Available online at www.sciencedirect.com
ScienceDirect
Electric Power Systems Research 77 (2007) 559–565
ELECTRIC POWER SYSTEMS RESEARCH
www.elsevier.com/locate/epsr

Adaptive control design for VSC-HVDC systems based on backstepping method

Si-Ye Ruan [a], Guo-Jie Li [a], Xiao-Hong Jiao [a], Yuan-Zhang Sun [a], T.T. Lie [b,*]

[a] *State Key Laboratory of Power System, Tsinghua University, Beijing, PR China*
[b] *School of EEE, Nanyang Technological University, Singapore*

Received 26 January 2006; received in revised form 2 May 2006; accepted 18 May 2006
Available online 11 July 2006

Abstract

An adaptive control design is proposed to improve dynamic performances of voltage source converter high voltage direct current (VSC-HVDC) systems. The adaptive controller design for nonlinear characteristics of VSC-HVDC systems, which is based on backstepping method, considers parameters uncertainties. For an original high-order system, the final control laws can be derived step by step through suitable Lyapunov functions. Thus, the design process is not complex. The effectiveness of the proposed adaptive controllers is demonstrated through digital simulation studies on a VSC-HVDC power system, using the PSCAD/EMTDC software package. The simulation results show that the controllers contribute significantly toward improving the dynamic behavior of the VSC-HVDC system under a wide range of operating conditions.

Keywords: VSC-HVDC; Adaptive backstepping control; Parameter uncertainties

1. Introduction

Voltage source converter high voltage direct current (VSC-HVDC) based on insulated gate bipolar transistor (IGBT) switch technology has received much attention in recent years [1–7]. A VSC-HVDC transmission system connects ac networks and includes converters at each ac side. In VSC-HVDC transmission schemes, the controls of dc voltage and power flows are of primary necessity and importance.

Many research works on VSC converter control have been carried out [7–13]. Traditional proportional integral (PI) controllers were proposed in Ref. [7] to control the phase and amplitude of the converter ac output voltage in conventional *a*–*b*–*c* coordinates. In Refs. [8,9], control in the synchronous frame was proposed. However, the controllers were designed depending on the exactly canceling of the nonlinearities in the system, on which linear control is based. If any parameter value in the formulation is not known exactly, the nonlinearities in the system cannot be thoroughly cancelled. It will consequently cause a constant error when the system is shifted to another operating point.

Ref. [10] presented a synthesis of nonlinear controllers for VSC-HVDC systems under balanced network conditions to highlight fast and slow dynamic associated with the current control loops and the dc bus voltage control loop respectively. Ref. [11] presented a control strategy under balanced and unbalanced network conditions which contains a main controller and an auxiliary controller. The main controller is implemented in the positive *d*–*q* frame using decoupling control without involving positive/negative sequence decomposition. The auxiliary controller is implemented in the negative sequence *d*–*q* frame using cross coupling control of negative sequence current. Ref. [12] aims at developing a fast controller that will give good performance and robustness at the nominal operation, but also enable satisfactory transients during faults. To improve the inverter dc voltage performance, an additional stabilizing feedback loop is developed at the rectifier side. The stabilizing loop is a lead–lag second order filter that is designed using the root locus methods. The VSC control under faults is achieved using a dedicated current controller at each converter station.

In practice, the parameter of system does not remain constant during operations, such as ac line impedance. Ref. [14] described a design controller for a VSC-HVDC system which is robust over a range of operating points. The design method exploited the structure of the uncertainty representing the range of operating conditions using linear matrix inequalities (LMIs).

* Corresponding author.
E-mail address: ettlie@ntu.edu.sg (T.T. Lie).

0378-7796/$ – see front matter
doi:10.1016/j.epsr.2006.05.006

However, the above design method based on LMIs is complex and complicated.

In this study, an adaptive backstepping control is applied in the synchronous frame to improve dynamic behavior performances of VSC-HVDC systems. The adaptive controller design for nonlinear characteristics of VSC-HVDC systems is presented based on the backstepping method [15]. Parameters uncertainties such as the change of ac line impedances will be considered in the design. For an original high-order system, the final control laws can be derived step by step through suitable Lyapunov functions. Thus, the design process is not complex. The effectiveness of the proposed adaptive controllers is demonstrated through digital simulation studies on a VSC-HVDC power system through the use of the PSCAD/EMTDC software package. The simulation results show that the controllers contribute significantly to improve dynamic behavior of the VSC-HVDC system under a wide range of operating conditions.

The rest of the paper is organized as follows. In Section 2, the modeling of the VSC-HVDC system is presented. In Section 3, adaptive control laws for VSC-HVDC systems based on backstepping are developed and discussed. Simulation study is presented in Section 4. At last, conclusions are discussed in Section 5.

2. Modeling of the VSC-HVDC system

An equivalent system model for the VSC-HVDC system is given in Fig. 1. There are two converter stations in the system. Each station shown in Fig. 1 is coupled with ac network via equivalent impedances $Z_1 = Z_{\mathrm{ac1}} + Z_{\mathrm{T1}} = R_1 + jX_1$ and $Z_2 = Z_{\mathrm{ac2}} + Z_{\mathrm{T2}} = R_2 + jX_2$, where Z_{ac1} and Z_{ac2} are the impedances of ac lines, respectively. Z_{T1} and Z_{T2} are the impedances of transformers. dc capacitor $C = C_1 = C_2$ is used across dc side of the VSC-HVDC system. It is assumed that ac networks at the terminal are very strong. It is possible because most of VSC-HVDC systems' capacities are small when compared with that of power system.

Each VSC has two degrees of freedom. The reactive modulation of each VSC will use up one degree. The other degree is used to control the real power or dc voltage. The active power modulation is applied in inverter station, while the dc voltage modulation is proposed in rectifier station to maintain power balance, as described in Eq. (8). In this paper, Station 1 used as a rectifier station is chosen to control the reactive power Q_1 and dc bus voltage v_{dc}. And Station 2 used as an inverter station is set to control the reactive power Q_2 and active power P_2.

The following equations govern the relationships among different variables of the system [10].

Rectifier station:

$$\frac{\mathrm{d}v_{\mathrm{dc1}}}{\mathrm{d}t} = \frac{3u_{sq1}i_{q1}}{2Cv_{\mathrm{dc}}} - \frac{i_{\mathrm{L}}}{C} \tag{1}$$

$$\frac{\mathrm{d}i_{q1}}{\mathrm{d}t} = -\omega i_{d1} - \frac{R}{L}i_{q1} + u_{q1} \tag{2}$$

$$\frac{\mathrm{d}i_{d1}}{\mathrm{d}t} = -\frac{R}{L}i_{d1} + \omega i_{q1} + u_{d1} \tag{3}$$

where $u_{q1} = (u_{sq1} - y_{rq1})/L$, $u_{d1} = (u_{sd1} - u_{rd1})/L$.

Inverter station:

$$\frac{\mathrm{d}v_{\mathrm{dc2}}}{\mathrm{d}t} = \frac{3u_{sq2}i_{q2}}{2Cv_{\mathrm{dc}}} + \frac{i_{\mathrm{L}}}{C} \tag{4}$$

$$\frac{\mathrm{d}i_{q2}}{\mathrm{d}t} = -\omega i_{d2} - \frac{R}{L}i_{q2} + u_{q2} \tag{5}$$

$$\frac{\mathrm{d}i_{d2}}{\mathrm{d}t} = -\frac{R}{L}i_{d2} + \omega i_{q2} + u_{d2} \tag{6}$$

where $u_{q2} = (u_{sq2} - y_{rq2})/L$, $u_{d2} = (u_{sd2} - u_{rd2})/L$.

Interconnected relationship between rectifier station and inverter station is:

$$v_{\mathrm{dc1}}i_{\mathrm{L}} = v_{\mathrm{dc2}}i_{\mathrm{L}} + 2R_0 i_{\mathrm{L}}^2. \tag{7}$$

It is supposed that sources' voltage signals can be transferred to HVDC stations using wide area measurement system (WAMS) in real time. Therefore, the *d*–*q* frames are placed on the source terminals in this study.

In the synchronous frame, u_{sd1}, u_{sd2}, u_{sq1} and u_{sq2} are the *d*- and *q*-axes components of the respective source voltages, i_{d1}, i_{d2}, i_{q1} and i_{q2} are that of the line currents, u_{rd1}, u_{rd2}, u_{rq1} and u_{rq2} are that of the converter input voltages. P_1, P_2, Q_1 and Q_2 are the active and reactive power transferred from the network to the station, v_{dc} the dc bus voltage and i_{L} is the load current.

At the side of Station 1, we set *q*-axis to be in phase with the source voltage U_{s1}. Correspondingly, we set *q*-axis to be in phase of the source voltage U_{s2} at the side of Station 2. Therefore, u_{sd1} and u_{sd2} are equal to 0 while u_{sq1} and u_{sq2} are equal to the magnitude of u_s, which will simplify the following discussion.

Then, the power flows from the sources can be given:

$$P_1 = \frac{3}{2}(u_{sq1}i_{q1} + u_{sd1}i_{d1}) = \frac{3}{2}u_{sq1}i_{q1},$$
$$Q_1 = \frac{3}{2}(u_{sq1}i_{d1} - u_{sd1}i_{q1}) = \frac{3}{2}u_{sq1}i_{d1} \tag{8}$$

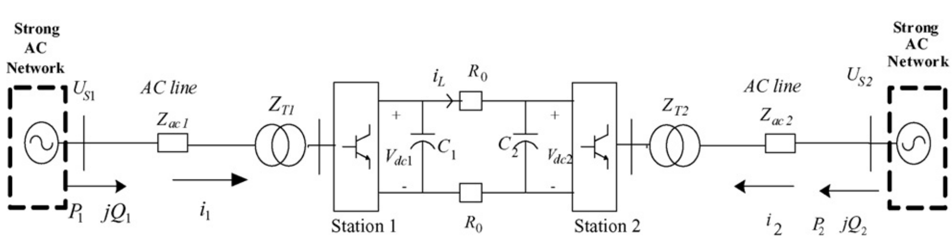

Fig. 1. A physical model for the VSC-HVDC system.

$$P_2 = \frac{3}{2}(u_{sq2}i_{q2} + u_{sd2}i_{d2}) = \frac{3}{2}u_{sq2}i_{q2},$$
$$Q_2 = \frac{3}{2}(u_{sq2}i_{d2} - u_{sd2}i_{q2}) = \frac{3}{2}u_{sq2}i_{d2} \tag{9}$$

It should be noted that in the transient situations, the equations are not changed.

The model of the VSC-HVDC system, from which the simulations have been made, is based on Eqs. (1)–(6) and a number of assumptions. To have the assumptions validated, it will be necessary to build IGBT models of the converters for testing. Short of building real-life models, simulations can be made through industry standard software such as EMTDC-PSCAD, EMTP-RV or others. Alternatively, the HVDC modeled in Kirchhoff's voltage and current laws, without any assumptions, can solve with the backstepping method as control. Until such a rigorous test is performed, the adequacy of the backstepping method remains pending. Thus, simulation studies are made through the PSCAD/EMTDC software package in the paper.

3. Adaptive control design for VSC-HVDC systems based on backstepping method

Adaptive backstepping is a control method for nonlinear systems with unknown but constant uncertainties [15–17]. The uncertainties in the paper are given by the change of system parameters such as ac line impedances. In practice, line impedances are designed according to the short-circuit capacity, which are bounded. What is more, the change of line impedances will shift system to another operating point. In that case, system states are uncertain but constant. Therefore, the uncertainties caused by change of system parameters must be constant and bounded, which can be reflected by θ_{q1}, θ_{d1}, θ_{q2} and θ_{d2} in the formulations. Then, adaptation control laws can be derived systematically step by step. The control objective is to improve dynamic behavior performances for VSC-HVDC systems. It is noted that the paper presented adaptive backstepping control for VSC-HVDC systems under balanced network conditions. The system behavior under unbalanced conditions is not considered.

In the design, we define the state variable by $x = [v_{dc1}, i_{q1}, i_{d1}, i_{q2}, i_{d2}]^T$. We consider a situation such as single-phase faults [13] occurrence will bring uncertainties to the system. The controls for rectifier and inverter are designed separately.

3.1. Control design for the rectifier station

A mathematical model for the rectifier station can be described:

$$\begin{cases} \dot{x}_1 = ax_2/x_1 + \mathrm{T} \\ \dot{x}_2 = -bx_2 - \omega x_3 + u_{q1} + \theta_{q1} \\ \dot{x}_3 = \omega x_2 - bx_3 + u_{d1} + \theta_{d1} \end{cases} \tag{10}$$

where the parameters are defined by

$$a = \frac{3u_{sq1}}{2C}, \qquad b = \frac{R}{L}, \qquad T = -\frac{i_L}{C}.$$

It is clear that the rectifier station is of third order and has two control inputs.

The uncertainties given by the change of ac line impedance at the side of inverter station can be reflected by θ_{q1} and θ_{d1} in the formulation, which are unknown constant values. Besides, they are also bounded.

Firstly, we introduce $z_1 = x_{1\text{ref}} - x_1$, $z_2 = \beta_1 - x_2$. The problem is therefore formulated in terms of z_1 and z_2. Consider β_1 is a virtual control law to stabilize z_1-system with respect to the Lyapunov function $V_{n0} = 1/2Cz_1^2$, where $1/2Cz_1^2$ represents the energy fluctuation in the dc capacitor.

The z_1-system and the corresponding $\dot{V}_1$ are

$$\dot{z}_1 = \dot{x}_{1\text{ref}} - \frac{ax_2}{x_1} - T \tag{11}$$

$$\dot{V}_{n0} = Cz_1(\dot{x}_{1\text{ref}} - \frac{a\beta_1}{x_1} - T) + \frac{aCz_2z_1}{x_1} \tag{12}$$

Then, if $z_2 = 0$, we obtain the equality $\dot{V}_{n0} = -k_{n1}C{z_1}^2$ with $\beta_1 = x_1/a(\dot{x}_{1\text{ref}} - T + k_{n1}z_1)$.

Then, introduce $z_3 = x_{3\text{ref}} - x_3$.

Consider the time derivative of (z_2, z_3):

$$\dot{z}_2 = \dot{\beta}_1 + bx_2 + \omega x_3 - u_{q1} - \theta_{q1} \tag{13}$$

$$\dot{z}_3 = \dot{x}_{3\text{ref}} - \omega x_2 + bx_3 - u_{d1} - \theta_{d1} \tag{14}$$

where

$$\dot{\beta}_1 = \frac{\dot{x}_1}{a}(\dot{x}_{1\text{ref}} - T + k_{n1}z_1) + \frac{x_1}{a}(\ddot{x}_{1\text{ref}} - \dot{T} + k_{m1}\dot{z}_1)$$

Choose a positive definite function $V_{n1} = V_{n0} + 1/2L(z_2^2 + z_3^2) + 1/2m_2(\hat{\theta}_{q1} - \theta_{q1})^2 + 1/2m_3(\hat{\theta}_{d1} - \theta_{d1})^2$, where $\hat{\theta}_{q1}$ and $\hat{\theta}_{d1}$ are the estimates of θ_{q1} and θ_{q2}. m_2 and m_3 are adaptation gains for the estimates of θ_{q1} and θ_{d1}, respectively ($m_2 > 0$, $m_3 > 0$). $1/2L(z_2^2 + z_3^2)$ represents the energy fluctuation of the ac reactor in the rectifier side.

Then, we get the time derivative of V_{n1}

$$\begin{aligned}\dot{V}_{n1} = {} & -k_{n1}Cz_1^2 + Lz_2\left(\frac{aCz_1}{Lx_1} + \dot{\beta}_1 + bx_2 + \omega x_3 - u_{q1} - \hat{\theta}_{q1}\right) \\ & + Lz_3(\dot{x}_{3\text{ref}} - \omega x_2 + bx_3 - u_{d1} - \hat{\theta}_{d1}) \\ & + (\hat{\theta}_{q1} - \theta_{q1})\left(\frac{\dot{\hat{\theta}}_{q1}}{m_2} + Lz_2\right) + (\hat{\theta}_{d1} - \theta_{d1})\left(\frac{\dot{\hat{\theta}}_{d1}}{m_3} + Lz_3\right)\end{aligned} \tag{15}$$

To eliminate $\hat{\theta}_{q1} - \theta_{q1}$ and $\hat{\theta}_{d1} - \theta_{d1}$ terms, the update laws can be determined through equations:

$$\dot{\hat{\theta}}_{q1} = -m_2Lz_2 \tag{16}$$

$$\dot{\hat{\theta}}_{d1} = -m_3Lz_3 \tag{17}$$

Now choose two control inputs for the rectifier side as

$$u_{q1} = \frac{aCz_1}{Lx_1} + \dot{\beta}_1 + bx_2 + \omega x_3 - \hat{\theta}_{q1} + k_{n2}z_2 \tag{18}$$

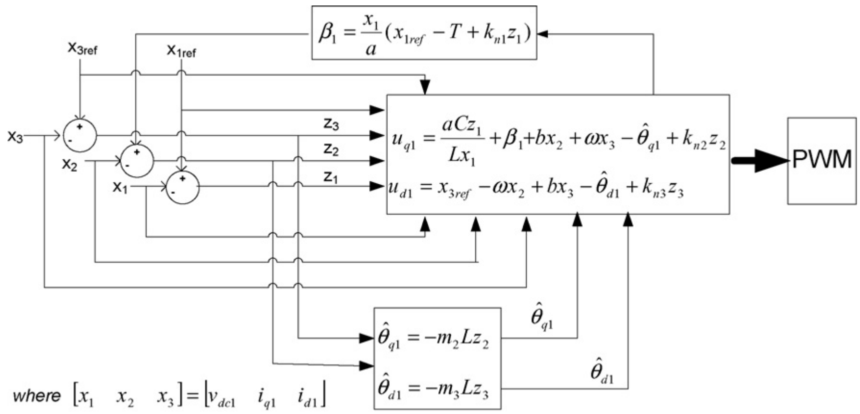

Fig. 2. Block diagram of adaptive backstepping design for the rectifier station.

$$u_{d1} = \dot{x}_{3\mathrm{ref}} - \omega x_2 + bx_3 - \hat{\theta}_{d1} + k_{n3}z_3 \tag{19}$$

Then, we obtain

$$\dot{V}_{n1} = -k_{n1}Cz_1^2 - k_{n2}Lz_2^2 - k_{n3}Lz_3^2 \leq 0 \tag{20}$$

where $k_{n1} > 0$, $k_{n2} > 0$ and $k_{n3} > 0$. Block diagram of adaptive backstepping design for the rectifier station is shown in Fig. 2.

3.2. Control design for the inverter station

Since the inverter station is not in charge of dc voltage regulation, a mathematical model for inverter station can be given by:

$$\begin{cases} \dot{x}_4 = -bx_4 - \omega x_5 + u_{q2} + \theta_{q2} \\ \dot{x}_5 = \omega x_4 - bx_5 + u_{d2} + \theta_{d2} \end{cases} \tag{21}$$

The uncertainties given by the change of ac line impedance at the side of inverter station can be reflected by θ_{q2} and θ_{d2} in the formulation, which are unknown constant values. Besides, they are also bounded.

It is clear that the inverter station is of second order and has two control inputs.

Define $z_4 = x_{4\mathrm{ref}} - x_4$ and $z_5 = x_{5\mathrm{ref}} - x_5$.

Consider the time derivative of (z_4, z_5):

$$\dot{z}_4 = \dot{x}_{4\mathrm{ref}} + bx_4 + \omega x_5 - u_{q2} - \theta_{q2} \tag{22}$$

$$\dot{z}_5 = \dot{x}_{5\mathrm{ref}} - \omega x_4 + bx_5 - u_{d2} - \theta_{d2} \tag{23}$$

Design a positive definite function $V_{m0} = 1/(2L)(z_4^2 + z_5^2) + 1/(2m_4)(\hat{\theta}_{q2} - \theta_{q2})^2 + 1/(2m_5)(\hat{\theta}_{d2} - \theta_{d2})^2$, where $\hat{\theta}_{q2}$ and $\hat{\theta}_{d2}$ are the estimates of θ_{q2} and θ_{d2}. m_4 and m_5 are adaptation gains ($m_4 > 0$, $m_5 > 0$) and $1/2L(z_4^2 + z_5^2)$ represents the energy fluctuation in the ac reactor of the inverter side.

Then, we have

$$\begin{aligned} \dot{V}_{m0} = {} & Lz_4(\dot{x}_{4\mathrm{ref}} + bx_4 + \omega x_5 - u_{q2} - \hat{\theta}_{q2}) \\ & + Lz_5(\dot{x}_{5\mathrm{ref}} - \omega x_4 + bx_5 - u_{d2} - \hat{\theta}_{d2}) \\ & + (\hat{\theta}_{q2} - \theta_{q2})\left(\frac{\dot{\hat{\theta}}_{q2}}{m_4} + Lz_4\right) + (\hat{\theta}_{d2} - \theta_{d2})\left(\frac{\dot{\hat{\theta}}_{d2}}{m_5} + Lz_5\right) \end{aligned} \tag{24}$$

To eliminate $\hat{\theta}_{q2} - \theta_{q2}$ and $\hat{\theta}_{d2} - \theta_{d2}$ terms, the update laws can be determined through the following equations:

$$\dot{\hat{\theta}}_{q2} = -m_4 L z_4 \tag{25}$$

$$\dot{\hat{\theta}}_{d2} = -m_5 L z_5 \tag{26}$$

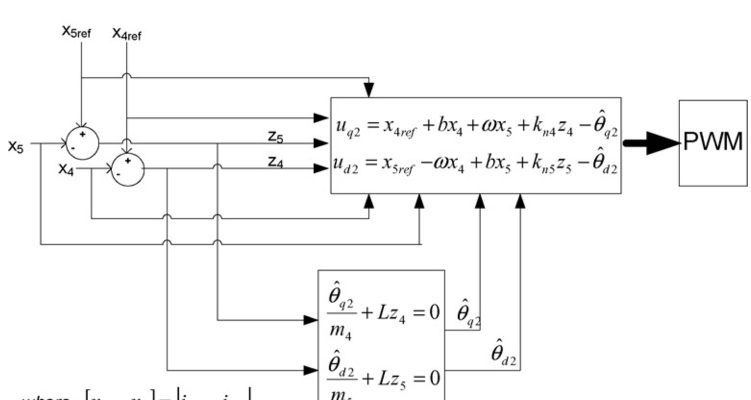

Fig. 3. Block diagram of adaptive backstepping design for the inverter station.

Finally, we choose two control inputs for the inverter side as

$$u_{q2} = \dot{x}_{4\mathrm{ref}} + bx_4 + \omega x_5 + k_{n4} z_4 - \hat{\theta}_{q2} \quad (27)$$

$$u_{d2} = \dot{x}_{5\mathrm{ref}} - \omega x_4 + bx_5 + k_{n5} z_5 - \hat{\theta}_{d2} \quad (28)$$

where $k_{n4} > 0$ and $k_{n5} > 0$. Block diagram of adaptive backstepping design for the inverter station is shown in Fig. 3.

Thus, we reach our goal of stabilization because

$$\dot{V}_{m0} = -k_{n4} L z_4^2 - k_{n5} L z_5^2 \le 0. \quad (29)$$

3.2.1. Remarks

From Eqs. (20) and (29), we know that the system can converge to the desired equilibrium point since the energy fluctuations in the dc capacitor and ac reactors converge to zero. In spite of parameters uncertainties, good performances can be achieved by introducing the estimation functions. According to the LaSalle–Yoshizawa theorem, it is established that z_1, z_2, z_3, z_4, z_5, $\hat{\theta}_{q1}$, $\hat{\theta}_{d1}$, $\hat{\theta}_{q2}$ and $\hat{\theta}_{d2}$ are bounded and $z_1(t) \to 0$, $z_2(t) \to 0$, $z_3(t) \to 0$, $z_4(t) \to 0$ and $z_5(t) \to 0$ as $t \to \infty$. Since $z_1 = x_{1\mathrm{ref}} - x_1$, $z_3 = x_{3\mathrm{ref}} - x_3$, $z_4 = x_{4\mathrm{ref}} - x_4$, $z_5 = x_{5\mathrm{ref}} - x_5$ and (x_1, x_3, x_4, x_5) are also bounded and converges to desired equilibrium point $(x_{1\mathrm{ref}}, x_{3\mathrm{ref}}, x_{4\mathrm{ref}}, x_{5\mathrm{ref}})$. The boundedness of x_2 then follows the boundedness of β_1. From $z_2 = \beta_1 - x_2$ and $\beta_1 = x_1/a(\dot{x}_{1\mathrm{ref}} - T + k_1 z_1)$, we conclude that the regulation of x_1 will imply the regulation of x_2. Thus, x_2 is not guaranteed to a constant value unless x_1 is constant. In addition, using Eqs. (18), (19), (27) and (28), it is clear that the control laws u_{q1}, u_{d1}, u_{q2} and u_{d2} are also bounded.

4. Simulation study

The performance of the proposed adaptive backstepping control will be carried out through simulation study as well as to be compared with that of linear control. Linear control is mostly adopted in the industrial VSC-converter, which is based on the exact cancellation of the items related with parameters. That will result in the system states' errors if the parameter values are changed, while the adaptive backstepping technique can compensate the errors.

The physical model in the simulation study is given in Fig. 4. To simulate the system behavior under parameters uncertainty conditions, a single-phase transient faults at the middle point of the transmission are applied in Cases A and B separately, as shown in Fig. 4. The fault points locate at the middle of the transmission line 2 and 4, respectively, as shown in Fig. 4. The path of the fault current from line to ground is of 5 Ω impedance.

Source voltage: $U_{s1} = U_{s2} = 1.0$ p.u.
ac lines: $Z_{\mathrm{line1}} = Z_{\mathrm{line2}} = 0.001 + j0.12$ p.u., $Z_{\mathrm{line3}} = Z_{\mathrm{line4}} = 0.001 + j0.06$ p.u.
Transformers: $Z_{T1} = j0.08$ p.u., $Z_{T2} = j0.07$ p.u.
dc capacitor: $X_{C1} = X_{C1} = 1.5$ p.u.
dc line resistor: $R_0 = 0.05$ p.u.

A 2000 Hz of modulation switching frequency is adopted in the simulations.

Now, we consider the following cases:

Case A. $t < 0.8$[s], the system operates in normal conditions.
$t = 0.8$[s], a single-phase transient fault occurs at the middle point of the transmission line 2.
$t = 0.9$[s], line 2 is de-energized to clear the fault.

Case B. $t < 0.8$[s], the system operates in normal conditions.
$t = 0.8$[s], a single-phase transient fault occurs at the middle point of the transmission line 4.
$t = 0.9$[s], line 4 is de-energized to clear the fault.

For the proposed adaptive backstepping control, the design gains are given as follows:

$$k_{n1} = 105, \quad k_{n2} = 116, \quad k_{n3} = 171, \quad m_2 = 150,000 \quad \text{and} \quad m_3 = 208,300$$

$$k_{n4} = k_{n5} = 251, \quad m_4 = 260,000 \quad \text{and} \quad m_5 = 186,000$$

In fact, the above values of design gains affect the final control design much; these values are selected according to Eqs. (16)–(19) and (25)–(28). Moreover, we try to get more effective simulation results comparing different values. However, it is difficult to get the optimal values of them. The method proposed in this paper does not give a way on how to select these values.

Simulation results of system responses are shown in Figs. 5 and 6, where the dash lines denote reference values. With linear control, it is shown that system states can follow the reference values well when the system is under normal conditions. However, there is poor dynamic behavior when faults occur at 0.8 s. When fault line 2 is de-energized in Case A and line 4 is de-energized in Case B, the system state values cannot recover to their reference values. Thus, it is obvious that the control with linear laws cannot deal with faults well since the controllers are designed using small signal analysis which is valid only around operation points.

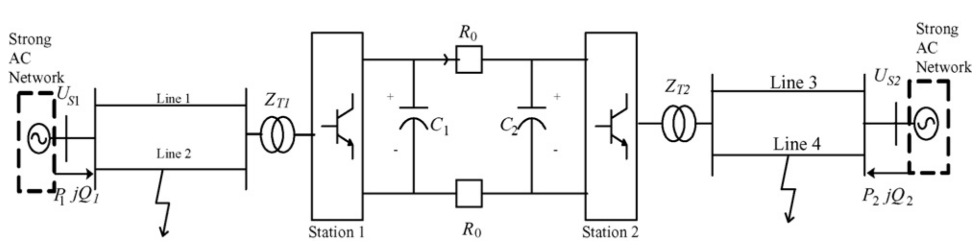

Fig. 4. The physical model in the simulation.

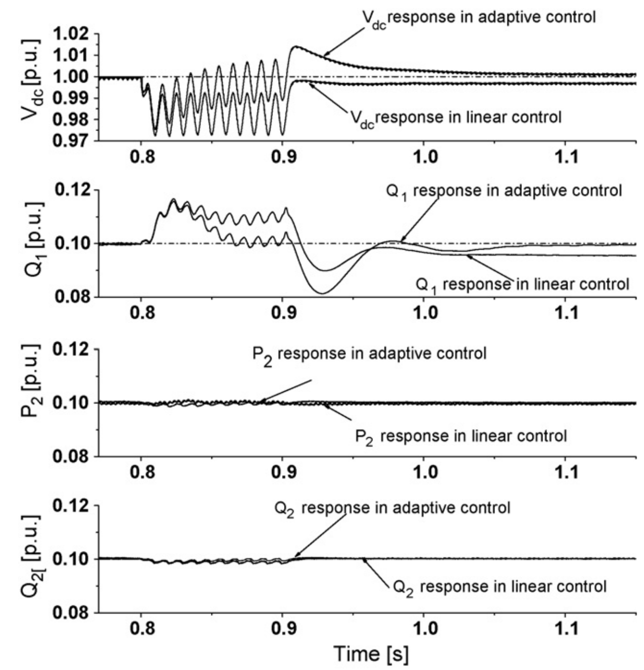

Fig. 5. System responses in Case A.

With adaptive control, the control performances are much better than the above linear control during the faults. After lines 2 and 4 are disconnected to clear faults in Cases A and B, respectively, the system state values can quickly return to the reference value within 0.3 s. Though there are drastic changes to system operating conditions, system state values can still track reference values due to the effectiveness of the adaptation laws. From these simulation results, it can be concluded that the proposed adaptive control for VSC-HVDC systems is effective to deal with parameter uncertainties.

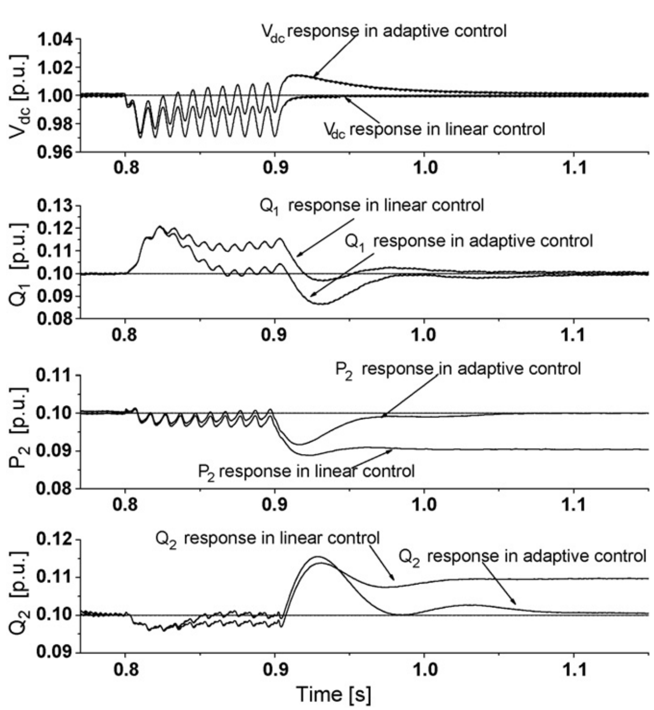

Fig. 6. System responses in Case B.

5. Conclusions

In this paper, proposed adaptive control is applied to the above VSC-HVDC system when parameters uncertainties are considered. The design process is simple and clear because control laws can be derived step by step based on backstepping method. Finally, the control performances have been compared with those of linear control. Simulation results show clearly that the proposed adaptive control contributes significantly to improved dynamic behaviors for VSC-HVDC systems. Thus, the adaptive control design is effective for VSC-HVDC systems containing parameters uncertainties.

Acknowledgement

This work was supported in part by the National Science Foundation of China under Grant 50377017.

References

[1] N.G. Hingorani, L. Gyugyi, Understanding FACTS, IEEE Press, 2000.
[2] G. Asplund, Application of HVDC light to power system enhancement, IEEE Power Engineering Society Winter Meeting, vol. 4, January 2000, pp. 2498–2503.
[3] B.R. Andersen, L. Xu, P.J. Horton, P. Cartwright, Topologies for VSC transmission, Power Eng. J. 16 (2002) 142–150.
[4] G. Venkataramanan, B.K. Johnson, A superconducting DC transmission system based on VSC transmission technologies", IEEE Trans. Appl. Supercond. 13 (2003) 1922–1925.
[5] F.A.R. Al Jowder, B.T. Ooi, VSC-HVDC station with SSSC characteristics, IEEE Trans. Power Electron. 19 (4) (2004) 1053–1059.
[6] X.-P. Zhang, Multiterminal voltage-sourced converter-based HVDC models for power flow analysis, IEEE Trans. Power Sys. 19 (4) (2004) 1877–1884.
[7] G. Zhang, Z. Xu, Steady-state model for VSC based HVDC and its controller design, IEEE Power Engineering Society Winter Meeting, vol. 3, 28 January–1 February 2001, pp. 1085–1090.
[8] H. Sugimoto, S. Morimoto, M. Yano, A high performance control method of a voltage-type PWM converter, in: Power Electronics Specialists Conference, vol. 1, 1988, pp. 360–368.
[9] C. Schauder, H. Mehta, Vector analysis and control of advanced static var ompensators, Generation, Transmission and Distribution, IEE Proceedings C 140 (4) (1993) 299–306.
[10] L. Thomas, S. Pdlain, A. Benchaib, Analysis of a robust DC-bus voltage control system for a VSC transmission scheme, Seventh International Conference on AC–DC Power Transmission, IEE Conference Publication No. 485, IEE 2001, London, UK, pp. 119–124.
[11] L. Xu, B.R. Andersen, P. Cartwright, Control of VSC transmission systems under unbalanced network conditions, in: Transmission and Distribution Conference and Exposition, IEEE PES, vol. 2, September 7–12, 2003, pp. 626–632.
[12] L.A. Lamont, Student member, in: Fast VSC Transmission Control Power Systems Conference and Exposition, IEEE PES, vol. 2, October 10–13, 2004, pp. 739–743.
[13] H. Akagi, et al., Performance of a self-commutated BTB HVDC link under a SLG fault condition, IEEE Trans. Power Electron. 18 (1) (2003) 278–285.
[14] M. Durrant, H. Werner, K. Abbott, Synthesis of multi-objective controllers for a VSC HVDC terminal using LMIs, in: 43rd IEEE Conference on Decision and Control, vol. 4, December 14–17, 2004, pp. 4473–4478.

[15] P.V. Kokotovic, The joy of feedback: nonlinear and adaptive, IEEE Trans. Control Sys. Technol. 12 (1992) 7–17.
[16] M. Krstic, I. Kanellakopoulos, P. Kokotovic, Nonlinear and Adaptive Control Design, Wiley, New York, 1995.
[17] Y. Zhang, B. Fidan, P.A. Ioannou, Backstepping control of linear time-varying systems with known and unknown parameters, IEEE Trans. Automatic Control 48 (11) (2003) 1908–1925.

Si-Ye Ruan received his bachelor degree in Electrical Engineering from Tsinghua University, PR China, in 2003. He is a Ph.D. candidate in the Department of Electrical Engineering, Tsinghua University, PR China. His current project is nonlinear control of VSC-HVDC transmission system.

Guo-Jie Li received his bachelor and master degrees in Electrical Engineering from Tsinghua University, PR China, in 1989 and 1993, respectively. He also received the Ph.D. degree in the School of Electrical and Electronic Engineering, Nanyang Technological University Singapore, in 1999. Currently, he is an associate professor in the Department of Electrical Engineering, Tsinghua University, PR China. His current research interests include power system analysis and control, power electronics, power quality and VSC-HVDC.

Xiao-Hong Jiao received the B.Eng. and M.Sc. degrees in Automatic Control from Northeast Heavy Machinery Institute, China, in 1988 and 1991, respectively, and the Ph.D. degree in Mechanical Engineering from Sophia University, Tokyo, Japan, in 2004. Now, she is doing postdoctoral work in the Department of Electrical Engineering, Tsinghua University, China. Simultaneously, she is a professor in the Department of Automatic Control, Yanshan University, China. She is working on robust control and adaptive control of nonlinear systems, time-delay systems.

Yuan-Zhang Sun received the B.S. degree from Wuhan University of Hydro and Electrical Engineering, China, in 1978, the M.S. degree from Electric Power Research Institute (EPRI), China, in 1982, and Ph.D. degree from Tsinghua University, Beijing, in 1988, all in electrical engineering. From 1982 to 1985, he was with the EPRI, China, working in the Power System Research Department. He is a professor at Tsinghua University and the head of Dynamic Simulation Power System Lab, and he has been appointed as a “ChangJiang Scholar” since 1999.

T.T. Lie received his bachelor degree in Electrical Engineering from Oklahoma State University, USA, in 1986. He also received his Master of Science and Ph.D. degrees in Electrical Engineering from Michigan State University, USA, in 1988 and 1992, respectively. Currently, he is an associate professor in the School of Electrical and Electronic Engineering, Nanyang Technological University Singapore. His current research interests include AI applications in power systems, power system control, planning and operation, deregulated power market and energy management.