전기자동차용 동기기의 속도제어기 설계

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Design of a Speed Controller for the Synchronous Motor in Electric Vehicle

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Abstract - In this paper, a robust adaptive backstepping controller will be proposed for the speed control of permanent magnet synchronous motors in using electrical vehicles. Stator resistance, damping coefficient, load torque are considered as uncertainties and noise generated at applying load torque to motor is also considered. It shows that the backstepping algorithm can be used to solve the problems of nonlinear system very well and robust controller can be designed without the variation of adaptive law. Simulation results are provided to demonstrate the effectiveness of the proposed controller.

1. INTRODUCTION

Much research on EV is recently focused on how to design the control structures for the propulsion system containing an electric motor as well as the battery problems. DC motor drives are widely used in many industries which needs appropriately speed control in a wide range. Especially, permanent magnet synchronous motors (PMSM) are being used increasingly in various industrial fields. However, the dynamic model of a PMSM is highly nonlinear, because of the coupling between the motor speed and the electrical quantities such as d-q axis currents. In this paper, robust speed controller based on backstepping technique will be designed to restrain the effect of parameter variations and load torque disturbances in EV. Simulation and experiment results will be show that the proposed controller is feasible for the wide speed control of PMSM for PEV.

2. PROBLEM FORMALIZATION

Advancements in magnetic materials, semiconductor power devices, and control theory have made the PMSM drive play a very important role in motion-control applications in the low-to-medium power range. The desirable features of the PMSM are its compactstructure, high air-gap flux density, high power density, high torque-to-inertia ratio, and high torque capability. However, the control performance of the PMSM drive system is still influenced by the uncertainties of the plant, which usually are composed of unpredictable plant parameter variations, external load disturbances, and unmodelled nonlinear dynamics. The dynamic model of a typical surface-mounted PMSM will be described in the d-q frame as follows.

$$\begin{aligned}\frac{d}{dt}i_d &= -\frac{R}{L}i_d + P\omega i_q + \frac{1}{L}u_d \\ \frac{d}{dt}i_q &= -\frac{R}{L}i_q - P\omega i_d - \frac{P\Phi}{L}\omega + \frac{1}{L}u_q \\ \frac{d}{dt}\omega &= \frac{3P\Phi}{2J}i_q - \frac{B}{J}\omega - \frac{T_L}{J}\end{aligned} \tag{1}$$

where i_d and i_q are the d-q axis currents, ω is the motor speed, u_d and u_q are the d-q axis voltages, R is the stator resistance, L is the stator inductance, P is the pole pairs, Φ is the permanent magnet flux, J is the rotor moment of inertia, B is the viscous friction coefficient and T_L is the load torque. From (1), it is clear that the dynamic model of PMSM is highly nonlinear due to the coupling between the speed and the currents. Meanwhile, parameters such as resistance may vary due to heating during operation and it is also possible to change the load torque. Thus, when a high-performance speed controller is required, the nonlinearity and uncertainties as well as the load torque disturbance have to be taken into account. Generally, the load torque in PEV is modeled by considering the aerodynamic, rolling resistance and grading resistance as Fig 1 and will be a function of rotational speed as follows.

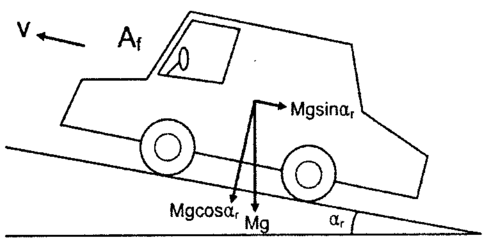


Fig 1. The load torque in PEV

$$\begin{aligned}F_a &= \frac{1}{2}\rho\, C_d\, A_f\, v^2 \quad &&: \text{aerodynamic drag} \\ F_r &= Mg\, C_r \cos\alpha_r &&: \text{rolling resistance} \\ F_g &= Mg \sin\alpha_r &&: \text{grading resistance}\end{aligned} \tag{2}$$

$$\text{total load torque}: \; T_L = \frac{R_t}{R_f}(F_a + F_r + F_g) + \delta_n$$

where, ρ is the air density, C_d is the aerodynamic drag coefficient, A_f is the frontal surface area, $v = (R_t/R_f)\,\omega$ is the linear speed of the vehicle, M is the mass of the vehicle, g is the gravitational constant, C_r is the rolling resistance coefficient, α_r is the grade angle. R_t is the radius of the tires, R_f is the total ratio between the motor shaft and the differential axle of the vehicle, and δ_n represents the irregular disturbance and noise. As shown in Equation 2, the load torque is a function of rotational speed represented as follows.

$$T_L = a_n\omega^2 + b_n \tag{3}$$

$$a_n = \frac{1}{2}\rho C_d A_f\left(\frac{R_t}{R_f}\right)^3, \quad b_n = Mg(C_r\cos\alpha_r + \sin\alpha_r)\frac{R_t}{R_f} + \delta_n$$

3. ROBUST SPEED CONTROLLER

The control objective in this paper is to design a robust speed controller, which can effectively stabilize and track the desired rotational speed reference and reject the effect of the parameter variations and disturbances, using the adaptive backstepping technique. Both the d-q voltages are taken as the control inputs. Backstepping control is a newly developed technique for the control of uncertain nonlinear systems, particularly those systems that do not satisfy matching conditions. The most appealing point of it is to use the virtual control variable to make the original high-order system simple, thus the final control outputs can be derived step by step through suitable Lyapunov functions. The compact form of the PMSM in (1) with uncertainties can be written as follows.

$$\frac{d}{dt}x = \bar{f}(x) + \Delta f(x) + g_1(x)u_d + g_2(x)u_q \tag{4}$$

$$x = [i_d \;\; i_q \;\; \omega],\; g_1 = [\tfrac{1}{L}\;\; 0\;\; 0]^T,\; g_2 = [0\;\; \tfrac{1}{L}\;\; 0]^T$$

$$\bar{f}(x) = \begin{bmatrix} -\frac{R_{nom}}{L}i_d + P\omega i_q \\ -\frac{R_{nom}}{L}i_q - P\omega i_d - \frac{P\Phi}{L}\omega \\ \frac{3P\Phi}{2J}i_q - \frac{B_{nom}}{J}\omega - \frac{a_{nom}}{J}\omega^2 - \frac{b_{nom}}{J}\end{bmatrix}$$

$$\Delta f(x) = \begin{bmatrix} -\frac{\Delta R}{L} i_d \\ -\frac{\Delta R}{L} i_q \\ -\frac{\Delta B}{J}\omega - \frac{\Delta a_n}{J}\omega^2 - \frac{\Delta b_n}{J} \end{bmatrix}$$

where R_{nom}, B_{nom}, a_{nom} and b_{nom} are the nominal values of R, B, a_n and b_n respectively. Define the uncertainties as $\Delta R = R - R_{nom}$, $\Delta B = B - B_{nom}$, $\Delta a_n = a_n - a_{nom}$ and $\Delta b_n = b_n - b_{nom}$. Define the new variables as follows.

$$z_1 = h_1(x) = \omega, \quad z_2 = L_f h_1(x), \quad z_3 = h_2(x) = i_d \tag{5}$$

In the new coordinates, it can be written as follows.

$$\frac{d}{dt}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} z_2 \\ L_f^2 h_1 \\ L_f h_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \bar{u}_d \\ \bar{u}_q \end{bmatrix} + \begin{bmatrix} \theta_1\phi_1 \\ \theta_2\phi_2 \\ \theta_3\phi_3 \end{bmatrix} \tag{6}$$

Now, a reference model is used to assign the desired output dynamic behaviour as follows.

$$\frac{d}{dt}\begin{bmatrix} z_{m1} \\ z_{m2} \\ z_{m3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -k_{m1} & -k_{m2} & 0 \\ 0 & 0 & -k_{m3} \end{bmatrix}\begin{bmatrix} z_{m1} \\ z_{m2} \\ z_{m3} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ k_{m1} & 0 \\ 0 & k_{m3} \end{bmatrix}\begin{bmatrix} \omega_{ref} \\ i_{dref} \end{bmatrix} \tag{7}$$

where, the model parameters k_{m1}, k_{m2} and k_{m3} are chosen by the designer for obtaining the response characteristics. The inputs of reference model are the rotational speed command ω_{ref} and the d-axis current command i_{dref} and in this paper we will use the method that the control inputs are only burdened by the q-axis current i_q while the d-axis current i_d is kept constant. Using the reference model, the performance of the system can easily be evaluated, as the tracking problem could be changed to a regulation problem. Define the error variables and parameter estimation errors as follows.

$$e = [e_1 \quad e_2 \quad e_3]^T = [z_1 - z_{m1} \quad z_2 - z_{m2} \quad z_3 - z_{m3}]^T \tag{8}$$

$$\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1, \ \tilde{\theta}_2 = \theta_2 - \hat{\theta}_2, \ \tilde{\theta}_3 = \theta_3 - \hat{\theta}_3 \tag{9}$$

Define the final Lyapunov function as follows.

$$V = \frac{1}{2}\bar{e}_1^2 + \frac{1}{2}\bar{e}_2^2 + \frac{1}{2}\bar{e}_3^2 + \frac{1}{2\gamma_1}\tilde{\theta}_1\tilde{\theta}_1^T + \frac{1}{2\gamma_2}\tilde{\theta}_2\tilde{\theta}_2^T + \frac{1}{2\gamma_3}\tilde{\theta}_3^2 \tag{10}$$

where, γ_1, γ_2 and γ_3 are the adaptation gains. Then the following results can be obtained.

$$\begin{aligned} \bar{u}_d &= -k_2\bar{e}_2 - \bar{e}_1 - L_f^2 h_1 - \hat{\theta}_2\phi_2 \\ &\quad + k_1^2\bar{e}_1 - k_1\bar{e}_2 - \phi_1^T\frac{d}{dt}\hat{\theta}_1^T - \hat{\theta}_1\frac{d}{dt}\phi_1 \\ \bar{u}_q &= -k_3\bar{e}_3 - L_f h_2 - \hat{\theta}_3\phi_3 \end{aligned} \tag{11}$$

$$\frac{d}{dt}\hat{\theta}_1 = \gamma_1(\bar{e}_1 + k_1\bar{e}_2)\phi_1^T, \ \frac{d}{dt}\hat{\theta}_2 = \gamma_2\bar{e}_2\phi_2^T, \ \frac{d}{dt}\hat{\theta}_3 = \gamma_3\bar{e}_3\phi_3 \tag{12}$$

Thus, the derivative of the Lyapunov function is negative definite as follows.

$$\frac{d}{dt}V = -k_1\bar{e}_1^2 - k_2\bar{e}_2^2 - k_3\bar{e}_3^2 \le 0 \tag{13}$$

Through Barbalat's lemma, it can be shown that $\bar{e}_1$, $\bar{e}_2$ and $\bar{e}_3$ will be converge to zero as $t \to \infty$. Therefore it can be concluded that the tracking objectives of the rotational speed ω and the d-axis current i_d have been achieved under parameter uncertainties and load torque disturbance. The block diagram of the nonlinear controller and adaptation laws for a speed tracking of PMSM in EV is given in Fig 2.

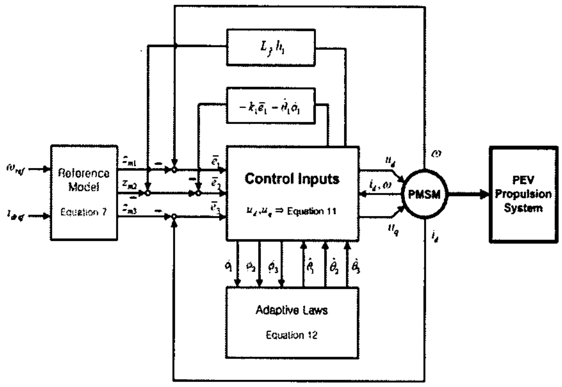
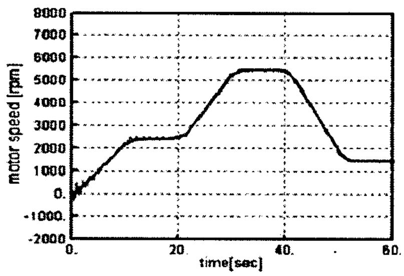


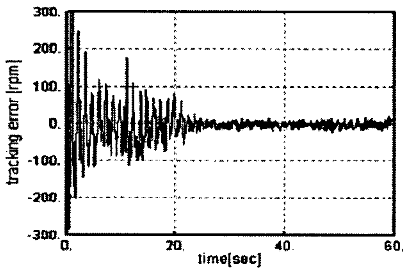
Fig 2. Block diagram for the proposed control system

4. SIMULATION RESULTS

Simulation results for speed control of PMSM in EV are depicted in Fig 3. It represents typical acceleration, constant speed and deceleration behaviors in a electric vehicle. The variations of load torque are appropriately given as a several sine functions and white noises. It is clearly known that the motor speed is tracking to the reference very well and tracking error decrease into ±20[rpm] ranges after 20[sec].



(a) Motor speed (red) and reference (black)



(b) Tracking error

Fig 3. Simulation results

5. CONCLUSIONS

In this paper, an robust adaptive backstepping controller was proposed for the speed control of permanent magnet synchronous motor(PMSM) in electric vehicles. Resistance, damping coefficient and load torque are considered as uncertainties and noise generated at applying load torque to motor is also considered. We will use the method that the control inputs are only burdened by the q-axis current while the d-axis current is kept to constant. Simulation results are provided to demonstrate the effectiveness of the proposed controller.

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