series compensation (TCSC) is an important member of FACTS family. It is installed in long-distance transmission systems for rapid adjustment of the effective value of a capacitor in series with transmission line by making use of the short-time over-load capability of the capacitor (Zhang & Zhou, 1999). It can change line equivalent reactance dynamically to control power flow, damp the power oscillation (Li, 2006), improve system stability (Dimirovski, Jing, Li, & Liu, 2006; Zhu, Liu, Cai, & Ni, 2006) and increase power transfer limit (Chaudhuri & Pal, 2004; Mei, Shen, & Liu, 2003; Zhang, 2002). Yet, serious situations of dynamical power system stability can occur involving bifurcation and chaos prior to power system stabilizes in a steady state due to rather realistic internal and external disturbances.

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doi:10.1016/j.conengprac.2008.12.004

In order to enhance further the stability potential of power systems, investigations on the advanced control mode of co-ordinated generator excitation and TCSC has become a timely task. The main goal of the coordinated controller design is to enable all the major fast response controllers in a power system to co-operatively improve the system performance (Wang, Tan, & Guo, 2002).

The coordinated control method of conventional power system stabilizer (PSS) and TCSC is based on using approximately linearized model without taking nonlinear features into consideration. Thus it cannot keep the system transient stability in the case where operational conditions and system parameters change significantly (Abdel-Magid & Abido, 2004; Abido, 2000; Kuiava, de Oliveira, Ramos, & Bretas, 2006). Such stabilizers are suitable only for small disturbances about the steady-state operation. The design synthesis based on feedback linearization using the differential geometric approach has the disadvantage that the parameters of the system have to be exactly and precisely known (Wang et al., 2002). Besides, this control cancels possible beneficial nonlinearities. In the feedback linearization approach the parameter uncertainties problem can be tackled only if combined with some other robust control methods. Therefore, in many cases, it cannot achieve robustness to system model and parameter variations. Lei, Li, and Povh (2001) presented a coordinated control scheme based on optimal-variable-aim strategies (OVAS) techniques for the TCSC and excitation system for a transmission power system. However, for nonlinear systems, the numerical computation burden of online optimization is huge and the demand of real-time control may not be satisfied. In addition, the electromagnetic transient course of TCSC itself is omitted. So far, to the best of authors' awareness, simultaneous consideration of the uncertainty of generator damping coefficient and the uncertain model error of TCSC have not been accounted for.

Passivity provides a physical insight and a useful tool for the analysis and design of nonlinear systems. It is well known that the nature of a power system is to produce, transmit and consume energy. In electrical systems, the power flow into the network must be greater than or equal to the rate of change of the energy stored in the network. Passivation designs fully exploit the inherent system properties, and also tend to require less control effort. The coordinated passivation (Chen, Ji, Wang, & Xi, 2006; Larsen, Janković, & Kokotović, 2003) is an improvement of the passivity based method (Khalil, 2002; Kokotović & Arcak, 2001), which releases some constraints in the case of multi-input multi-output (MIMO) systems. For MIMO systems, the coordinated passivation method divides the system into two parts and carries out the design, respectively. First, some input–output pairs are chosen for which the relative degree is one or zero. Then, the zero dynamics are stabilized by the remaining inputs. In this way, the design complexity is remarkably reduced. While the design for the other part yields an improved design effect for the whole system. The coordinated passivation design method has been applied to the diesel engine model (Larsen et al., 2003) and the dual-excited and steam-valving control for synchronous generators (Chen et al., 2006). However, no parameter uncertainty in system model was considered in these results.

This paper studies the control problem of generator excitation and TCSC system by the coordinated passivation method. The damping coefficient uncertainty and uncertain model error of TCSC are simultaneously considered to enhance the transient stability. The design procedure consists of two steps. First, the excitation voltage input is obtained by adaptive back-stepping and Lyapunov methods to achieve stability of rotor angle, speed, and voltage. A parameter updating law is also presented. Then, the reactance modulated input is designed to ensure the feedback passivity of the whole system, which gives a stabilizing controller for the whole closed-loop system. This paper is organized as follows. Section 2 gives an outline of the coordinated passivation method. The adaptive coordinated passivation control design is presented in Section 3. Section 4 gives simulation results. Conclusions follows thereafter.

2. Coordinated passivation

A system with state $x \in R^n$ is said to be feedback passive for an input–output pair $(u, y) \in R$ if there exist a positive definite storage function $V(x)$ and a change of feedback law $u = \varphi(x) + \zeta(x)\nu$ such that along the system trajectory $\dot{V} \leqslant \nu y$ holds, where ν is a new input.

Consider the two-input system

$$\dot{x} = f(x) + g_1(x)u_1 + g_2(x)u_2, \tag{1}$$

where $x \in R^n, u_1 \in R, u_2 \in R$. Choose y such that the relative degree from u_1 to y is one.

For clarity, the normal form (Isidori, 1995) of system (1) is explicitly given by

$$\dot{z} = q(z, y) + p(z, y)u_2, \tag{2}$$

$$\dot{y} = \alpha(z, y) + \beta_1(z, y)u_1 + \beta_2(z, y)u_2. \tag{3}$$

Therefore, the zero dynamics system is

$$\dot{z} = q(z, 0) + p(z, 0)u_2, \tag{4}$$

which is assumed to be stabilized by u_2 with $z \in R^{n-1}$.

The coordinated passivation design method is carried out in the following two steps: zero dynamics stabilization and feedback passivation.

Firstly, find a control Lyapunov function (CLF), denoted by $W(z)$, for the zero dynamics subsystem, for which there exists a control law $u_2 = \gamma(z)$ such that

$$\dot{W} = \frac{\partial W(z)}{\partial z}(q(z, 0) + p(z, 0)\gamma(z)) < -\alpha(\|z\|), \quad \forall z \neq 0,$$

where α is a class-K function. Then, achieve the feedback passivation of the whole system (2) and (3) with the input u_1 and the output y. To this end, rewrite (2) with $u_2 = \gamma(z)$ as

$$\dot{z} = q(z, y) + p(z, y)\gamma(z) = \tilde{q}(z) + \tilde{p}(z, y)y,$$

where $\tilde{q}(z) = q(z, 0) + p(z, 0)\gamma(z)$.

Choose the storage function $V = W(z) + \frac{1}{2}y^2$ whose derivative along the trajectory of (2) and (3) is

$$\dot{V} = \dot{W}\dot{z} + y\dot{y} = \frac{\partial W}{\partial z}(\tilde{q} + \tilde{p}y) + y[\alpha(z, y) + \beta_1(z, y)u_1 + \beta_2(z, y)u_2].$$

Then design the control law as

$$u_1 = \beta_1^{-1}(z, y)\left[-\beta_2(z, y)u_2 - \alpha(z, y) - \frac{\partial W}{\partial z}\tilde{p}(z, y) + \nu\right].$$

Thus, $\dot{V} = \partial W/\partial z\tilde{q} + \nu y \leqslant -\alpha(\|z\|) + \nu y \leqslant \nu y$, which means passivity. Additional output feedback $\nu = -\phi(y)$, where $\phi(y)$ is a sector-nonlinearity satisfying $y\phi(y) > 0$ for $y \neq 0$ and $\phi(0) = 0$, does achieve $\dot{V} \leqslant -y\phi(y) \leqslant 0$, which ensures stability of the closed-loop system. Moreover, if the system is zero state detectable, this also guarantees asymptotic stability.

3. Design of adaptive coordinated passivation controller

A dynamic model of single-machine infinite-bus (SMIB) power system with the generator excitation and TCSC is considered, which is widely used as a benchmark example in the literature (Abdel-Magid & Abido, 2004; Wang et al., 2002). A standard

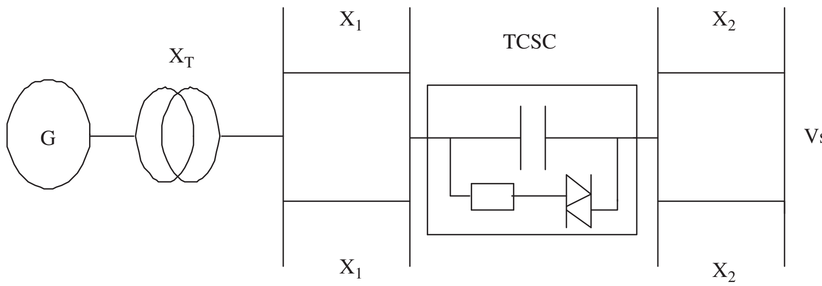

Fig. 1. A single machine infinite bus system with TCSC.

model of a power generator is often decomposed into a mechanical and an electrical parts (Damm et al., 2004; Lu & Sun, 1993; Wang et al., 1993). The one-order inertial block represents the natural response of the TCSC (Zhu et al., 2006). The schematic diagram is depicted in Fig. 1. For the convenience of modeling and without loss of generality, the TCSC is located at the midpoint of the transmission lines. It is worth noting that the TCSC can be located anywhere in the transmission lines (Wang et al., 2002).

3.1. System model and control objective

The dynamics of this system can be expressed by means of the following nonlinear differential equations (Wang et al., 2002):

$$\begin{cases} \dot{\delta} = \omega - \omega_0, \\ \dot{\omega} = -\dfrac{D}{H}(\omega - \omega_0) + \dfrac{\omega_0}{H}\left(P_m - \dfrac{E'_q V_s \sin\delta}{X'_{d\Sigma} + X_{tcsc}}\right), \\ \dot{E}'_q = \dfrac{(X_d - X'_d)(V_s \cos\delta - E'_q)}{T_{d0}(X'_{d\Sigma} + X_{tcsc})} - \dfrac{1}{T_{d0}}E'_q + \dfrac{K_c}{T_{d0}}u_{fd}, \\ \dot{X}_{tcsc} = -\dfrac{1}{T_c}(X_{tcsc} - X_{tcsc0}) + \dfrac{K_T}{T_c}u_c + \varepsilon_{tcsc}(X_{tcsc} - X_{tcsc0}), \end{cases} \tag{5}$$

where δ and ω are the angle and relative speed of the generator rotor, respectively; H is the inertia constant; P_m is the mechanical power on the generator shaft; D is the damping coefficient; E'_q and V_s are the inner generator voltage and infinite bus voltage, respectively; T_c is the time constant of TCSC; T_{d0} is the direct axis transient open circuit time constant; V_t is the terminal voltage; $X'_{d\Sigma} = X_T + X'_d + \frac{1}{2}(X_1 + X_2), X_{d\Sigma} = X_T + X_d + \frac{1}{2}(X_1 + X_2); X_T$ is the reactance of the transformer; X_d and X'_d are the direct axis reactance and transient reactance of the generator, respectively; X_1 and X_2 are the line reactance whereas X_{tcsc} is the reactance of TCSC device; X_{tcsc0} is the initial stable value of X_{tcsc}; K_c is the gain of the excitation amplifier; u_{fd} is the excitation voltage; K_T is the gain of TCSC regulator and u_c is the reactance modulated input of TCSC; $\varepsilon_{tcsc}(X_{tcsc} - X_{tcsc0})$ stands for the uncertain model error of TCSC, which is a function of $(X_{tcsc} - X_{tcsc0})$. Moreover, the uncertain model error is assumed to satisfy the linear growth condition, that is, $|\varepsilon_{tcsc}(X_{tcsc} - X_{tcsc0})| \leqslant \psi |X_{tcsc} - X_{tcsc0}|$ for an unknown positive constant ψ.

Usually, the damping coefficient D cannot be measured accurately in practical engineering applications (Dimirovski et al., 2006; Zhu et al., 2006). Hence $\theta = -D/H$ is taken as an unknown and/or uncertain constant parameter that has to be estimated on-line in real time.

The control objective is to design a coordinated controller which globally asymptotically stabilizes system (5).

3.2. Controller design

A globally asymptotically stabilizing controller for system (5) will be designed in this subsection.

Let $(\delta_0, \omega_0, E'_{q0}, X_{tcsc0})$ represent an operating point of system (5). Define the new system state variables as $x_1 = \delta - \delta_0$, $x_2 = \omega - \omega_0$, $x_3 = E'_q - E'_{q0}$, and $x_4 = X_{tcsc} - X_{tcsc0}$. Let the inputs be $u_1 = u_c$ and $u_2 = u_{fd}$. Choose the output $y = x_4 = X_{tcsc} - X_{tcsc0}$. Then, system (5) can be rewritten as

$$\dot{x} = \begin{bmatrix} x_2 \\ \dfrac{\omega_0}{H}P_m + \theta x_2 - \dfrac{\omega_0(x_3 + E'_{q0})V_s sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + y + X_{tcsc0})} \\ \dfrac{(X_d - X'_d)(V_s cos(x_1 + \delta_0) - x_3 - E'_{q0})}{T_{d0}(X'_{d\Sigma} + y + X_{tcsc0})} - \dfrac{x_3 + E'_{q0}}{T_{d0}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{K_c}{T_{d0}} \end{bmatrix} u_2, \tag{6}$$

$$\dot{y} = -\frac{1}{T_c}y + \frac{K_T}{T_c}u_1 + \varepsilon_{tcsc}(y). \tag{7}$$

Obviously, the relative degree from the input u_1 to the output y is one.

The design is divided into two parts. First, design the control input u_2 to stabilize the zero dynamics. Then, design the control input u_1 by passivation method to stabilize the whole system.

(1) Design of u_2 by adaptive back-stepping

From (6), the zero dynamics subsystem with the uncertain damping coefficient can be written as follows:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = \dfrac{\omega_0}{H}P_m + \theta x_2 - \dfrac{\omega_0(x_3 + E'_{q0})V_s sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})}, \\ \dot{x}_3 = \dfrac{(X_d - X'_d)(V_s cos(x_1 + \delta_0) - x_3 - E'_{q0})}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})} - \dfrac{x_3 + E'_{q0}}{T_{d0}} + \dfrac{K_c}{T_{d0}}u_2. \end{cases} \tag{8}$$

In the following, the control law is designed by the adaptive back-stepping method.

Step 1: For the first subsystem of system (8), x_2 is taken as the virtual control variable. Then, the virtual control of is designed as $x_2^* = -c_1 x_1$, where $c_1 > 0$ is a design constant. Define the error variable $z_2 = x_2 - x_2^*$ and $z_1 = x_1$. Then,

$$\dot{z}_1 = z_2 - c_1 x_1. \tag{9}$$

For system (9) choose Lyapunov function

$$V_1 = \tfrac{1}{2}z_1^2. \tag{10}$$

The time derivative of V_1 along the system trajectory is $\dot{V}_1 = z_1(z_2 - c_1 z_1) = z_1 z_2 - c_1 z_1^2$. It is apparent that $\dot{V}_1 \leqslant 0$ when $z_2 = 0$.

Step 2: Augment Lyapunov function of *Step* 1 as

$$V_2 = V_1 + \tfrac{1}{2} z_2^2. \tag{11}$$

Notice that

$$\dot{z}_2 = \dot{x}_2 - \dot{x}_2^* = \frac{\omega_0}{H} P_m + \theta x_2 - \frac{\omega_0 (x_3 + E'_{q0}) V_s}{H(X'_{d\Sigma} + X_{tcsc0})} \sin(x_1 + \delta_0) + c_1 x_2, \tag{12}$$

the time derivative of V_2 along the system trajectory is

$$\dot{V}_2 = \dot{V}_1 + z_2 \dot{z}_2 = -c_1 z_1^2 + z_2 \left[z_1 + \frac{\omega_0}{H} P_m + \theta x_2 - \frac{\omega_0 (x_3 + E'_{q0}) V_s}{H(X'_{d\Sigma} + X_{tcsc0})} \sin(x_1 + \delta_0) + c_1 x_2 \right]. \tag{13}$$

For (12), x_3 is taken as the virtual control variable. Define the error variable $z_3 = x_3 - x_3^*$. Then the virtual control is chosen as $x_3^* = [H(X'_{d\Sigma} + X_{tcsc0})/\omega_0 V_s \sin(x_1 + \delta_0)][z_1 + (\omega_0/H)P_m + \hat{\theta} x_2 + c_1 x_2 + c_2 z_2] - E'_{q0}$, where $\hat{\theta}$ stands for the estimate of θ, and $c_2 > 0$ is another design constant. Next, define the estimation error $\tilde{\theta} = \theta - \hat{\theta}$. Then, it holds that

$$\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 + z_2 \tilde{\theta} x_2 - z_2 \frac{\omega_0 V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})} z_3.$$

Step 3: Augment Lyapunov function of *Step* 2 by

$$V_3(z_1, z_2, z_3, \tilde{\theta}) = V_2 + \frac{1}{2} z_3^2 + \frac{1}{2\gamma} \tilde{\theta}^2, \tag{14}$$

where $\gamma > 0$ is the adaptive gain coefficient. Note that $\dot{\tilde{\theta}} = -\dot{\hat{\theta}}$, and $\dot{z}_3 = \dot{x}_3 - \dot{x}_3^*$, the time derivative of V_3 along the system trajectory is

$$\begin{aligned}
\dot{V}_3 &= \dot{V}_2 + z_3 \dot{z}_3 + \frac{1}{\gamma} \tilde{\theta} \dot{\tilde{\theta}} \\
&= -c_1 z_1^2 - c_2 z_2^2 + z_2 \tilde{\theta} x_2 - \frac{1}{\gamma} \tilde{\theta} \dot{\hat{\theta}} \\
&\quad + z_3 \left\{ -z_2 \frac{\omega_0 V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})} + \frac{(X_d - X'_d) V_s \cos(x_1 + \delta_0)}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})} \right. \\
&\quad - \frac{(X_d - X'_d)(x_3 + E'_{q0})}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})} + \frac{H(X'_{d\Sigma} + X_{tcsc0})}{\omega_0 V_s \sin(x_1 + \delta_0)} \Big[x_2 + c_1 c_2 x_2 \\
&\quad + (\hat{\theta} + c_1 + c_2) \Big(\frac{\omega_0}{H} P_m + \theta x_2 + c_1 x_2 \Big) + \dot{\hat{\theta}} x_2 - \Big(x_1 + \frac{\omega_0}{H} P_m \\
&\quad \left. + c_1 x_2 + c_2 z_2 + \hat{\theta} x_2 \Big) ctg(x_1 + \delta_0) \Big] + \frac{K_c}{T_{d0}} u_2 - (x_3 + E'_{q0}) \right\}.
\end{aligned}$$

Design the feedback controller as

$$\begin{aligned}
u_2 = \frac{T_{d0}}{K_c} \Bigg\{ & z_2 \frac{\omega_0 V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})} - \frac{(X_d - X'_d) V_s \cos(x_1 + \delta_0)}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})} \\
& + \frac{(X_d - X'_d)(x_3 + E'_{q0})}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})} - \frac{H(X'_{d\Sigma} + X_{tcsc0})}{\omega_0 V_s \sin(x_1 + \delta_0)} \Big[c_1 c_2 x_2 + x_2 \\
& + (\hat{\theta} + c_1 + c_2) \Big(\frac{\omega_0}{H} P_m + \hat{\theta} x_2 + c_1 x_2 \Big) + \dot{\hat{\theta}} x_2 - \Big(x_1 + c_1 x_2 \\
& + \frac{\omega_0}{H} P_m + c_2 z_2 + \hat{\theta} x_2 \Big) ctg(x_1 + \delta_0) \Big] + (x_3 + E'_{q0}) - c_3 z_3 \Bigg\},
\end{aligned} \tag{15}$$

where $c_3 > 0$ is again a design constant.

Designing the parameter update law

$$\dot{\hat{\theta}} = \gamma \left[z_2 + z_3 \frac{H(X'_{d\Sigma} + X_{tcsc0})(\hat{\theta} + c_1 + c_2)}{\omega_0 V_s \sin(x_1 + \delta_0)} \right] x_2 \tag{16}$$

results in $\dot{V}_3 = \sum_{i=1}^{3} z_i \dot{z}_i = \sum_{i=1}^{3} -c_i z_i^2 < -\alpha(\|z\|)$, where $c_i (i = 1, 2, 3)$ are positive constants, α is a class-K function. Therefore, under the feedback control law (14), the zero dynamics closed-loop system

$$\begin{cases}
\dot{z}_1 = z_2 - c_1 z_1, \\
\dot{z}_2 = -c_2 z_2 - z_1 + \tilde{\theta} x_2 - \dfrac{\omega_0 V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})} z_3, \\
\dot{z}_3 = -c_3 z_3 + z_2 \dfrac{\omega_0 V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})} \\
\qquad + \dfrac{H(X'_{d\Sigma} + X_{tcsc0})(\hat{\theta} + c_1 + c_2)}{\omega_0 V_s \sin(x_1 + \delta_0)} \tilde{\theta} x_2, \\
\dot{\hat{\theta}} = \gamma \left[z_2 + z_3 \dfrac{H(X'_{d\Sigma} + X_{tcsc0})(\hat{\theta} + c_1 + c_2)}{\omega_0 V_s \sin(x_1 + \delta_0)} \right] x_2
\end{cases} \tag{17}$$

is globally asymptotically stable. In fact, $\dot{V}_3 < -\alpha(\|z\|) \leqslant 0$ implies $V_3(t) \leqslant V_3(0)$, i.e. z_1, z_2, z_3 are all bounded. Define $\Omega = -\dot{V}_3$, then $\int_0^t \Omega(\tau)\,d\tau = V_3(0) - V_3(t)$. Since $V_3(0)$ is bounded and $V_3(t)$ is nonincreasingly bounded, $\lim_{t\to\infty} \int_0^t \Omega(\tau) d\tau < \infty$ holds. In addition, since $\dot{\Omega}$ is bounded, $\lim_{t\to\infty} \Omega = 0$ holds due to Barbalat's lemma. Therefore, $z_1 \to 0, z_2 \to 0$, and $z_3 \to 0$ as $t \to \infty$. From the definitions of $x_1, x_2, x_3, x_2^*, x_3^*$, it is clear that the system state variables x_1, x_2, x_3 also converge to zero.

(2) Design of u_1 by the coordinated passivation method

Next, a stabilizing controller is designed for the whole system (6) and (7) by feedback passivation.

Let $W = V_3$. Select the storage function

$$V = W(z) + \frac{1}{2} y^2 + \frac{1}{2\rho} \tilde{\psi}^2,$$

where $\rho > 0$ is another adaptive gain coefficient, $\hat{\psi}$ stands for the estimate of ψ. Define the estimation error $\tilde{\psi} = \psi - \hat{\psi}$. Now design the control law as

$$\begin{aligned}
u_1 = u_c = \frac{T_c}{K_T} \Bigg\{ & -z_2 \frac{\omega_0 (x_3 + E'_{q0}) V_s \sin(x_1 + \delta_0)}{H(X'_{d\Sigma} + X_{tcsc0})(X'_{d\Sigma} + X_{tcsc0} + y)} \\
& + z_3 \frac{(X_d - X'_d)[x_3 + E'_{q0} + V_s \cos(x_1 + \delta_0)]}{T_{d0}(X'_{d\Sigma} + X_{tcsc0})(X'_{d\Sigma} + X_{tcsc0} + y)} - \hat{\psi} y + v \Bigg\}
\end{aligned} \tag{18}$$

and choose the parameter update law as

$$\dot{\hat{\psi}} = \rho y^2. \tag{19}$$

Then the time derivative of V along the system trajectory is

$$\begin{aligned}
\dot{V} &= \dot{W} + y\dot{y} - \frac{1}{\rho} \tilde{\psi} \dot{\hat{\psi}} \\
&= \frac{\partial W(z)}{\partial z} \dot{z}|_{y=0} - \frac{1}{T_c} y^2 + vy + y(\varepsilon_{tcsc} - \hat{\psi} y) - \frac{1}{\rho} \tilde{\psi} \dot{\hat{\psi}} \\
&\leqslant -\frac{1}{T_c} y^2 + vy + |y|[sgn(y)\varepsilon_{tcsc} - \psi |y|] + \tilde{\psi} y^2 - \frac{1}{\rho} \tilde{\psi} \dot{\hat{\psi}} \\
&\leqslant -\frac{1}{T_c} y^2 + vy,
\end{aligned}$$

which means that the system output is strictly passive. Choosing $v = -\beta y (\beta > 0)$ yields $\dot{V} < 0$, if $y \neq 0$ and $y(t) \to 0$ as $t \to \infty$.

Applying LaSalle's invariance principle immediately gives asymptotic stability of (6) and (7).

Remark 1. Under the normal operating conditions $0 < \delta < \pi$ always holds, which in turn guarantees $sin(x_1 + \delta_0) \neq 0$.

4. Simulation results

Simulations of the proposed design method have been carried out by using Matlab software. The SMIB system is from the following parameters with Wang et al. (2002): $E'_{q0} = 1.0149 p.u.$, $V_s = 1.0 p.u.$, $X_T = 0.127 p.u.$, $X_1 = X_2 = 0.2426 p.u.$, $X_d = 1.863 p.u.$, $X'_d = 0.257 p.u.$, $\omega_0 = 314.159$ rad/s, $X_{tcsc0} = 0.0 p.u.$, $T_{d0} = 6.9$ s, $T_c = 0.06$ s, $D = 5.0 p.u.$, $H = 4.0$ s. A set of responses are depicted in the following figures corresponding to arbitrary chosen nonzero initial conditions in the normal range.

First, the following operating point Pml is considered: $\delta_0 = 57.3^\circ, P_m = 0.8p.u.$

In order to show the effectiveness of the proposed adaptive coordinated passivation (ACP) controller, comparisons with the conventional direct feedback linearization (DFL) controller by Wang et al. (2002) are given under the same nonzero initial condition. The responses of the generator rotor angle δ, relative speed ω, and the reactance controlled by TCSC X_{tcsc}, under the ACP controller and the DFL controller are shown in Figs. 2–7, respectively with the same initial condition $\delta(0) = 57.6^\circ$ and $\delta(0) = 56.7^\circ$.

Fig. 2–7 show that the proposed ACP controller produces faster speed response and stronger robustness than the DFL controller.

Next, the proposed controller is tested at a different operating point Pm2: $\delta_0 = 27^\circ, P_m = 0.5p.u.$

The result is depicted in Fig. 8. Again, the ACP controller provides better transient stability.

In order to test the robustness of the ACP controller, comparisons with the DFL controller for the same uncertainties are given. Simulation results for different values of D and ε_{tcsc} are

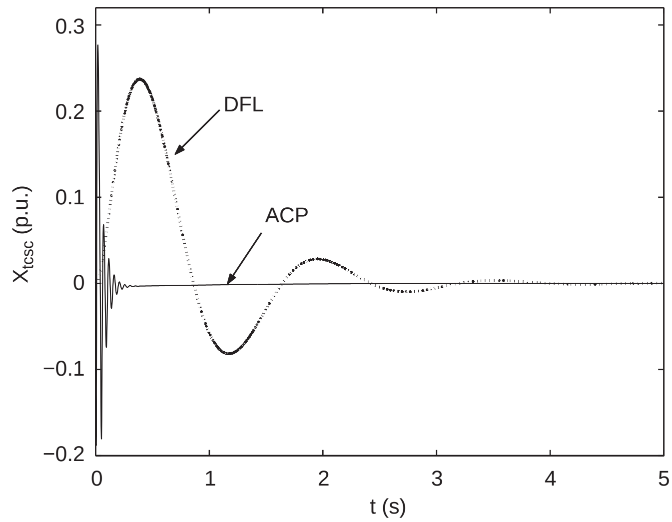

Fig. 4. Transient responses of the reactance controlled by TCSC under $\delta(0) = 57.6^\circ$.

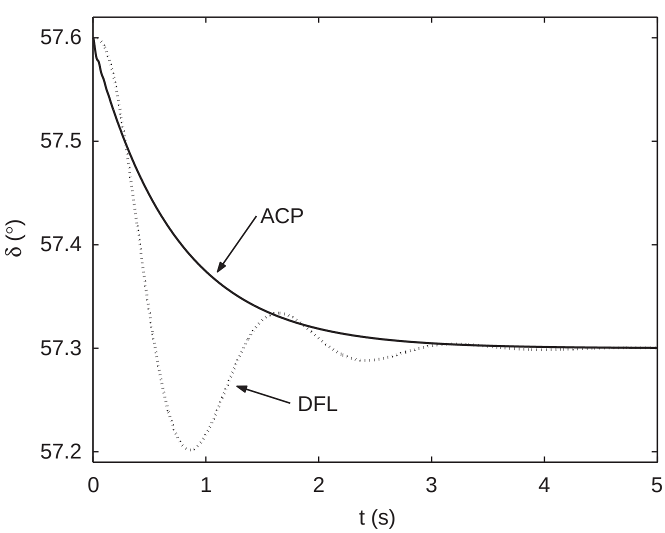

Fig. 2. Transient responses of the angle under $\delta(0) = 57.6^\circ$.

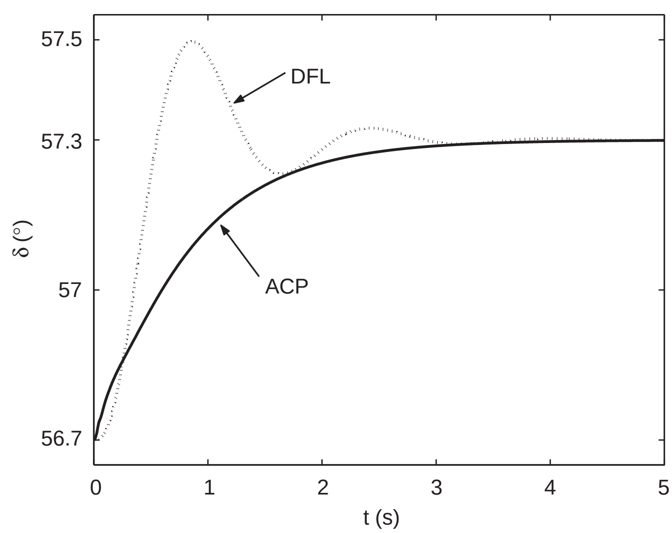

Fig. 5. Transient responses of the angle under $\delta(0) = 56.7^\circ$.

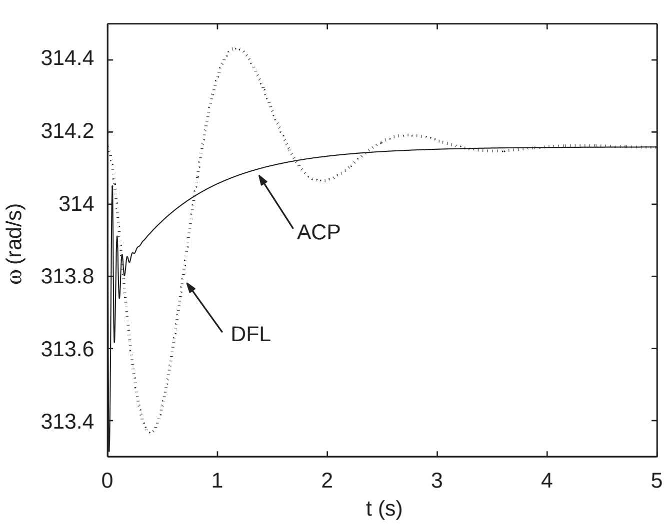

Fig. 3. Transient responses of the relative speed under $\delta(0) = 57.6^\circ$.

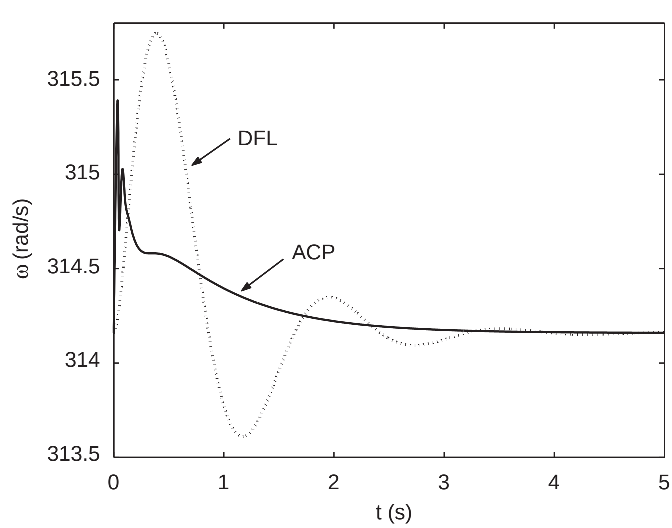

Fig. 6. Transient responses of the relative speed under $\delta(0) = 56.7^\circ$.

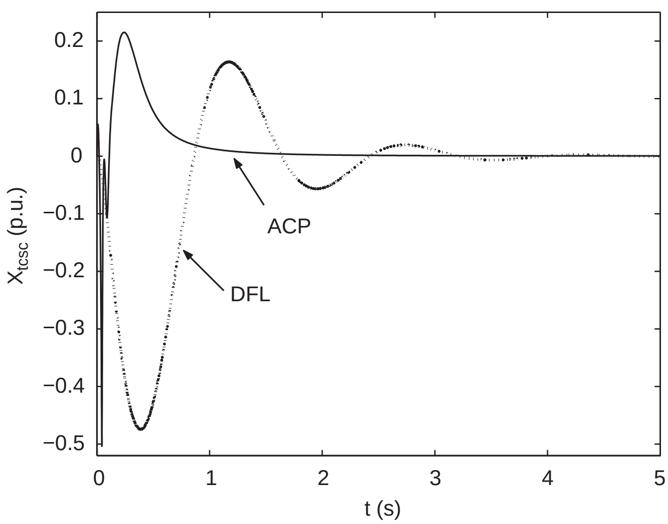

Fig. 7. Transient responses of the reactance controlled by TCSC under $\delta(0) = 56.7^{\circ}$.

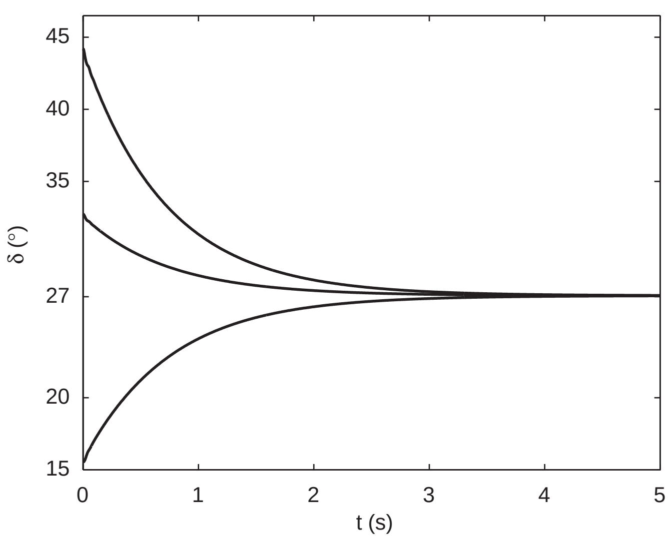

Fig. 8. Transient responses of δ under different initial conditions.

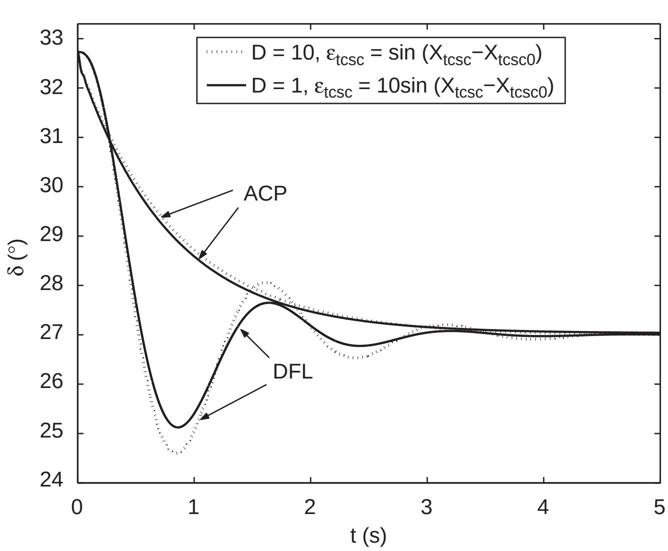

Fig. 9. Transient responses of δ with different uncertainties.

depicted in Fig. 9, which validates the strong robustness of the proposed ACP controller.

5. Conclusions

For the generator excitation and TCSC system with the damping coefficient uncertainty and the uncertain model error of TCSC, an adaptive coordinated passivation controller consisting of generator excitation and reactance modulated controllers has been designed via the coordinated passivation method to guarantee asymptotic stability of the system. Since the controller design is based on the nonlinear model of the plant dynamics without linearization, nonlinear features of the plant model are exploited to the full yielding an adaptive nonlinear controller. Robustness to system parameter variation is considerably improved because the damping coefficient and the uncertain model error of TCSC are simultaneously considered within the setting of internal uncertainties. At the controller design stage, applying coordinated passivation method divides the system into two parts, which allows to design individual controllers separately. For the first part, the design complexity is remarkably reduced. The design for the other part yields an improved design effect for the whole system. Simulations results verify the effectiveness of the proposed controller. Extension of this method to robust control design for the case of simultaneous presence of internal time-varying uncertainties and external disturbances deserves further study.

Acknowledgments

The authors gratefully acknowledge the reviewers' valuable comments and suggestions. This work was supported by the National Natural Science Foundation of China under Grants 60874024, 60574013, and 90816028, and the Specialized Research Fund for the Doctoral Program of Higher Education of China under Grant 200801450019, and the Dogus University Fund for Science.

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