Nonlinear adaptive controller design of SSSC for damping inter-area oscillation

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Abstract: This paper presents a novel nonlinear adaptive control scheme of static synchronous series compensator (SSSC) to enhance the transmission power and damping of inter-area oscillation mode for multi-machine power system.. The SSSC device was treated as a first order voltage resource and the multi-machine system was simplified into a two-machine model. Based on the exact feedback linearization theory, Lyapunov stability theory, and adaptive control law, the nonlinear adaptive controller of SSSC is derived. Unknown system parameters are considered for improving robustness. The simulation results validate the efficacy of the proposed controller.

Key-Words: power system; SSSC; inter-area oscillation; nonlinear adaptive control; Lyapnuov stability

1 Introduction

Power systems are steadily growing with ever larger capacity and formerly separated systems are interconnected to each other. The transmission and distribution systems face interconnection and increasing demands for more power with better quality and higher reliable at lower cost. Low frequency electromechanical oscillations, involving groups of synchronous machines have been observed because these lines have to be operated in the vicinity of the stability limit in case of heavily-loads. It is difficult to maintain the stability in the inter-area systems. The traditional approach for damping oscillations is through installation of power system stabilizer (PSS) [1,2], which provides damping control action through excitation system of the generators. It has been achieve good results in single machine, infinite bus (SMIB) system. However, the problem of robustness, damping of inter-area oscillation and exchange of oscillation energy over wide geographic regions still remains. The researchers have investigated the advanced control scheme and devices to enhance the stability of the expanding power system [3-7].

The recent advances in power electronics have led to the development of the flexible alternating current transmission system (FACTS)[8]. FACTS devices have been extensively used in voltage regulation, improving the transient stability and providing additional damping to power system oscillations in recent years. Among the FACTS family, thyristor controlled series capacitor (TCSC)[9], static synchronous compensator (STATCOM) [10] and static synchronous series compensator (SSSC) can be used to damp the oscillations of the power system[11].

The SSSC has been developed as an alternative to the conventional capacitor based on the series compensators [12]. SSSC is a solid-state voltage source inverter, which generates a controllable AC voltage source, and connected in series to power transmission lines in a power system. The injected voltage is in quadrature with the line current and emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines.

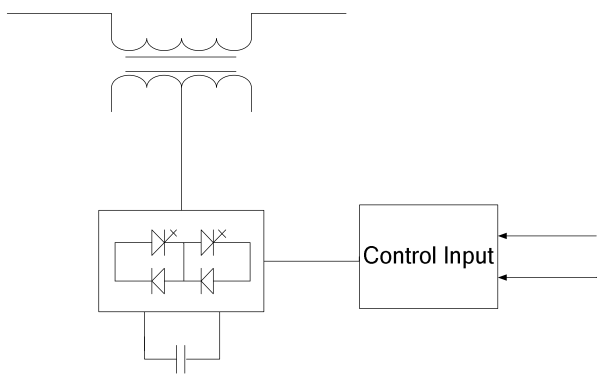

Fig. 1 Schematic diagram of SSSC

The SSSC offers excellent inherent characteristics and compensation features, stemming from the unique attributes of a solid state voltage source, for series line compensation not achievable by thyristor controlled series capacitor [13], such as: independently of the magnitude of the line current, keeping the effective X/R ratio high, excluding classical series resonance with the reactive line impedance and damping of power oscillation by modulating the series reactive compensation for the line resistance. The basic operating and performance characteristic of the SSSC are discussed by Laszlo Gyugyi , and those characterizing are compared with the more conventional compensators based on thyristor-switched or controlled series capacitors in Ref. [13-15]. By the virtue of the H_∞ optimal control theory, a robust controller for regulating DC link voltage of SSSC is designed in Ref. [15], which also presented the sub-synchronous resonance (SSR) analysis of the robust SSSC compensated power system. The action of SSSC is taken into account in rotor motion equations of power system and an adaptive nonlinear variable parameter control method for SSSC is proposed in Ref. [16]. The controllers [14-16] obtained from these approaches are simple but tend to lack robustness since, at times, they failed to produce adequate damping at other operating conditions, because they are designed to ensure desired performance under a particular operating condition. The power system operation is that following a disturbance switches to a different operating condition and some parameters of the system will be changed [17,18].

To address these problems, this paper investigates a novel adaptive scheme for designing controller of SSSC device. The SSSC installed on the connection line expect to enhance the transmission power and voltage stability in power system. The new approach treats the SSSC as a first order voltage resource and the multi-machine system was simplified into a two machine model. Based on the Lyapunov stability theory and direct feedback linearization theory, the adaptive control law is derived [19, 20]. The control law is applied to design the nonlinear controller of SSSC. Unknown system parameters are considered for improving the robust characteristic. The simulation results show the controller can improve the transient stability and the inter-area oscillation effectively.

2 Power System modeling

The SSSC can provide controllable compensating voltage over an identical and inductive range, independent of the magnitude of the line current to maintain the transmission power of the interconnected systems. This section treats the SSSC as a first order voltage resource and simplifies the multi-machine system into a two machine model as shown in Fig. 2.

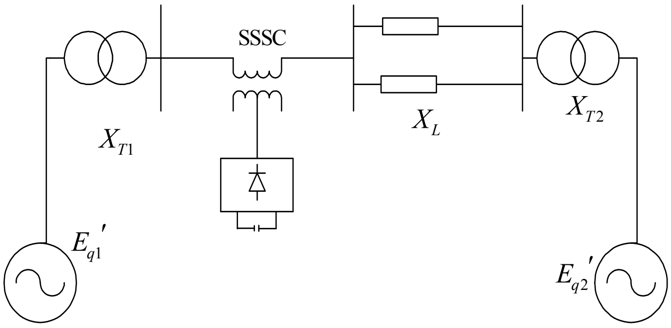

Fig. 2 The multi-machine systems with SSSC

Regardless of the function of the generator excitation, and we assume that the input mechanical power P_m is constant, the system is described as:

$$\dot{\delta}_1(t) = \omega_1(t) - \omega_0 ; \tag{1a}$$

$$\dot{\omega}_1(t) = -\frac{D_1}{2H_1}(\omega_1(t) - \omega_0) - \frac{\omega_0}{2H_1}(P_1(t) - P_{m1}), \tag{1b}$$

$$\dot{\delta}_2(t) = \omega_2(t) - \omega_0 ; \tag{2a}$$

$$\dot{\omega}_2(t) = -\frac{D_2}{2H_2}(\omega_2(t) - \omega_0) - \frac{\omega_0}{2H_2}(P_2(t) - P_{m2}), \tag{2b}$$

and SSSC dynamic equation can be expressed as:

$$\dot{U}_q = \frac{1}{T_u}(u_s - U_q). \tag{3}$$

Let us define

$\Delta\delta_i = \delta_i - \delta_0$,

$\Delta\omega_i = \omega_i - \omega_0$,

and $\Delta P_i = P_i - P_m$, here $i = 1,2$, so (1) and (2) can be written as:

$$\Delta\dot{\delta}_1(t) = \Delta\omega_1 ; \tag{4a}$$

$$\Delta\dot{\omega}_1 = -\frac{D}{2H}\Delta\omega_1 - \frac{\omega_0}{2H}\Delta P_1. \tag{4b}$$

$$\Delta\dot{\delta}_2(t) = \Delta\omega_2 ; \tag{5a}$$

$$\Delta\dot{\omega}_2 = -\frac{D}{2H}\Delta\omega_2 - \frac{\omega_0}{2H}\Delta P_2. \tag{5b}$$

According to the analysis in Ref. [12], the transmission power P_L can be express as follows:

$$P_L = \frac{V^2}{X_\Sigma}\sin\delta_{12} + \frac{V}{X_\Sigma}U_q\cos(\delta_{12}/2), \quad (6)$$

where $\delta_{12} = \delta_1 - \delta_2$, $X_\Sigma = X_{1\Sigma} + X_{2\Sigma} + X_{sssc}$, $-1 \le U_q \le 1$. Here, the bus voltage V is assumed to be constant, by differentiating (6),

$$\Delta\dot{P}_L = \frac{V}{X_\Sigma}\Delta\omega_{12}(V\cos\delta_{12} + \frac{U_q\sin(\delta_{12}/2)}{2})$$

$$+\frac{V}{X_\Sigma}\dot{U}_q\cos(\delta_{12}/2), \quad (7)$$

Then we assume that $D_1/H_1 = D_2/H_2 = D/H$, and define $\Delta\delta_{12} = \Delta\delta_1 - \Delta\delta_2$, $\Delta\omega_{12} = \Delta\omega_1 - \Delta\omega_2$, $\Delta P_L = \Delta P_1 - \Delta P_2$, so (4) 、 (5) and (7) can be expressed as:

$$\Delta\dot{\delta}_{12} = \Delta\omega_{12}; \quad (8a)$$

$$\Delta\dot{\omega}_{12} = -\frac{D}{2H}\Delta\omega_{12} - \frac{\omega_0}{2H}\Delta P_L; \quad (8b)$$

$$\Delta\dot{P}_L = \frac{V}{X_\Sigma}\Delta\omega_{12}(V\cos\delta_{12} - \frac{U_q\sin(\delta_{12}/2)}{2})$$

$$-\frac{V}{X_\Sigma T_u}\cos(\delta/2)U_q + \frac{V}{X_\Sigma T_u}\cos(\delta/2)u_s . \quad (8c)$$

3 Nonlinear adaptive control[19,20]

3.1 DFL theory and controller design

Consider a class of nonlinear systems as follows:

$$\dot{x} = f(x) + g(x)u; \quad (9a)$$

$$y = h(x), \quad (9b)$$

where $x = [x_1, x_2, \cdots x_n]^T$, $u \in \Re$, and $y \in \Re$ are the n-dimensional state vector, system input and system output, respectively. f and g are sufficiently smooth vector fields.

The system (9) is assumed to have the relative degree r, we choose the suitable coordinates：

$$Z = (\xi^T, \eta^T)^T, \quad (10)$$

where

$$\xi^T = [(h(x), L_f(h(x)), \cdots, L_f^{r-1}(h(x))]^T \ ;$$

$$\eta^T = [\varphi_{r+1}(x), \cdots, \varphi_n(x)]^T,$$

and satisfy $L_g(\varphi_i(x)) = 0$, $i = r+1, \cdots n$, Here L represent the Lie derivative, such that the original system (9) can be transformed into the following normal form:

$$\dot{z}_i = z_{i+1}, \quad , i = 1, \cdots r-1, \quad (11a)$$

$$\dot{z}_r = a(\xi,\eta) + b(\xi,\eta)u, \quad (11b)$$

$$\dot{z}_j = q(\xi,\eta), \quad \xi \in \Re^r, \eta \in \Re^{n-r}, \ j = r+1, \cdots n, \quad (11c)$$

and the output y can be transformed into:

$$y = z_1, \quad (12)$$

here we define a new input $v_f = a(\xi,\eta) + b(\xi,\eta)u$, and $b(\xi,\eta) \ne 0$, so

$$u = \frac{1}{b(\xi,\eta)}(-a(\xi,\eta) + v_f). \quad (13)$$

The former r equations can be expressed as:

$$\dot{\xi} = A\xi + Bv_f, \quad (14)$$

the latter $n-r$ equations of (11) can be expressed as:

$$\dot{\eta} = A_0\xi + B_0\eta, \quad (15)$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \cdots & \cdots & 1 \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix}_{r\times r},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \cdots \\ 1 \end{bmatrix}_{r\times 1}.$$

Here we choose the new control law as follows:

$$v_f = -(a_1\xi_1 + a_2\xi_2 + \cdots + a_r\xi_r)$$

$$+(a_{r+1}\eta_1 + a_{r+2}\eta_2 + \cdots + a_n\eta_{n-r})$$

$$\equiv -(a_1\xi_1 + a_2\xi_2 + \cdots + a_r\xi_r) + A_\eta\eta \quad (16)$$

then the closed-loop system can be expressed as:

$$\dot{X} = A_C X \quad (17)$$

where

$$X = [\eta^T, \xi^T]^T;$$

$$A_c = \begin{bmatrix} A_0 & B_0 \\ BA_\eta & C \end{bmatrix};$$

$$\mathrm{C}=\begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \cdots & \cdots & 1 \\ -\mathrm{a}_1 & -\mathrm{a}_2 & \cdots & \cdots & -\mathrm{a}_\mathrm{r} \end{bmatrix}_{r\times r}, \quad (18)$$

and choose the suitable parameters of $a_i \ (i = 1, 2, \cdots r)$ and the vector A_η makes that A_c is an asymptotically stable matrix and the SSSC controller is derived.

3.2 Adaptive nonlinear controller design

The nonlinear controller is derived based on the exact parameters known in advance. However, in practical applications, there are existing unknown parameters or uncertainty. In this paper, (13) is assumed to have some unknown parameters but satisfy the following condition, there exist known functions $\psi_1 : \Re^n \times \Re^l \to \Re^{l1}$, $\psi_2 : \Re^n \times \Re^m \to \Re^{m1}$, and such that

$$a(x) = \Theta_1^T \psi_1(x) \ ;$$

$$b(x) = \Theta_2^T \psi_2(x) ,$$

where $\Theta_1 \in \Re^{l1}$ and $\Theta_2 \in \Re^{m1}$ denote unknown parameters.

In order to achieve the control aims, a nonlinear controller is derived as

$$u = \frac{1}{\hat{b}(\xi,\eta)}(-\hat{a}(\xi,\eta) + v_f)$$

$$= \frac{1}{\hat{\Theta}_2^T \psi_2(x)}(-\hat{\Theta}_1^T \psi_1(x) + v_f) \quad (19)$$

with

$$v_f = -(a_1\xi_1 + a_2\xi_2 + \cdots + a_r\xi_r) + A_\eta\eta , \quad (20)$$

where $\hat{\Theta}_1$ and $\hat{\Theta}_2$ represent the estimations of Θ_1 and Θ_2 . The estimated parameters are updated according to a certain adaptation algorithm.

According to control law (18), the closed loop system can be expressed as

$$\dot{X} = A_c X + B_c((\Theta_1 - \hat{\Theta}_1)^T \psi_1(x) + (\Theta_2 - \hat{\Theta}_2)^T \psi_2(x)u) ,(21)$$

where

$$B_c = [\underbrace{0,\cdots,0}_{n-1},1]^T .$$

In order to derive the parameter updating algorithm, we choose a candidate Lyapunov function as

$$W(X,\Theta_1,\hat{\Theta}_1,\Theta_2,\hat{\Theta}_2) = X^T P_c X + (\Theta_1 - \hat{\Theta}_1)^T$$

$$\times\Omega_1^{-1}(\Theta_1 - \hat{\Theta}_1) + (\Theta_2 - \hat{\Theta}_2)^T \Omega_2^{-1}(\Theta_2 - \hat{\Theta}_2), \quad (22)$$

where Ω_1 and Ω_2 are positive definite matrices, and P_c is also a positive definite matrix which is a solution of the following equation

$$A_c^T P_c + P_c A_c = -I . \quad (23)$$

Differentiating Lyapunov function (21) and substituting into (20),

$$\dot{W} = -X^T X + 2X^T P_c B_c (\Theta_1 - \hat{\Theta}_1)^T \psi_1 + 2X^T P_c B_c$$

$$\times(\Theta_2 - \hat{\Theta}_2)^T \psi_2 u - 2(\Theta_1 - \hat{\Theta}_1)^T \Omega_1^{-1}\dot{\hat{\Theta}}_1$$

$$-2(\Theta_2 - \hat{\Theta}_2)^T \Omega_2^{-1}\dot{\hat{\Theta}}_2 . \quad (24)$$

Updating law:

$$\dot{\hat{\Theta}}_1 = \Omega_1 X^T P_c B_c \psi_1 ; \quad (25)$$

$$\dot{\hat{\Theta}}_2 = \Omega_2 X^T P_c B_c \psi_1 u , \quad (26)$$

substituting (24) and (25) into (23), we have

$$\dot{W} = -X^T X \le 0 . \quad (27)$$

Since W is a positive define and $\dot{W}$ is negative semi-definite, we can conclude that system (21) at the equilibrium point $X = 0$, $\Theta_1 = \hat{\Theta}_1$; $\Theta_2 = \hat{\Theta}_2$ is uniformly stable.

4 SSSC adaptive controller design

Following the discussion above, the inter-area dynamic system can be expressed as:

$x = [\Delta\delta_{12}, \Delta\omega_{12}, \Delta P_L]^T$;

$$f(x) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} ; \; g(x) = \begin{bmatrix} 0 \\ 0 \\ \frac{V}{X_\Sigma T_u}\cos(\delta/2) \end{bmatrix} ,$$

where

$$f_1 = \Delta\omega_{12} ;$$

$$f_2 = -\frac{D}{2H}\Delta\omega_{12} - \frac{\omega_0}{2H}\Delta P_L ;$$

$$f_3 = \frac{V^2}{X_\Sigma}\cos\delta_{12}\Delta\omega_{12} - \frac{V}{2X_\Sigma}U_q \sin(\delta_{12}/2)\Delta\omega_{12}$$

$$-\frac{V}{X_\Sigma T_u}\cos(\delta/2)U_q .$$

In the control design, we use the SSSC to damp the oscillation and keep the bus voltage, so we define the output

$$y = h(x) = x_3 ,$$

it can be easily found that $L_g h(x) = V / X_\Sigma T_u \cos(\delta/2)$, here $V / X_L T_u \ne 0$, and $0^\circ < \delta < 180^\circ$. Therefore, the relative degree is 1. We assume the new control law $v_f = L_f h(x) + L_g h(x) u$, system (8) can be expressed as:

$$\Delta\dot{P}_L = L_f h(x) + L_g h(x) u ; \quad (28a)$$

$$\Delta\dot{\delta}_{12} = \Delta\omega_{12} ; \quad (28b)$$

$$\Delta\dot{\omega}_{12} = -\frac{D}{2H}\Delta\omega_{12} - \frac{\omega_0}{2H}\Delta P_L , \quad (28c)$$

so

$$\Delta\dot{P}_L = v_f \quad (29)$$

with

$$v_f = -k_{\Delta\delta}\Delta\delta_{12} - k_{\Delta\omega}\Delta\omega_{12} - k_{\Delta P}\Delta P_L . \quad (30)$$

The parameters $k_{\Delta\delta}$, $k_{\Delta\omega}$ and $k_{\Delta P}$ are chosen such that the following matrix

$$A_c = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{D}{2H} & -\frac{\omega_0}{2H} \\ -k_{\Delta\delta} & -k_{\Delta\omega} & -k_{\Delta P} \end{bmatrix}$$

is asymptotically stable.

The system as illustrated in Fig 2., those parameters D , H , T_u and δ_{12} are unknown, the functions $L_f h(x)$ and $L_g h(x)$ can be rewritten in the parameter associated with known nonlinear functions, they can be expressed as:

$$L_f h(x) = \frac{V^2}{X_\Sigma}\cos\delta_{12}\Delta\omega_{12} - \frac{V}{2X_\Sigma}U_q \sin(\delta_{12}/2)\Delta\omega_{12}$$

$$-\frac{V}{X_\Sigma T_u}\cos(\delta/2)U_q$$

$$= \theta_{11}V^2\Delta\omega_{12} - \theta_{12}VU_q\Delta\omega_{12} - \theta_{13}VU_q ; \quad (31)$$

$$L_g h(x) = \frac{V}{X_\Sigma T_u}\cos(\delta/2) = \theta_{21}V . \quad (32)$$

An adaptive control law with the estimated parameters is designed as

$$u_s = \frac{1}{\hat{\theta}_{21}V}[v_f - \hat{\theta}_{11}V^2\Delta\omega_{12} + \hat{\theta}_{12}VU_q\Delta\omega_{12} + \hat{\theta}_{13}VU_q], \quad (33)$$

and the parameter updating law (24) and (25),

$$\dot{\hat{\theta}}_{11} = (p_{13}\Delta\delta_{12} + p_{23}\Delta\omega_{12} + p_{33}\Delta P_L)V^2\Delta\omega_{12}; \quad (34a)$$

$$\dot{\hat{\theta}}_{12} = (p_{13}\Delta\delta_{12} + p_{23}\Delta\omega_{12} + p_{33}\Delta P_L)VU_q\Delta\omega_{12}; \quad (34b)$$

$$\dot{\hat{\theta}}_{13} = (p_{13}\Delta\delta_{12} + p_{23}\Delta\omega_{12} + p_{33}\Delta P_L)VU_q; \quad (34c)$$

$$\dot{\hat{\theta}}_{21} = (p_{13}\Delta\delta_{12} + p_{23}\Delta\omega_{12} + p_{33}\Delta P_L)Vu_s, \quad (34d)$$

where $[p_{13}, p_{23}, p_{33}]^T$ is the third column vector of P_c which is the solution of the equation (23).

5 Simulations and results

To test the effectiveness of the proposed nonlinear adaptive controller for damping and transient stability enhancement, two detailed nonlinear fault simulation studies have been carried out using Matlab platform in this section. The testing system consists of 2 generators, with a SSSC installed on the tie line, as shown in Fig. 2. As we mentioned before, the SSSC is treated as a first order voltage resource and the multi-machine system is simplified into a two machine model. This small system retains some properties of interarea power system dynamics, regarding electromechanical oscillations. Unknown system parameters are considered for improving robustness. The parameters of the system list in Tab. 1 and Tab. 2, and proposed controller derived from the nonlinear adaptive theory lists in Tab. 3.

Tab. 1 Generator parameters

	D	H	x_d	x_q	x'_d
Gen1	6.5	4.0s	2	1.91	0.244
	D	H	x_d	x_q	x'_d
Gen2	3.25	2	1.6	1.53	0.21

Tab. 2 Line and transformer parameters

	X
Tran1	0.15
Tran2	0.13
Line1	0.1
Line2	0.1

Tab. 3 The parameters of the controller

	$k_{\Delta\delta}$	$k_{\Delta\omega}$	$k_{\Delta P}$
value	-10	-5	-10

Case 1: A three phase short circuit on the midpoint of the tie line occurs at t=1s, the fault was cleared and the transmission line was restored at t=1.1s. The active power transmitted by the tie line is 450MW. The active power response and rotor angle response are shown in Fig. 3 and Fig. 4. From Fig. 5 to Fig. 8, the variations of the unknown parameters which are derived according to the updating law (33) are shown as well. As we all known, linear optimal control theory used in the design of controller is referred in many research works. Therefore, the performance of the conventional controller is compared with adaptive controller.

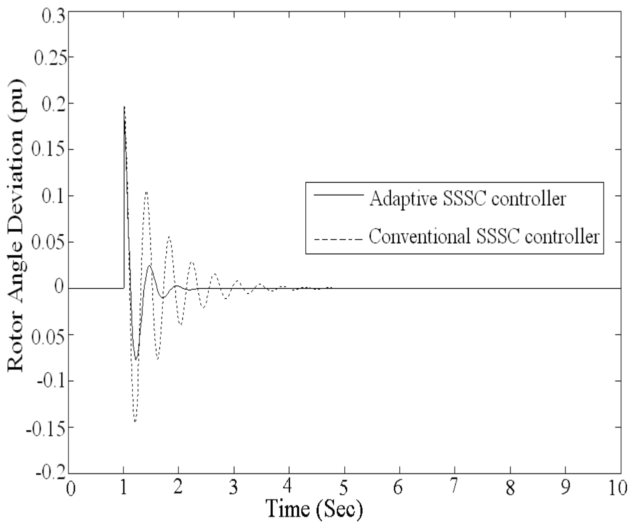

Fig. 3 Rotor angle response for 3-phase 5-cycle fault

('—': adaptive controller; '- -':conventional controller)

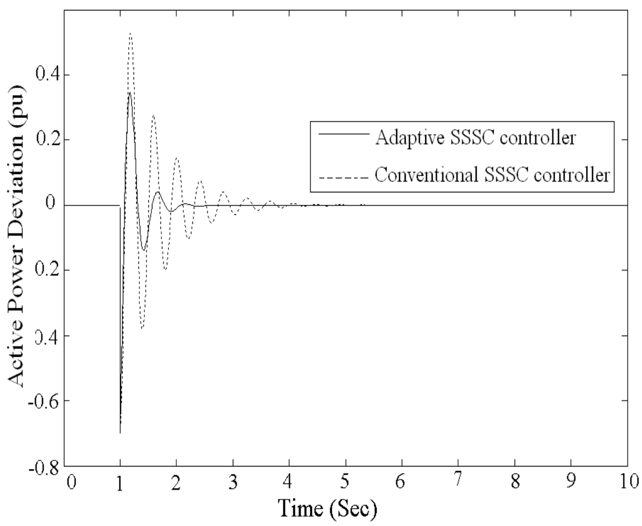

Fig. 4 Tie-line active power response for 3-phase 5-cycle fault

('—': adaptive controller; '- -':conventional controller)

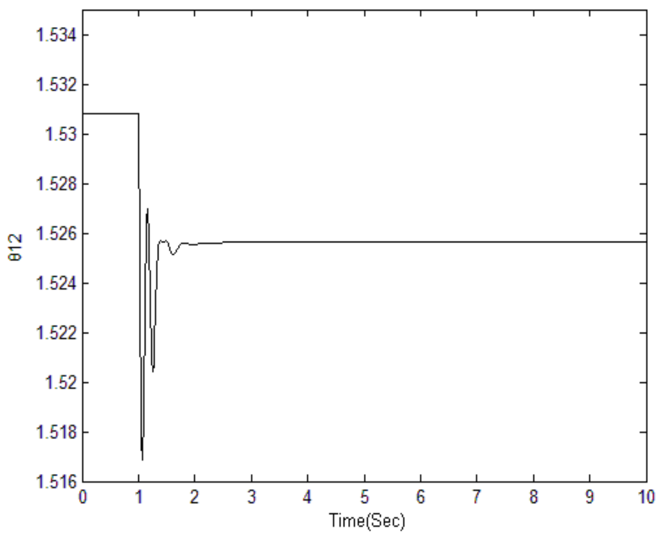

Fig. 6 The estimated parameter θ_{12} response for 3-phase 5-cycle fault

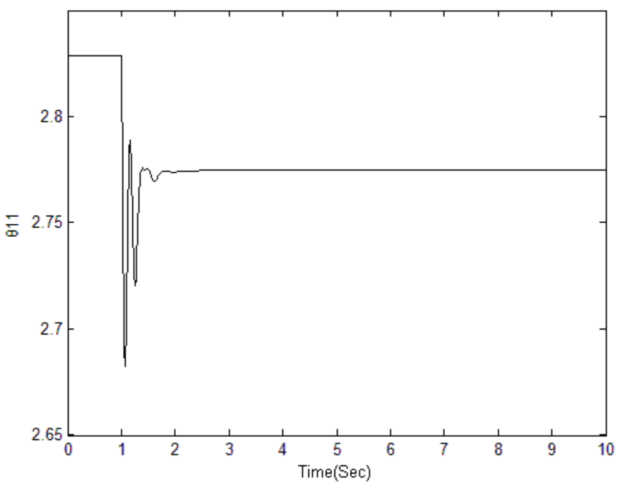

Fig. 5 The estimated parameter θ_{11} response for 3-phase 5-cycle fault

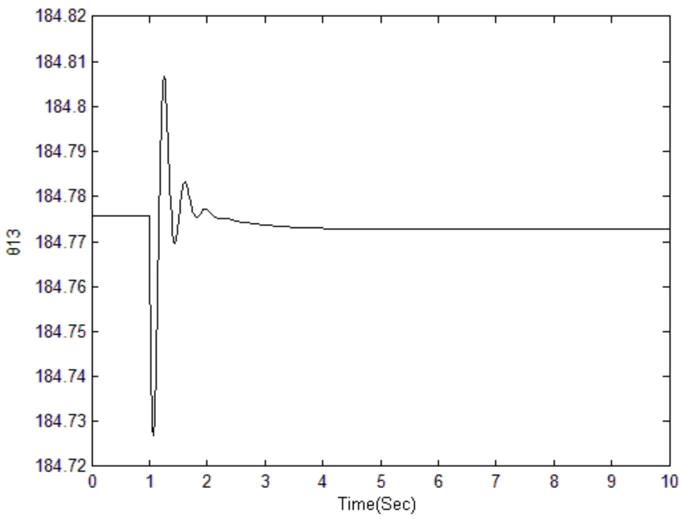

Fig. 7 The estimated parameter θ_{13} response for 3-phase 5-cycle fault

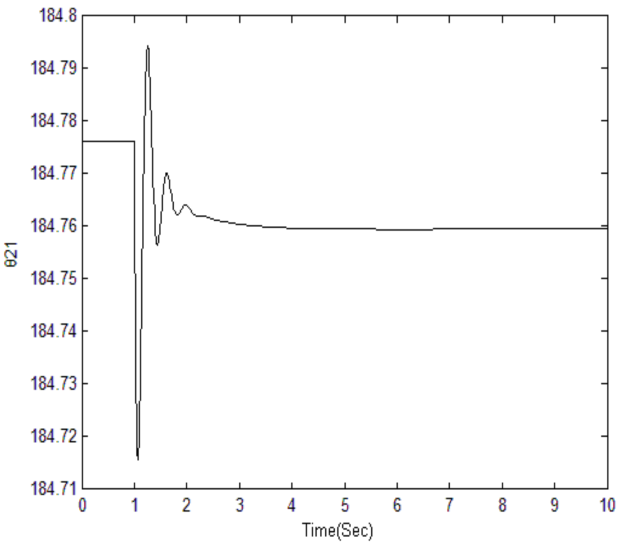

Fig. 8 The estimated parameter θ_{21} response for 3-phase 5-cycle fault

The rotor angle and active power deviations as shown in Fig. 3 and Fig. 4 prove the great performance of the adaptive controller. The interarea active power oscillation is greatly suppressed by the controller. From these simulation results, it is observed that the performance of the adaptive controller is better than the conventional controller. In addition, the controller's performance is satisfactory for the unknown parameters and the large range of operating points.

Case 2: A three phase short circuit at the end of generator bus of occurs at t=1s, the fault was cleared and the transmission line was restored at t=1.1s. The active power transmitted by the tie line is 600MW. The active power response and rotor angle response are shown in Fig. 9 and Fig. 10. As it is not possible to include all the results due to the space limitations, only the rotor angle deviations and active power deviations results are shown below.

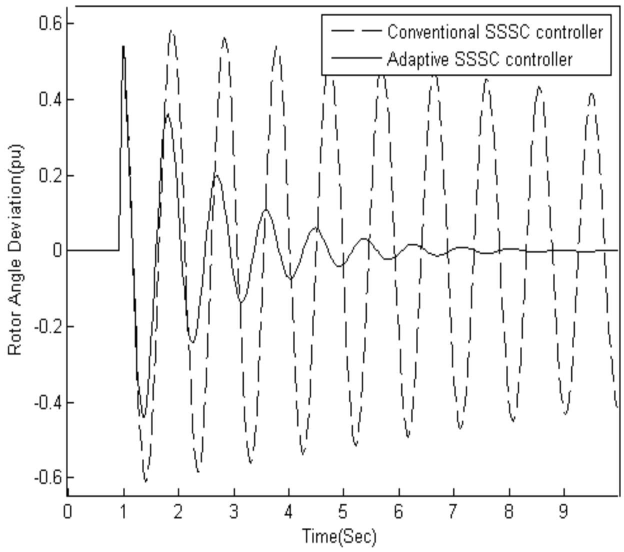

Fig. 9 Rotor angle response for 3-phase 5-cycle fault

('—': adaptive controller; '- -':conventional controller)

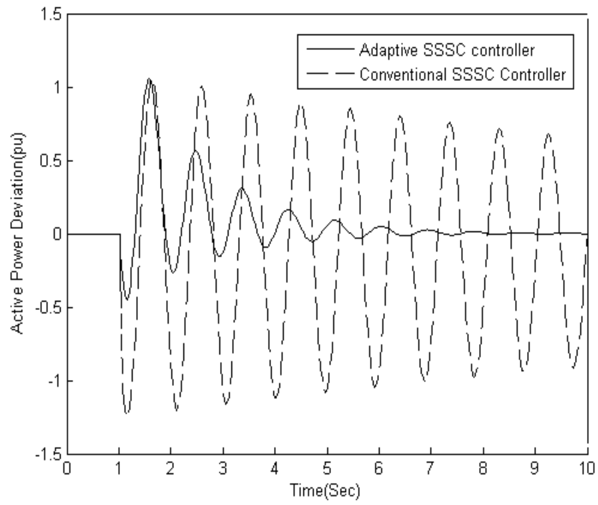

Fig. 10 Tie-line active power response for 3-phase 5-cycle fault

('—': adaptive controller; '- -':conventional controller)

For a rigorous evaluation of the performance of the designed damping, fault simulation under the heavy load condition(133% loading) is also studied in this section. The results corresponding to this case are shown in Fig. 9 and Fig. 10. These figures prove the effectiveness of the proposed controller for improving the system damping. The rotor angle and active power deviations prove the controller is satisfactory for the large range of operating points, when the conventional controller is can't meet the security level needed by the power system.

6 Conclusions

This paper presents a nonlinear adaptive controller for damping the inter-area power oscillation and enhancing transient stability in power systems. Based on the Lyapunov stability theory and exact feedback linearization theory, the nonlinear adaptive control law is derived.

The approach treats the SSSC as a first order voltage resource and the multi-machine system was simplified into a two machine model. Unknown system parameters are considered for improving robustness. The simulation results validate the proposed controller, which can greatly improve the transient stability and the inter-area oscillation damping. The simulation results prove the simplified model is sufficient to project application as well. Although the nonlinear adaptive design scheme is designed for SSSC, the approach is applicable to the design of the other FACTS damping controllers.

References:

[1] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.

[2] H.A.M. Moussa, and Y.N. Yu, Optimal power system stabilization through excitation and/or governor control, *IEEE Trans. Power Appar. Syst*. PAS-91, 1972, pp. 1166–1174.

[3] R.J. Fleming, M.A. Mohan, and K. Parvatisam, Selection of parameters of stabilizers in multi-machine power systems, I*EEE Trans. Power Appar. Syst*. PAS-100, 1981, pp. 2329–2333.

[4] S. Panda, N.P. Padhy, and R.N. Patel, Robust coordinated design of PSS and TCSC using PSO technique for power system stability enhancement, *J. Elect. Systs.* vol 3, 2007, pp. 109–123.

[5] F.X. Wu, H. Wu, Z.X. Han, and D.Q. Gan, Validation of power system nonlinear modal analysis methods, *Electric Power Syst. Res.*, vol. 77,2007, pp. 1418–1424

[6] J.V. Milanovic, Damping of the low-frequency oscillations of the generator: dynamic interactions and the effectiveness of the controllers, *IEE Proc. Gen. Transm. Distrib.*, pp. 2002, 753–760.

[7] Y. Wang, H. Chen, and R. Zhou, A nonlinear controller design for SVC to improve power system voltage stability, *Elect. Power Energy Systs.*, vol. 22, 2000, pp. 463-470.

[8] N.G. Hingorani, and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems,* IEEE Press, New York, 2000.

[9] Q. Liu, V. Vittal, and N. Elia, LPV supplementary damping controller design for a thyristor controlled series capacitor (TCSC) device, *IEEE Trans. Power Syst.*, vol.21, 2006, pp. 1242-1249.

[10] S. Panda, and N.P. Padhy, Optimal location and controller design of STATCOM for power system stability improvement using PSO, *J. Franklin Inst.,* Vol. 345, pp. 2008, 166–181 .

[11] M.S. Castro, H.M. Ayres, V.F. da Costa, and C.L.P. da Silva, Impacts of the SSSC control modes on small-signal transient stability of a power system, *Elect. Power Syst. Res.,* vol. 77, 2007, pp. 1–9.

[12] G. Laszlo, D.S. Colin, and K.S. Kalyan, Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines, *IEEE Trans. Power Dev.,* vol. 12, 1997, pp. 406-417.

[13] K.S. Kalyan, SSSC-static synchronous series compensator theory, model, and applications, *IEEE Trans. Power Dev.* 13 vol. 13, 1998, pp. 241-246.

[14] K.L. Sunil, and G. Arindam, Modeling and control design of a static synchronous series compensator, *IEEE Trans. Power Dev.* vol. 14, 1999, pp. 1448-1453.

[15] G.N. Pillai, G.S. Arindam, and A. Joshi, Robust control of SSSC to improve torsional damping, *IEEE-winter meeting-2001*, pp. 1115-1120.

[16] J.J. Zhao, J.B. Guo, and X.X. Zhou, Design of

transient stability controller of Static Synchronous Series Compensator based on variable parameters nonlinear control, *Power Syst. Tech*. vol. 29, 2005, pp. 14-19.

[17] Q. Lu, and Y.Z. Sun, *Electric Power System Nonlinear Control*, China Science Press, 1992.

[18] W. Yan, W.S. Wu, and Z.M. Hua, Direct feedback linearization method for designing SSSC nonlinear control law, *Proc. CSEE* vol 23, 2003, pp. 65-68.

[19] T.L. Liao, Design of an adaptive nonlinear controller to improve stabilization of a power system, *Int. J. Electr. Power Energy Syst.,* vol 21, 1999, pp. 433-441.

[20] J. Wang, C. Chen, and H. Wu. H, Theory and method for parametric adaptive control design of multi-machine power systems, *Proc. CSEE, vol 22,* 2002, pp. 5-9.