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RESEARCH ARTICLE

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A robust adaptive control with unmodeled dynamic for HVDC transmission systems

Abstract Utilizing the feature of quick response of HVDC to improve the performance of AC/DC system has become the emphasis to be researched. This paper introduces firstly the principle of the robust adaptive control of nonlinear systems with unmodeled dynamics, then developed the robust adaptive additional control of HVDC with unmodeled dynamics of generator in order to improve stability of power system. The additional control of HVDC with unmodeled dynamics only uses the local signals and its design is simple, furthermore it can obviously improve the stability of power system in different operational conditions. Experimental results using the presented concepts obtained on single machine infinite bus model are also included. These results prove the efficiency of the control scheme. The design process of controller provided a new idea to design controller by use of simplified model.

Keywords HVDC, unmodeled dynamics, robust adaptive control, the stability of power system

1 Introduction

With merits such as quick adjustment, flexible operation and capability to change power distribution, HVDC is widely used in remote bulk power transmitting and interconnection of area power systems. With the development of modern power systems, increasing attention is focused on the better utilization of quick responses to improve the performance and stability of power systems. The controllers designed by such methods that are in existence such as the nonlinear optimal control and PID control show poor performance under different operating conditions and disturbances. The controller based on nonlinear backstepping design method shows a good robust performance, but the unmodel dynamic of the generator is not considered. References [1, 2] pointed out that the unmodel dynamics may cause a deterioration in the stability of the adaptive control system and may even lead to the adaptive controller becoming ineffectual in long run.

For a power system that is a typical large-scale nonlinear system, the utilization of global decentralized control for improving system dynamic performance is an essential issue. In recent years various nonlinear adaptive control schemes have been presented. Because of the simple design and the nice robust performance, there has been increasing focus on the nonlinear robust adaptive control theory with unmodeled dynamics. As the first step to realizing the global decentralized control by using of the nonlinear robust adaptive control theory with unmodeled dynamics, the main task in this paper is to develop a robust adaptive control of HVDC based on local measurement. The robust adaptive controller of HVDC with unmodeled dynamics is developed based on the second model of generator with unmodeled dynamics and the quasi-steady-state model of HVDC, with a view to improving the stability of the system. It can be noted that only local measurable quantities are used in the controller. In the final stage, case studies of single machine infinite bus (SMIB) prove the validation of the robust adaptive controller.

2 The model of AC\DC power system

The typical AC\DC power system is illustrated in Fig. 1: the machine is adopted as a classical model with the unmodeled dynamics of the generator. Due to the quick response of HVDC compared with mechanic-electrical dynamic, the process of power changing for HVDC can be ignored and we approximately think that the transit power of HVDC can

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be immediately adjusted by control. Assuming G2 is infinite compared to G1, the rotor motion equation of G1 is derived as follows:

$$\begin{cases}\dot{\delta}_1=\omega_1\\ \dot{\omega}_1=\dfrac{-P_{\mathrm{dc}}}{T_{\mathrm{J}_1}}-\dfrac{P_{\mathrm{m1}}-\omega_1 D_1-\dfrac{\mathrm{E}'_{\mathrm{q}_1}U\left(\sin\delta_1\right)}{X'_{\mathrm{d1}}}}{T_{\mathrm{J}_1}}\end{cases} \tag{1}$$

The unmodeled dynamics of the generator G1 is:

$$\dot{\mathrm{E}}'_q=\frac{\mathrm{E}_{\mathrm{fd}}-\left(\mathrm{E}'_{\mathrm{q}}+\left(x_{\mathrm{d}}-x'_{\mathrm{d}}\right)\dfrac{\mathrm{E}'_q-V_t\cos\delta}{x'_{\mathrm{d}}}\right)}{T_{\mathrm{d0}}} \tag{2}$$

where δ_1, ω_1, D_1, T_{J_1}, P_{m1}, E'_{q} are respectively rotor angle, angular velocity of the rotor, damping coefficient, inertia constant, mechanical power and the voltage behind transient reactance of generator G1.

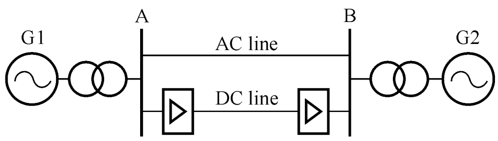

Fig. 1 Single machine infinite bus system

3 The additional controller design of HVDC

For AC\DC power system, the control object is to keep the constant rotor angle after the disturbance or faults. Referencing the design method of robust adaptive controller with unmodeled dynamics in Refs. [3, 4], the additional controller of HVDC is developed. Let

$$y=\delta_1,\quad \dot{y}=\dot{\delta}_1=\omega_1,\quad u=-P_{\mathrm{dc}}/T_{\mathrm{J}_1}$$

Then

$$\ddot{y}=f\left(y,\dot{y}\right)+\Delta\left(y,u\right)+u+d(t) \tag{3}$$

where

$$f\left(y,\dot{y}\right)=\left(P_{\mathrm{m1}}-\dot{y}D_1\right)/T_{\mathrm{J}_1}$$

$$\Delta\left(y,u,E'_{\mathrm{q1}}\right)=-\mathrm{E}'_{\mathrm{q1}}U\left(\sin\delta_1\right)/X'_{\mathrm{d1}}$$

$d(t)$ is unknown disturbance and satisfy $d(t)\leqslant d_{\sup}$ $\left(d_{\sup}=\sup\left(\mathrm{E}'_{\mathrm{q1}}U/X'_{\mathrm{d1}}\right)\right)$.

Assuming $e_1=y-\delta_{10}$, $e_2=\dot{y}-\omega_{10}$, we get

$$\dot{e}=\boldsymbol{Ae}+\boldsymbol{b}\left[f\left(\boldsymbol{e}+\widehat{\boldsymbol{y}}_{\mathrm{r}}\right)+u+\Delta\left(\boldsymbol{e}+\widehat{\boldsymbol{y}}_{\mathrm{r}},u,\mathrm{E}'_{\mathrm{q}}\right)+d(t)\right] \tag{4}$$

where

$$\widehat{\boldsymbol{y}}_{\mathrm{r}}=\left(y_r,\dot{y}_r\right)^{\mathrm{T}},\quad \boldsymbol{e}=\left[e_1,e_2\right]^{\mathrm{T}}$$

$$\boldsymbol{A}=\begin{bmatrix}0&1\\0&0\end{bmatrix},\quad \boldsymbol{b}=\begin{bmatrix}0\\1\end{bmatrix}$$

Let $\boldsymbol{A}_{\mathrm{m}}=\boldsymbol{A}-\boldsymbol{bK}$, where $\boldsymbol{K}=\begin{bmatrix}k_1 & k_2\end{bmatrix}$ is chosen so that $\boldsymbol{A}_{\mathrm{m}}$ is Hurwitz. Then, there exists a matrix $\boldsymbol{P}$ satisfying

$$\boldsymbol{PA}_{\mathrm{m}}+\boldsymbol{A}_{\mathrm{m}}^{\mathrm{T}}\boldsymbol{P}=-\boldsymbol{Q} \tag{5}$$

where $\boldsymbol{Q}=\boldsymbol{Q}^{\mathrm{T}}>0$

Then, we have

$$\dot{e}=\boldsymbol{A}_{\mathrm{m}}\boldsymbol{e}+\boldsymbol{b}\left[\boldsymbol{Ke}+f\left(\boldsymbol{e}+\widehat{y}_{\mathrm{r}}\right)+u+\Delta\left(\boldsymbol{e}+\widehat{y}_{\mathrm{r}},u,\mathrm{E}'_q\right)+d(t)\right] \tag{6}$$

For unmodeled dynamics $\omega=\mathrm{E}'_{q1}$, we get

$$\left|\varDelta\left(y,u,\omega\right)\right|\leqslant\max\left(U/X'_{\mathrm{d}_1}\right)\left|\omega\right|,\quad \Delta\left(0,u,0\right)=0$$

Let $V_\omega\left(\omega\right)=E'^2_{\mathrm{q}}$, $\alpha_1\left(\left\|E'_{\mathrm{q1}}\right\|\right)=0.8E'^2_{\mathrm{q}}$, $\alpha_2\left(\left\|E'_{\mathrm{q1}}\right\|\right)=1.2E'^2_{\mathrm{q}}$, we get

$$\alpha_1\left(\left\|E'_{\mathrm{q1}}\right\|\right)\leqslant V_\omega\left(\omega\right)\leqslant\alpha_2\left(\left\|E'_{\mathrm{q1}}\right\|\right) \tag{7}$$

$$\dot{V}_\omega\left(\omega\right)\leqslant-2\frac{x_{\mathrm{d}}}{x'_{\mathrm{d}}T_{\mathrm{d0}}}V_\omega\left(\omega\right)+2\frac{\left(x'_{\mathrm{d}}E_{\mathrm{fd}}+\left(x_{\mathrm{d}}-x'_{\mathrm{d}}\right)V_t\right)^2}{x'_{\mathrm{d}}T_{\mathrm{d0}}x_{\mathrm{d}}}+\gamma\left(\left\|x\right\|\right) \tag{8}$$

$$\gamma\left(\left\|x\right\|\right)=\left\|x\right\|^2$$

In order to counteract the effects of unmodeled dynamics to the control system, we use a dynamic signal described by

$$\dot{\boldsymbol{r}}=-\overline{c}_0\boldsymbol{r}+r_{\mathrm{m}}\left(\boldsymbol{e},\overline{\boldsymbol{y}}_{\mathrm{r}}\right),\ \boldsymbol{r}\left(0\right)>0 \tag{9}$$

where

$$r_{\mathrm{m}}\left(\boldsymbol{e},\overline{\boldsymbol{y}}_{\mathrm{r}}\right)=\left\|\boldsymbol{e}+\overline{\boldsymbol{y}}_{\mathrm{r}}\right\|^2+d_0$$

$$d_0=\max\left(2\frac{\left(x'_{\mathrm{d}}E_{\mathrm{fd}}+\left(x_{\mathrm{d}}-x'_{\mathrm{d}}\right)V_t\right)^2}{x'_{\mathrm{d}}T_{\mathrm{d0}}x_{\mathrm{d}}}\right)$$

In order to counteract the effects of uncertainty of parameter and disturbance to the control system, we use a dynamic signal described by

$$\dot{\beta}=\beta_m-\Gamma\sigma\beta \tag{10}$$

where $\Gamma>0$, $\sigma>0$ are design constants. β_{m} will be deduced later.

The control law of HVDC additional controller is deduced by using Lyapunov theory in the following context.

Consider the Lyapunov function candidate

$$\boldsymbol{V}=\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pe}+\Gamma^{-1}\left(\beta-\beta^*\right)^2 \tag{11}$$

where $\beta^*>0$ is a constant, which is the desired value of β. Taking the time derivative of $\boldsymbol{V}$ along the solutions of Eqs. (8) and (9), we get

$$\begin{aligned}\dot{\boldsymbol{V}}\leqslant&-\boldsymbol{e}^{\mathrm{T}}Q\boldsymbol{e}+2\left|\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pb}\right|\cdot\left|\boldsymbol{Ke}\right|+2\left|\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pb}\right|\\&\cdot\left[\overline{f}\left(\boldsymbol{e}+\widehat{\boldsymbol{y}}_{\mathrm{r}},u\right)+c_3\left\|\omega\right\|+\left|d\left(t\right)\right|\right]-2\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pb}u\\&+2\Gamma^{-1}\beta\beta_m-2\Gamma^{-1}\beta^*\beta_m-2\sigma\beta\left(\beta-\beta^*\right)\end{aligned} \tag{12}$$

From the conclusion in Ref. [3], we get

$$2c_3\left|\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pb}\right|\cdot\left\|\omega\right\|\leqslant2c_3\left|\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pb}\right|c'_3$$

$$c'_3=\sup\left(\alpha^{-1}\left(2r\right)+\alpha^{-1}\left(2D\left(t\right)\right)\right) \tag{13}$$

where $D(t) = 0, t \geqslant T^0 \geqslant 0$

Then, we get

$$\dot{V} \leqslant -e^{\mathrm{T}}Qe - 2\beta^*\left(\left|e^{\mathrm{T}}Pb\right|\cdot\left|Ke\right| - \frac{1}{2\beta^*}\right)^2$$
$$-2\beta^*\left(\left|e^{\mathrm{T}}Pb\right|\cdot\bar{f}\left(e+\hat{y}_{\mathrm{r}},u\right) - \frac{1}{2\beta^*}\right)^2$$
$$-2\beta^*\left(\left|e^{\mathrm{T}}Pb\right|\cdot\left|e+\hat{y}_{\mathrm{r}}\right| - \frac{c_3}{2\beta^*}\right)^2 - 2\beta^*$$
$$\cdot\left(\left|e^{\mathrm{T}}Pb\right|\cdot - \frac{c_3' + d_{\mathrm{sup}}}{2\beta^*}\right)^2 - 2e^{\mathrm{T}}Pbu$$
$$+2\Gamma^{-1}\beta\beta_m - 2\Gamma^{-1}\beta^*\beta_m - 2\sigma\beta\left(\beta-\beta^*\right)$$
$$+H + 2\beta^*\left(e^{\mathrm{T}}Pb\right)^2 M \tag{14}$$

where $H = \sigma\beta^{*2} + \left[c_3^2 + \left(c_3' + d_{\mathrm{sup}}\right)^2 + 1\right] \big/ 2\beta^*$,

$$M = \left[P_{\mathrm{mi}} - \frac{\left(\mathrm{E_q} + \dfrac{(x_{\mathrm{d}} - x_{\mathrm{d}}')V_t}{2x_{\mathrm{d}}'}\right)U}{X_{\mathrm{d}}'}\right]^2$$
$$+\delta^2 + \omega^2 + u^2 + 2r + (Ke)^2 + 1,$$

Let $-2\Gamma^{-1}\beta^*\beta_m + 2\beta^*\left(e^{\mathrm{T}}Pb\right)^2 \times M = 0$

$-2e^{\mathrm{T}}Pbu + 2\Gamma^{-1}\beta^*\beta_m = 0$

From Eq. (13), we get

$$\dot{V} \leqslant -e^{\mathrm{T}}Qe - \sigma\left(\beta-\beta^*\right)^2 + H \tag{15}$$

Thus

$$\dot{V} \leqslant \mu V + H \tag{16}$$

where $\mu = \min\left\{\dfrac{\lambda_{\min}(Q)}{\lambda_{\max}(Q)}, \sigma\Gamma\right\}$

Therefore, V decreases monotonically. Furthermore, it can be seen from Eq. (16) that choosing Q and design constants σ, Γ appropriately will make the tracking error arbitrarily small.

The control law of HVDC additional controller is derived as followed:

$$u = -\beta e^{\mathrm{T}}PbM \tag{17}$$

$$\beta_{\mathrm{m}}\left(e, z, r, \bar{y}_{\mathrm{r}}\right) = \Gamma\left(e^{\mathrm{T}}Pb\right)^2 M \tag{18}$$

It can be seen from the process of controller design that the control input needs only local signals such as the rotor angle of generator and frequency of power system. Therefore, the control is local and the control input is adaptive to the uncertainties of disturbance and operation.

4 Case study

The proposed control algorithms were tested using single-line diagram of SMIS shown in Fig.1 and parameters of generator G1 are shown in Table 1. To test the robust and adaptive performance of the controller, two cases are studied. The electrical power of generator G1 in case 1 and case 2 is respectively 1 000 MW and 1 200 MW. In each case, the PID control and the robust adaptive control presented in this paper are respectively adopted as the HVDC additional controller. Disturbance is a fault at bus A at time t = 0.2 s, which is cleared at t = 0.3s.The simulation results are illustrated in Figs. 2 and 3. Figures. 2 and 3 show respectively the rotor angle swing curve under the disturbance in case 1 and in case 2.

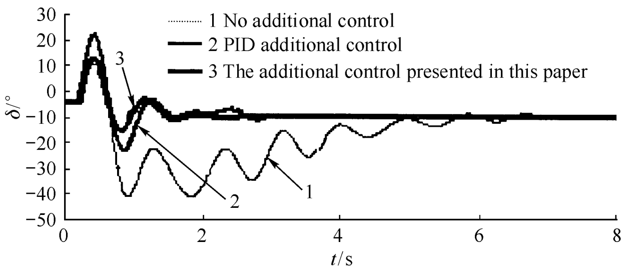

Fig. 2 Three phase short circuits at bus A in case 1

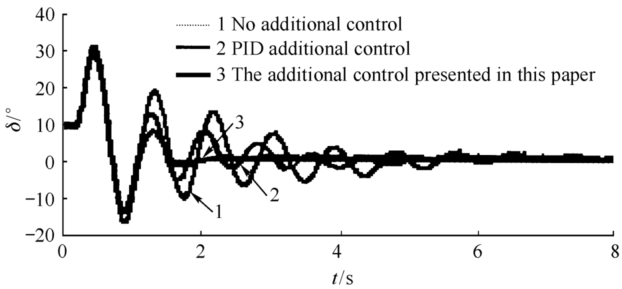

Fig. 3 Three-phase short circuits at bus A in case 2

The controller design constants presented in this paper are shown in Table 2. The conventional PID controller parameters are shown in Table 3.

Table 1 Parameters of generator

T_{d0}	x_{d}	x_{d}'	T_{J}	D
0.9	2.15/pu	0.34/pu	7/s	1.5

Table 2 Design constants of additional control with unmodeled dynamics

σ	Γ	$\bar{c}_0$	$r(0)$	$\beta(0)$	d_0
10	0.1	0.1	1	10	40

Table 3 Parameters of PID control

	T	K
DC1	0.05	20

It can be seen from Fig. 2 and Fig. 3 that the system damping is poor in both case 1 and case 2 when there is no additional control of HVDC. The system performance is improved to a certain degree, but it is undesirable due to the long time oscillation in both case 1 and case 2 when there is PID additional control of HVDC. The reduction of oscillation time and scope show the obvious improvement to the system performance in both case 1 and case 2 when there is additional control of HVDC presented in this paper.

5 Conclusions

In this paper, the utilization of the additional control of HVDC to improve transient stability is studied. Based on the nonlinear robust adaptive control theory, the nonlinear robust adaptive additional controller of HVDC is developed. The deducing process of additional controller proved that it is effective to deal with the uncertainties of parameters and disturbances. Further, the control is decentralized since it depends solely upon measurements made and fed back at each generator. The simulation results also prove that the control is adaptive, robust against arbitrary disturbances and the parameter uncertainty. Furthermore, due to its simple design process and easy realization, the method opens a new way in designing robust adaptive controller by using the reduced model of power system.

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References

1. Pierre D. A., A perspective on adaptive control of power systems, IEEE Transactions on power systems, 1987, 2: 387–396
2. Rohrs, C. E., Valavani, Athans M. et al., Robustness of continuous-time adaptive control algorithms in the presence of unmodeled dynamics, IEEE Transactions on Automatic Control, 1985, 30: 881–889
3. Liu Yu-sheng, Li Xing-yuan, Robust adaptive control of nonlinear systems represented by input-output model, IEEE Transactions on Automatic Control, 2003, 48(6): 1041–1045
4. Liu Yu-sheng, Li Xing-Yuan, Decentralized robust adaptive control of nonlinear systems with unmodeled dynamics, IEEE Transactions on Automatic Control, 2002, 47: 848–856
5. Khalil H. K., Adaptive output feedback control of nonlinear systems represented by input-out models, Automat. Contr., 1996, 42: 177–188
6. Jiang Z. P., Praly L., Design of robust adaptive controllers for nonlinear systems with dynamic uncertainties, Automatica, 1998, 34: 825–840
7. Li Xing-yuan, Liu Hong-chao, Qiu Xiao-yan et al., A nonlinear control strategy of HVDC for improving transient stability of power system, Automation of E1ectric Power Systems, 2002, 26(14): 16–19 (in Chinese)
8. Chen ling-yun, Li Xing-yuan, Liu Hong-chao et al., Design of nonlinear variable-structure controller in HVDC systems, Automation of E1ectric Power Systems, 2003, 27(4): 6–9 (in Chinese)
9. Zhu Ming, Liu Yu-sheng, Li Xing-yuan et al., Design of decentralized robust adaptive controllers for HVDC converts, Automation of E1ectric Power Systems, 2003, 27(2): 41–45 (in Chinese)
10. Shao Zhen-xia, Li Xing-yuan, Method of implementating digital simulation for HVDC controller, Journal of Sichuan University (Engineering Science Editon), 2002, 34(3): 80–83 (in Chinese)
11. Li Xing-yuan, Operation and control of HVDC transmission system, Beijing: Science Press, 1998 (in Chinese)