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Short communication

Adaptive backstepping control for hybrid excitation synchronous machine with uncertain parameters

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ABSTRACT

This paper proposes an adaptive backstepping speed controller for a novel hybrid excitation synchronous machine (HESM) with nonlinear coupling and parametric uncertainty. With the proposed adaptive backstepping controller, the speed tracking of the HESM possesses the advantages of good transient control performance and robustness to the parametric uncertainty and load torque disturbance. Stability analysis for the control system is presented theoretically. Simulation results validate the effectiveness of the proposed control scheme.

1. Introduction

The HESM was first advanced in 1988 (Dou, 2002). Different from general excitation synchronous machine and permanent-magnet synchronous machine in structure, HESM has permanent-magnet and field winding and its two-magnetization sources are concurrent. Inheriting the advantages of both permanent-magnet machine and excitation machine, it has a widely development prospect (Matsuuchi, Fukami, Naoe, & Hanaoka, 2005; Zhao & Yan, 2005). Vulnerable to the influence of various perturbations, the HESM system is highly nonlinear multivariable system with strong coupling. The high nonlinearity is due to the coupling between speed and armature currents, and the perturbations such as inadequate modeling (torque ripple, magnetic circuit saturation, friction torque, inverter nonlinearity etc. are not taken into account), uncertain parameters (armature winding resistance, moment of inertia etc.), as well as errors caused by sensors (angular position, angular velocity) and discretization influences (delay, numerical errors).

Recently, HESM attracts increasing attention and becomes one of the new research hotspots as much work has been done on saving energy and wide timing drive system (Zhao & Yan, 2005). Most of the recent researches on HESM focus on machine design, manufacture and test analysis (Dou, 2002; Matsuuchi et al., 2005; Zhao & Yan, 2005), while almost non of them refers to speed regulating. The HESM system is affine in control; hence it is natural to apply geometric theory of nonlinear system to the HESM. The main results are that the HESM system is locally weakly controllable, strongly accessible and locally weakly observable, that it is input–output invertible and linearizable, and that linear control strategy has been effectively applied for the HESM (Kang, Xie, & Yang, 2006; Kang, Xie, & Zheng, 2007; Xie & Kang, 2006). The linear control strategy is realized depending on the accurate elimination of nonlinear terms which will lead to performance deterioration. The linear control strategy can guarantee stability of system in a neighborhood of the equivalent equilibrium point with uncertainties. The uncertainties derive from uncertain parameters or variable environment temperature. As a result, the linear control strategy will fail to guarantee the global stability within the scope of servo drive (Kang et al., 2006; Kang et al., 2007). Therefore, it is necessary to consider the uncertainties in the research of control strategy for HESM.

In the control field, backstepping control receives wide attention since it is fit for uncertain nonlinear systems, particularly for the control systems with mismatched uncertainties (Khailil, 2002; Kokotovic, 1992). It has been extended to the adaptive control, robust control, sliding variable structure control and other control designs. Backstepping design can guarantee global stability and good tracking performance for a broad class of strict-feedback systems. Also, it is applied efficiently in electric machines (Dawson, Hu, & Burg, 1998; Hu & Zou, 2006; Lin & Lee, 2000; Rahman, Vilathgamuwa, Duddin, & Tseng, 2003; Taylor, 1994; Zhou & Wang, 2002). The justification for backstepping design is established through Lyapunov analysis, similar design tool is introduced in electric machines (Dawson et al., 1998). An adaptive backstepping approach was presented to obtain the robustness for uncertainties for linear induction motor (Lin & Lee, 2000). Backstepping design is summarized for nonlinear control of electric machines in reference (Taylor, 1994). In order to take the advantage of the backstepping control for mismatched perturbation and uncertainties, we apply it to the speed control system for HESM with uncertain parameters in this paper.

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This paper is organized as follows. The HESM drive model in the synchronously rotating rotor $d-q$ coordinates is presented in Section 2. In Section 3, a nonlinear adaptive controller is designed according to backstepping technique. This method effectively compensates for the HESM system parametric uncertainty. Section 4 analyzes the stability of the overall control system. Numerical simulation illustrated in Section 5 shows the effectiveness of the designed controller. Section 6 concludes this paper.

2. HESM drive model

The HESM can be described by the following dynamical equations in the synchronously rotating rotor $d-q$ coordinates (Kang et al., 2007):

$$\begin{cases} \frac{d\omega}{dt} = -\frac{R_\Omega}{J}\omega + \frac{P_n}{J}(L_d - L_q)i_d i_q + \frac{P_n \Psi_a}{J} i_q + \frac{P_n M_f}{J} i_q i_f - \frac{1}{J}T_l, \\ \frac{di_d}{dt} = -L_f RKi_d + L_f L_q K p_n \omega i_q + M_f R_f K i_f + L_f K u_d - M_f K u_f, \\ \frac{di_q}{dt} = \frac{-L_d}{L_q} P_n \omega i_d + \frac{-R}{L_q} i_q - \frac{M_f}{L_q} P_n \omega i_f + \frac{-\Psi_a}{L_q} P_n \omega + \frac{1}{L_q} u_q, \\ \frac{di_f}{dt} = M_f RKi_d - M_f L_q K P_n \omega i_q - L_d R_f K i_f - M_f K u_d + L_d K u_f, \end{cases} \tag{1}$$

where u_d, u_q, u_f are d- and q-axes stator, auxiliary excitation winding voltages, respectively; i_d, i_q, i_f are d- and q-axes stator, auxiliary excitation winding currents, respectively; R, R_f are stator per-phase, auxiliary excitation winding resistances respectively; L_d, L_q, L_f are d- and q-axes stator, auxiliary excitation winding inductances, respectively; M_f is the mutual induction between auxiliary excitation winding and d-axis winding; Ψ_a is the flux linkage of rotor permanent-magnet; P_n is the number of poles of the machine; ω is the rotor speed in angular frequency; J is the moment of inertia of the machine and load; R_Ω is the friction coefficient of the machine; and T_l is the load torque.

$$K = \frac{1}{L_d L_f - M_f^2}.$$

In the model, u_d, u_q and u_f are input variables, which is suitable for the HESM driven by voltage source. The model is affine in inputs and the inputs never appear in the first equation. It happens to provide a precondition for the application of backstepping technique.

3. Adaptive backstepping controller design

The objective of this paper is to obtain the HESM control voltages in order to achieve high-performance speed tracking. In this section, we design a nonlinear adaptive controller according to backstepping technique.

Set state variables as: $x = [\omega\ i_d\ i_q\ i_f]^T$.

The process of the controller design is divided into two steps. In the first step, the last three state components are treated as virtual inputs and a virtual control law is designed to make the first component of state track the measurable reference speed x_{1d}. In the second step, the last three components should be approached to the corresponding virtual control laws respectively. In this step the HESM control voltages will be designed completely with the adaptive control laws overcoming the parametric uncertainty.

Step1 : Design of the virtual control laws.

Let x_{1d} be the reference input which should be tracked. Define the errors as follows:

$$z_1 = x_1 - x_{1d}, \tag{2}$$

$$z_2 = x_2 - \alpha_2, \tag{3}$$

$$z_3 = x_3 - \alpha_3, \tag{4}$$

$$z_4 = x_4 - \alpha_4, \tag{5}$$

where α_2, α_3 and α_4 are the undetermined virtual control laws.

Differentiating z_1, it leads to

$$\dot{z}_1 = \frac{p_n}{J}(L_d - L_q)i_q(z_2 + \alpha_2) + \frac{p_n \Psi_a}{J}(z_3 + \alpha_3) + \frac{p_n M_f}{J} i_q(z_4 + \alpha_4) - \frac{R_\Omega}{J}(z_1 + x_{1d}) - \frac{1}{J}T_l - \dot{x}_{1d}. \tag{6}$$

Choose

$$V_1 = \frac{1}{2}z_1^2 \tag{7}$$

as a Lyapunov function of subsystem (6), and suppose $z_2 = 0, z_3 = 0, z_4 = 0$, then the derivative of V_1 along with subsystem (6) is

$$\dot{V}_1 = z_1\left[\frac{p_n}{J}(L_d - L_q)i_q\alpha_2 + \frac{p_n \Psi_a}{J}\alpha_3 + \frac{p_n M_f}{J} i_q \alpha_4 - \frac{R_\Omega}{J}(z_1 + x_{1d}) - \frac{1}{J}T_l - \dot{x}_{1d}\right]. \tag{8}$$

Let

$$\alpha_2 = 0, \tag{9}$$

$$\alpha_4 = 0, \tag{10}$$

$$\alpha_3 = -\frac{J}{p_n \Psi_a}\left(c_1 z_1 - \frac{R_\Omega}{J}(z_1 + x_{1d}) - \frac{T_l}{J} - \dot{x}_{1d}\right), \tag{11}$$

where $c_1 > 0$. Then Eq. (8) is simplified as follows:

$$\dot{V}_1 = -c_1 z_1^2. \tag{12}$$

Eq. (12) implies that the tracking error z_1 converges to zero asymptotically. In other words, the state x_1 will track the reference speed x_{1d} asymptotically.

So the controller should be designed to ensure that $[x_2\ x_3\ x_4]$ converges to $[\alpha_2\ \alpha_3\ \alpha_4]$ given in Eqs. (9)–(11). Eq. (11) includes moment of inertia J, friction coefficient R_Ω and load torque T_l, which varies along with the load. To simplify, we define

$$F = \frac{R_\Omega}{J}, \tag{13}$$

$$\Gamma = \frac{T_l}{J}. \tag{14}$$

And $\widehat{F}$ and $\widehat{\Gamma}$ are their normal values, respectively.

$$\begin{cases} \widetilde{J} = \widehat{J} - J, \\ \widetilde{F} = \widehat{F} - F, \\ \widetilde{\Gamma} = \widehat{\Gamma} - \Gamma, \end{cases} \tag{15}$$

where $\widehat{J}$ is the normal value of J, $\widetilde{J}$, $\widetilde{F}$ and $\widetilde{\Gamma}$ are the corresponding estimated errors, respectively.

Eq. (11) is rewritten as follows:

$$\alpha_3 = -\frac{\widehat{J}}{p_n \Psi_a}(c_1 z_1 - \widehat{F}(z_1 + x_{1d}) - \widehat{\Gamma} - \dot{x}_{1d}). \tag{16}$$

Substituting Eq. (16) into Eq. (8), we obtain

$$\begin{aligned} \dot{V}_1 &= z_1\left[\frac{p_n}{J}(L_d - L_q)i_q z_2 + \frac{p_n \Psi_a}{J}(z_3 + \alpha_3) + \frac{p_n M_f}{J} i_q z_4 - F(z_1 + x_{1d}) - \Gamma - \dot{x}_{1d}\right] \\ &= z_1\left[\frac{p_n}{J}(L_d - L_q)i_q z_2 + \frac{p_n M_f}{J} i_q z_4 - (\widehat{F} - \widetilde{F})(z_1 + x_{1d}) - \widehat{\Gamma} + \widetilde{\Gamma} - \dot{x}_{1d} \right. \\ &\quad \left. + \frac{p_n \Psi_a}{J}(z_3 - \frac{\widehat{J}}{p_n \Psi_a}(c_1 z_1 - \widehat{F}(z_1 + x_{1d}) - \widehat{\Gamma} - \dot{x}_{1d}))\right] \\ &= z_1\left[\frac{p_n}{J}(L_d - L_q)i_q z_2 + \frac{p_n \Psi_a}{J} z_3 - (1 + \frac{\widetilde{J}}{J})(c_1 z_1 - \widehat{F}(z_1 + x_{1d}) - \widehat{\Gamma} - \dot{x}_{1d}) \right. \\ &\quad \left. + \frac{p_n M_f}{J} i_q z_4 - (\widehat{F} - \widetilde{F})(z_1 + x_{1d}) - \widehat{\Gamma} + \widetilde{\Gamma} - \dot{x}_{1d}\right] \\ &= z_1\left[\frac{p_n}{J}(L_d - L_q)i_q z_2 + \frac{p_n \Psi_a}{J} z_3 - \frac{\widetilde{J}}{J}(c_1 z_1 - \widehat{F}(z_1 + x_{1d}) - \widehat{\Gamma} - \dot{x}_{1d}) \right. \\ &\quad \left. + \frac{p_n M_f}{J} i_q z_4 + \widetilde{F}(z_1 + x_{1d}) + \widetilde{\Gamma} - c_1 z_1\right]. \end{aligned} \tag{17}$$