Nonlinear Backstepping Design of Robust Adaptive Modulation Controller for TCSC

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***Abstract*—In this paper, a nonlinear robust adaptive modulation controller (RAMC) for thyristor controlled series capacitor (TCSC) in interconnected power systems is developed. The controller drives centers of inertial of different areas (COIs) to maintain synchronous operation based on the dynamic COI signals obtained from the wide area measurement system (WAMS). The overall system model is established using COI coordinates. The control law of the RAMC is then derived using the backstepping method, and not only is it adaptive to unknown parameters such as damping coefficients of generators, but also robust to uncertain disturbances and model errors. Computer simulation results illustrate that the proposed controllers can improve system dynamic more effectively when compared with conventional linear controllers.**

***Index Terms*—TCSC, robust adaptive modulation controller, backstepping, WAMS, COI**

I. Introduction

To achieve optimal utilization of global resources and reliable operation, modern power systems tend to be interconnected. As a result, many ac/dc tie lines are built for transferring large amounts of electric power over geographically dispersed areas especially from generation centers to load centers over long distances. As a result, many challenging issues arise in modern large-scale interconnected power systems. For example, low frequency power oscillations may occur on the heavily loaded long distance ac tie lines because of the lack of sufficient damping torque. PSS is widely used to provide damping torque and improve system dynamics currently, but PSS design is usually based on linear control theory and may have poor performance in situations where the operation point is far from the design point; or where it is required that the system nonlinearities be taken into consideration. In recent years, FACTS devices have been widely employed in large-scale interconnected power systems and provide very good controllability to improve global system dynamics. Hence, research and development on control strategies of FACTS devices control has become a significant task. Thyristor controlled series capacitor (TCSC) is a type of FACT device which has powerful capability in damping power oscillations, scheduling power flow, reducing unsymmetrical components and mitigating subsynchronous resonance [1,2,3]. Previous work on TCSC control is mainly based on linear control theory and is inadequate for coping with the requirements of modern power systems. In this paper, the nonlinear robust adaptive modulation control of the TCSC will be designed to damp the inter-area power oscillations and enhance the synchronous stability of interconnected power systems.

It is well known that a nonlinear power system can be transformed into a linear one based on differential geometry and feedback linearization [4,5]. Usually, such transformation is based on the exact mathematic model of the studied power system, while system uncertainties and model errors, system disturbances and varying parameters are neglected. However, it is sometimes required for model errors and slowly time-varying system parameter to be taken into consideration, and in such situations robust adaptive control which explicitly considers system model uncertainties and is adapt to time-varying system parameters should be used.

Research on control strategies for TCSCs can be traced back long before. Literature shows that TCSC has been successfully used to improve power system transient stability in interconnected multi-machine power systems. A conventional method is to use an extra signal from the power swing damping loop, together with a first-order output loop and a limitation loop. This extra signal is usually based on some frequency domain method and the eigenvalue analysis of a linearized power system model. A controller targeted at a specific operation point may not work well at other operation points, and may also not work well in the situation that there are large disturbances. Direct feedback linearization (DFL) can also applied to a multi-machine power system [6]. However, the drawback in using this method is that precise information regarding the system model is required, which may not be the case for in many power systems. Moreover, this method does not guarantee good robustness. Ref [7] introduces PCH models of FACTS with adaptive L2 gain control. However, its implementation is too difficult.

Backstepping is a good technology which is based on nonlinear theory that combines the Lyapunov function with feedback control. However, the controller design in Ref [8,9]

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is only appropriate for a single machine infinite bus (SMIB) power system, and does not consider the unknown damping parameter. A new controller based on the backstepping method is proposed for the TCSC in this paper. It should also be noted that with the rapid development of WAMS technology, it is possible to design control strategies using global signals from WAMS, such as the system center of inertia (COI) trajectory. Therefore, in designing our controller, system global signals from WASMS are utilized. Using COI signals has several obvious advantages of which one is that our controller doesn't need detailed dynamic information of the considered inter-connected systems, and is also insensitive to system topological complexity. With the global information of dynamic COI, the performance of the designed controller should be superior to that of conventional controllers using local signals. Another advantage is that our controller only concerns COI information, and the need for coordination between controllers in different areas is naturally eliminated.

II. Mathematical models of interconnected AC system

A power system with TCSC is studied here, which is divided into two areas according to the position of TCSC, namely area A and area B respectively. The two areas are interconnected by two parallel ac lines with TCSC installing in one line and a constant capacitor in the other, see Fig. 1.

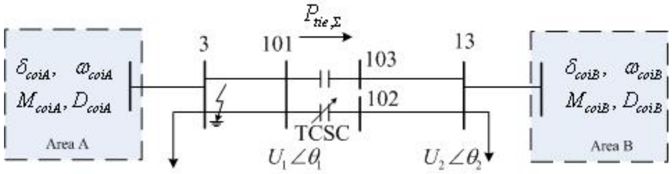


Fig. 1 Equivalent circuit of multi-machine system with TCSC

There are N_A generators in area A and the rotor dynamics of i^{th} generator in area A will be :

$$\begin{cases}\dot{\delta}_{Ai}=\omega_{Ai}-\omega_0\\ M_{Ai}\dot{\omega}_{Ai}=\omega_0(P_{mAi}-P_{eAi})-D_{Ai}(\omega_{Ai}-\omega_0)\end{cases}\quad i=1,\cdots,N_A \quad (1)$$

where δ_{Ai}, ω_{Ai}, P_{mAi}, P_{eAi}, M_{Ai}, D_{Ai} are the rotor angle, the rotor speed, the mechanical power, the electrical power, the rotor inertia time constant and damping coefficient of i^{th} generator respectively. $\omega_0=2\pi f_0$ ($f_0=50$ Hz) is the base value of rotor speed. All variables are in p.u except that ω_i and ω_0 are in rad/s and t is in second.

The COI's angle and speed of area A are

$$\begin{cases}\delta_{coiA}=\dfrac{1}{M_{coiA}}\sum_{i=1}^{N_A}M_{Ai}\delta_{Ai}\\ \omega_{coiA}=\dfrac{1}{M_{coiA}}\sum_{i=1}^{N_A}M_{Ai}\omega_{Ai}\end{cases}\quad (2)$$

From (1) and (2), we could get the COI's dynamics

$$\begin{cases}\dot{\delta}_{coiA}=\omega_{coiA}-\omega_0\\ \dot{\omega}_{coiA}=\dfrac{1}{M_{coiA}}[\omega_0(P_{mA}-P_{eA})-D_{coiA}(\omega_{coiA}-\omega_0)]\end{cases}\quad (3)$$

where $P_{mA}=\sum_{i=1}^{N_A}P_{mAi}$, $P_{eA}=\sum_{i=1}^{N_A}P_{eAi}=P_{LA}+P_{LossA}+P_{tie,\Sigma}$, P_{LA}, P_{LossA} are the total loads and loss in area A respectively, $P_{tie,\Sigma}$ is the extraction power from area A, which is equal to the power flow on the parallel tie lines.

The COI's dynamic equations similar to Eqns. (1) – (3) can also be developed for area B.

TCSC is described as one order closed loop model with boundary output, which could picture the ability of changing its reactance rapidly and smoothly, see Fig.2.

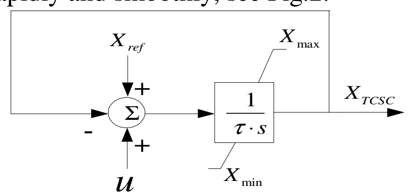


Fig. 2. 1st order dynamic model of TCSC

In Fig. 2, X_{ref} is the reference value of reactance of TCSC, u is the modulation signal, and τ is time constant. In this paper, the output of TCSC is limited between [-0.3 X , 0.3 X], here X is the total reactance of one of the parallel tie line.

Based on the above equations and analysis, the whole dynamic models of interconnected system in COI coordinates are

$$\begin{cases}\dot{\delta}_{coiA}-\dot{\delta}_{coiB}=\omega_{coiA}-\omega_{coiB}\\ \dot{\omega}_{coiA}-\dot{\omega}_{coiB}=\left[\dfrac{\omega_0}{M_{coiA}}(P_{mA}-P_{LA}-P_{LossA})-\dfrac{\omega_0}{M_{coiB}}(P_{mB}-P_{LB}-P_{LossB})\right]\\ \qquad -\left[\dfrac{D_{coiA}}{M_{coiA}}(\omega_{coiA}-\omega_0)-\dfrac{D_{coiB}}{M_{coiB}}(\omega_{coiB}-\omega_0)\right]\\ \qquad -\left(\dfrac{\omega_0}{M_{coiA}}+\dfrac{\omega_0}{M_{coiB}}\right)P_{tie,\Sigma}+\varepsilon_\omega+\varepsilon_D\\ \dot{X}_{TCSC}=\dfrac{1}{\tau}(-X_{TCSC}+X_{ref}+u)+\varepsilon_{TCSC}\end{cases}\quad (4)$$

where ε_ω and ε_{TCSC} are uncertain model errors, ε_D is the error of unknown damping coefficients.

In the process of modeling, we assume:

① The equivalent damping coefficients of each area are equal, that is $\bar{D}_{coiA}=\bar{D}_{coiB}=\frac{D_{coiA}}{M_{coiA}}=\frac{D_{coiB}}{M_{coiB}}=\bar{D}$. The valid assumption can simplify the design of the total control system.

② Regardless of the transmission line losses, then the extraction power from area A is,

$$\begin{aligned}P_{tie,\Sigma}&=P_{AB1}+P_{AB2}\\ &=\frac{U_1U_2\sin(\theta_1-\theta_2)}{X_{line1}}+\frac{U_1U_2\sin(\theta_1-\theta_2)}{X_{line2}}\end{aligned}$$

where $X_{line1}=X_{cons}+X_{line}$, $X_{line2}=X_{TCSC}+X_{line}$, X_{line} is the initial reactance of each tie line, X_{cons}, X_{TCSC} are the reactances of constant capacitor and TCSC respectively, U_1,

U_2, θ_1, θ_2 are voltage magnitudes and voltage angles of bus 101 and bus 13.

In engineering applications, the angle and speed of rotor could be obtained from WAMS signals, and the differential parameters of them could be realized using tracking-differentiator (TD) method.

The complexity of system model is irrelative with the power system scale, since only the COIs information of each area are concerned about. Assuming there is no synchronous stability issues inside each area, what we care about is the relative stability of the COIs of all areas.

III. Robust Adaptive Control Design

Without any linearization, a nonlinear robust adaptive control law is derived based on the backstepping method.

$$x=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}(\delta_{coiA}-\delta_{coiB})-(\delta_{coiA0}-\delta_{coiB0})\\ \omega_{coiA}-\omega_{coiB}\\ \dot{\omega}_{coiA}-\dot{\omega}_{coiB}\end{bmatrix} \tag{5}$$

Eqn. (5) can be normalized via a coordinate change,

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=x_3\\ \dot{x}_3=v+\theta\cdot\phi+\varepsilon(t)\end{cases} \tag{6}$$

where

$v=\frac{\omega_0}{M_{coiA}}(\dot{P}_{mA}-\dot{P}_{LA}-\dot{P}_{LossA})-\frac{\omega_0}{M_{coiB}}(\dot{P}_{mB}-\dot{P}_{LB}-\dot{P}_{LossB})-\left(\frac{\omega_0}{M_1}+\frac{\omega_0}{M_2}\right)\dot{P}_{tie,\Sigma}$, is the virtual control input of system; the modulation signal u is the actual control signal, see Fig. 2, which can be solved if the virtual control signal of v was known; $\theta=-\overline{D}$ is the vector of unknown parameters; $\phi=x_3$ is the known function vector;

$\varepsilon(t)=\dot{\varepsilon}_\omega+\dot{\varepsilon}_D-\varepsilon_{TCSC}(\frac{\omega_0}{M_1}+\frac{\omega_0}{M_2})U_1U_2\sin(\theta_1-\theta_2)/X_{line1}^2$

represents the total model error. Obviously, $\dot{\varepsilon}_\omega,\dot{\varepsilon}_D$ and ε_{TCSC} are all bounded, so that $|\varepsilon|\le\psi$ and ψ is an unknown positive constant. Moreover, the equilibrium point of system (4) is still the origin.

A. Step 1

A coordinate conversion is applied to the state variable $\boldsymbol{x}$

$$\begin{cases}z_1=x_1\\ z_2=x_2-\alpha_1(x_1)\\ z_3=x_3-\alpha_2(x_1,x_2)\end{cases} \tag{7}$$

where α_1, α_2 are undecided smooth functions, and $\alpha_1(0)=0$, $\alpha_2(0,0)=0$. The equilibrium point of the system in the new coordinate does not change.

Then the Lyapunov function is defined as

$$V_1=\frac{1}{2}z_1^2 \tag{8}$$

then

$$\dot{V}_1=z_1\dot{z}_1=z_1(z_2+\alpha_1)$$

Let $\alpha_1=-k_1x_1=-k_1z_1$, we have

$$\dot{V}_1=z_1z_2-k_1z_1^2 \tag{9}$$

B. Step 2

Expanding the Lyapunov function to

$$V_2=V_1+\frac{1}{2}z_2^2 \tag{10}$$

then

$$\begin{aligned}\dot{V}_2&=\dot{V}_1+z_2\dot{z}_2\\&=-k_1z_1^2+z_2(z_1+z_3+k_1x_2+\dot{\alpha}_2)\end{aligned} \tag{11}$$

Let $\alpha_2=-z_1-k_1x_2-k_2z_2$, we have

$$\dot{V}_2=-k_1z_1^2-k_2z_2^2+z_2z_3 \tag{12}$$

C. Step 3

Finally, we define the whole Lyapunov function as

$$V=V_2+\frac{1}{2}z_3^2+\frac{1}{2}\tilde{\theta}^T\Gamma^{-1}\tilde{\theta}+\frac{1}{2\gamma}\tilde{\psi}^2 \tag{13}$$

where $\tilde{\theta}=\hat{\theta}-\theta$ and $\tilde{\psi}=\hat{\psi}-\psi^M$ are parameters estimation error; $\hat{\theta}$ and $\hat{\psi}$ are the dynamic estimation of θ and ψ^M respectively; $\psi^M=\max\{\psi,\psi^0\}$, $\psi^0>0$ is the initial value of ψ; Γ is a positive-definite real matrix, and γ is a given positive constant.

The derivative of V is

$$\begin{aligned}\dot{V}=&-k_1z_1^2-k_2z_2^2-k_3z_3^2+\tilde{\theta}^T(\Gamma^{-1}\dot{\hat{\theta}}-z_3\phi)+\frac{1}{\gamma}\tilde{\psi}\dot{\hat{\psi}}\\&+z_3(z_2+k_3z_3+v+\hat{\theta}^T\phi+\Delta-\dot{\alpha}_2)\end{aligned} \tag{14}$$

We choose the virtual control input as:

$$v=-z_2-k_3z_3-\hat{\theta}^T\phi+\dot{\alpha}_2-\beta \tag{15}$$

where β is a compensation item for the total model error Δ.

Substituting (15) into (14), we have：

$$\begin{aligned}\dot{V}=&-k_1z_1^2-k_2z_2^2-k_3z_3^2+z_3(\Delta-\beta)\\&+\tilde{\theta}^T(\Gamma^{-1}\dot{\hat{\theta}}-z_3\phi)+\frac{1}{\gamma}\tilde{\psi}\dot{\hat{\psi}}\end{aligned} \tag{16}$$

Based on the theorem in [10], we take the following adaptive law,

$$\begin{cases}\beta=\hat{\psi}w\\ \dot{\hat{\theta}}=\Gamma[z_3\phi-\sigma_1(\hat{\theta}-\theta^0)]\\ \dot{\hat{\psi}}=\gamma[z_3w-\sigma_2(\hat{\psi}-\psi^0)]\\ w=\tanh(z_3/\varepsilon)\end{cases} \tag{17}$$

The system (6) can be proved to remain practically stable with the control law (17). Finally, the modulation control signal u can be obtained:

$$u=\frac{\frac{v-c_1}{c_2}-c_3}{c_4}+X_{TCSC}-X_{ref} \tag{18}$$

where, $c_1=\frac{\omega_0}{M_{coiA}}(\dot{P}_{mA}-\dot{P}_{LA}-\dot{P}_{LossA})-\frac{\omega_0}{M_{coiB}}(\dot{P}_{mB}-\dot{P}_{LB}-\dot{P}_{LossB})$

$c_2=-\left(\frac{\omega_0}{M_1}+\frac{\omega_0}{M_2}\right)$

$$c_3 = \frac{(\dot{U}_1 U_2 + U_1 \dot{U}_2)\sin(\theta_1 - \theta_2)}{X_{line1}} + \frac{(\dot{U}_1 U_2 + U_1 \dot{U}_2)\sin(\theta_1 - \theta_2)}{X_{line2}} + \frac{U_1 U_2 \cos(\theta_1 - \theta_2)\cdot(\dot{\theta}_1 - \dot{\theta}_2)}{X_{line1}} + \frac{U_1 U_2 \cos(\theta_1 - \theta_2)\cdot(\dot{\theta}_1 - \dot{\theta}_2)}{X_{line2}}$$

$$c_4 = -\frac{U_1 U_2 \sin(\theta_1 - \theta_2)}{\tau X_{line1}^2}$$

A brief discussion is made as follows:

(1) Rotor angles and speeds of individual generator (δ_i, ω_i) are supposed to be measured real-timely with rapid development of WAMS technology; $P_{tie,\Sigma}$ could be measured locally; the differential of some parameters can be obtained easily with TD [11,12].

(2) With the ability to self-correct and adapt unknown parameters, the performances of RAMC are superior to them of conventional controller. In practical applications, real time values of mechanical power and load are difficult to be measured. However, in this paper, we assume that the load could be approximately modeled as constant power load and the mechanical power would not change too much in transient stability dynamics. Eqn. (4) has included the model errors caused by treating load and mechanical power as constants. In the next section, the simulation results will demonstrate that this approximation has little impact on the controller performance.

(3) The focus of the control law is to drive system (6) to its equilibrium point (the origin). For a power system, the control law could keep synchronization of the two interconnected systems by driving their dynamic COIs to a stable equilibrium point, $(\delta_{coiA} - \delta_{coiB}) - (\delta_{coiA0} - \delta_{coiB0}) \to 0$, $\omega_{coiA} - \omega_{coiB} \to 0$ and $\dot{\omega}_{coiA} - \dot{\omega}_{coiB} \to 0$. Based on the above, the inter-area oscillation will certainly be damped.

(4) Other than other literatures, the bound of model error is not fixed in this paper. For example, $\psi^M = \max\{\psi, \psi^0\}$, if ψ^0 is determined to be a very small value, the convergence speed would be improved noticeably.

(5) Since all the models and processes hold the nonlinear terms, the format of Eqn. (18) is complicated. However, the design process is simple and easy.

IV. Computer Simulation Results

A 2-area 4-generator interconnected power system is used for the computer test, see Fig. 3. The effectiveness of RAMC is investigated with comparison to conventional modulation controller (CMC). The sub-transient model is used for the generator with simple excitation control, conventional power system stabilizer (PSS) is installed on each generator. The mechanical power of each generator is fixed as a constant, and loads are expressed as constant impedance.

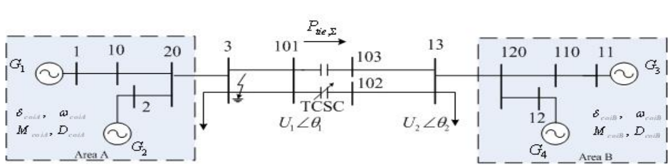


Fig. 3. Equivalent circuit of 4-machine system with TCSC

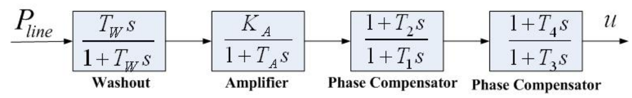
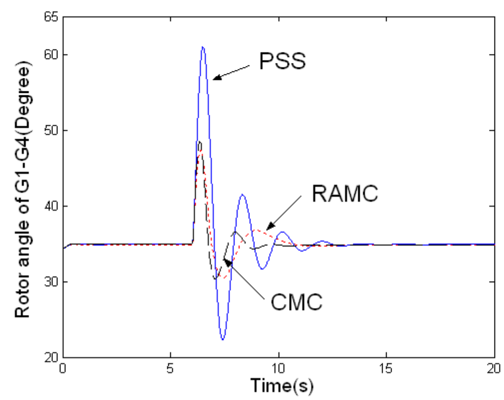
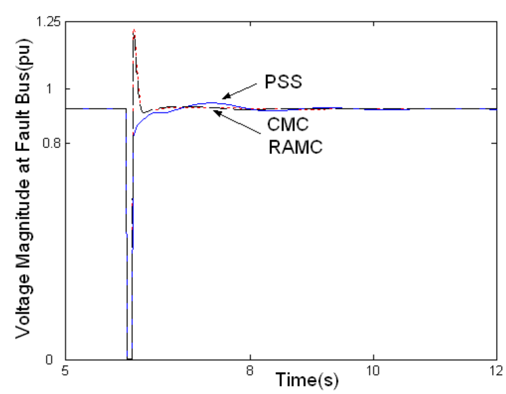


Fig. 4. Block of TCSC Conventional Modulation Controller

Test Case 1: The total transmission power of parallel tie lines is $P_{tie,\Sigma} = 350$ MW. A temporary three-phase earth fault is applied at $t = 6$ second on bus-3, and it disappears in 0.1 s. In this case the parameters of CMC are designed by phase compensation method: $T_w = 1$, $T_A = 2$, $K_A = 3$, $T_1 = 0.2$, $T_2 = 0.07$, $T_3 = 0.2$, $T_2 = 0.05$; the parameters of RAMC are designed as: $k_1 = 1$, $k_2 = 3$, $k_3 = 5$, $\gamma = 10$, $\Gamma = 10$, $\sigma_1 = 1$, $\sigma_2 = 1$, $\varepsilon = 1$; and time constant of TCSC is $\tau = 0.1$.



(a) Rotor angles of G1-G4

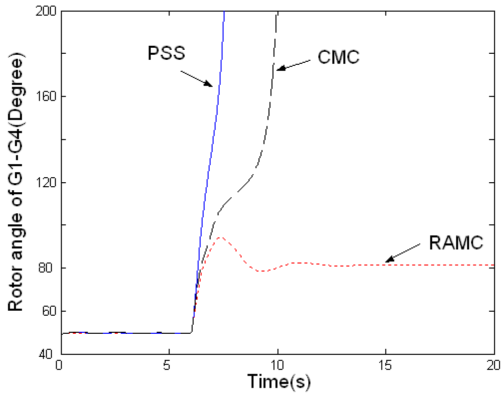


(b) Voltage magnitude at fault bus

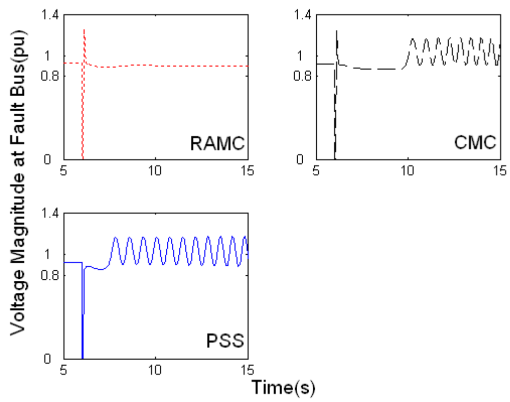
Fig. 5. Simulation curves in Case1

Test Case 2: The total transmission power of parallel tie lines is $P_{tie,\Sigma} = 500$ MW. A three-phase earth fault is applied at $t = 6$ second on bus-3, and cleared by tripping one circuit of line 3-101 in 0.1 s.

Transient stability time simulation results are shown in Fig. 5 and Fig. 6. It can be seen that in Case 1 all controllers have good performance in damping low-frequency oscillation, and RAMC and CMC are a little better than PSS. Which show that TCSC has the ability to damp power oscillation. There is almost no difference between RAMC and CMC in case 1 because the disturbance is set at the designed operation point, and post-fault SEP is the same as pre-fault SEP.



(a) Rotor angles of G1-G4



(b) Voltage magnitude at fault bus

Fig. 6. Simulation curves in Case2

However, it can be seen that when equilibrium point changes after large disturbance in Case 2, PSS and CMC can not guarantee the system stability, while RAMC can still provide good damping to the inter-area oscillation, which are shown in Fig. 6. By increasing the power flow step by step, we could find the transfer limit between two areas of the system with RAMC is 540 MW. However, the transfer limit with CMC is only 440MW.

Test Case 3: If the real equivalent damping coefficient $D_1 = 6$, we set the initial estimation value $D_2 = 8$ to verify the adaptive performance of RAMC. The disturbance and controller parameters are the same as in Case 1. The dynamic estimation for unknown parameters and the relative rotor angle δ_{14} are showed in Fig. 7 and Fig. 8 respectively. It can be seen that RAMC is insensitive to the initial value.

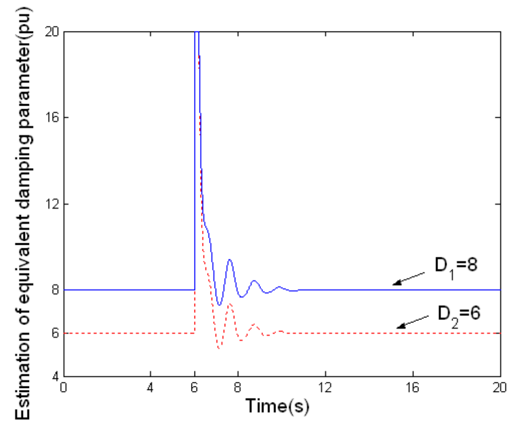


Fig. 7. Estimation of equivalent damping parameter

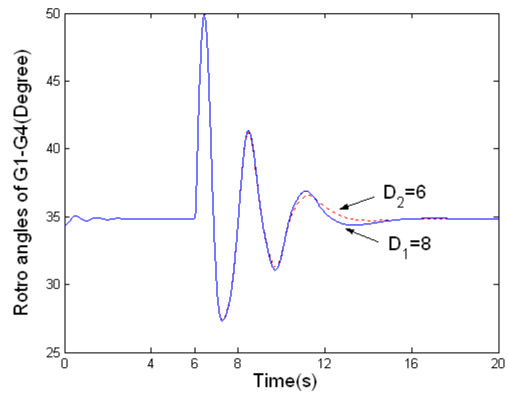


Fig. 8. Rotor angles of G1-G4 in Case3

Test Case 4: To test the robustness of RAMC, 3 different model errors are applied.

Case A: $\varepsilon_1 = 0$, that is no error in the model;

Case B: $\varepsilon_2 = 0.4$ is applied from 0.5 to 1 second, which is a temporary error in the model;

Case C: $\varepsilon_3 = 0.4$ is applied at 0.5 second, which is a permanent error in the model.

It can be seen that temporary model error has little effect on the controller output from Fig.9 and Fig.10. The permanent model error might change rotor angles of G1-G4, but it looks not to affect the convergence.

Some discussions can be made based on simulation results:

(1) One of the key ideas of the proposed controller is to drive the COIs of two interconnected areas to be synchronous to an equilibrium point. The control scheme is effective in damping inter-area oscillation and can enhance the stability and transfer limit of interconnected systems.

(2) In Case 2, the post-fault operation point is different from the designed operation point, RAMC can perform well to keep the stability while CMC can not, which verify the robustness of RAMC.

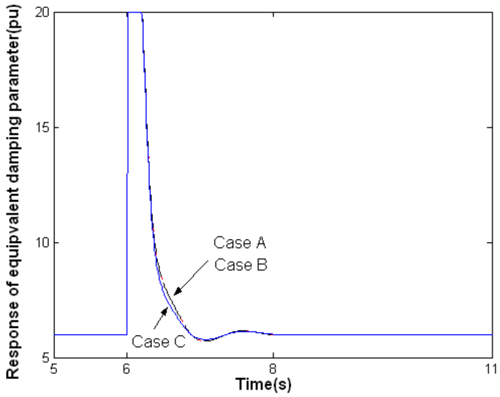


Fig. 9. Response of control variable with different ε

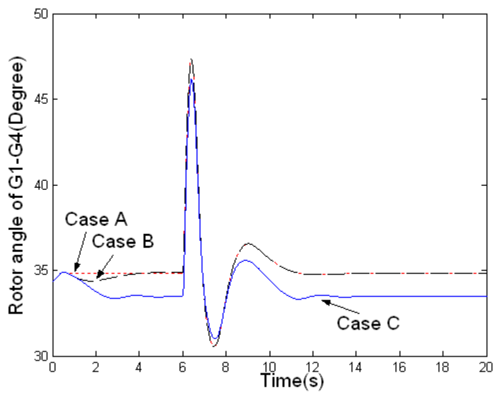


Fig. 10. Rotor angles of G1-G4 with different ε

(3) Since responses of RAMC is fast and sensitive, the optimization of controller parameters would be important, and should be implemented as further study.

(4) In this paper, the time constant of TCSC controller is taken as $\tau = 0.1$, which already includes time-delay of WAMS signals in a way.

V. Conclusion

Based on the idea of driving the COIs of interconnected areas to a stable equilibrium point, a nonlinear robust adaptive control scheme for TCSC has been introduced, in which the COIs' information is from WAMS. The model of a multi-machine ac interconnected system with TCSC in COI coordinate is derived, which contains the unknown parameters, model errors and disturbances. Then a nonlinear robust adaptive control law is designed using the backstepping method. Test results show that the RAMC is more effective than the CMC in damping inter-area oscillations and can enhance transfer limit noticeably. Furthermore, RAMC has the performance of robustness to model errors and adaptability to unknown parameters.

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VII. Biographies

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