PMSM control for electric vehicle based on fuzzy PI

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Abstract: A fuzzy PI speed controller based on fuzzy control theory is proposed, which makes the drive control system of electric vehicle insensitive to disturbance and parameter change. The mathematical model of permanent magnet synchronous motor (PMSM) in d-q reference frame is established, fuzzy PI speed controller is designed based on fuzzy control theory, and simulation models of PMSM based on fuzzy PI control theory and sliding mode control theory are built in this paper. Two simulation models are simulated and analysed by Simulink, and simulation result shows that fuzzy PI control has faster dynamic response speed, better dynamic performance and better anti-interference ability than sliding mode control. Therefore, fuzzy PI control is an ideal control method, which has a certain reference value in vector control of PMSM for electric vehicle.

Keywords: electric vehicle; PMSM; permanent magnet synchronous motor; fuzzy PI; vector control; simulation analysis.


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1 Introduction

Permanent magnet synchronous motor (PMSM) is more and more applied in electric vehicle driving system for which it has many advantages, such as high efficiency, high power density and satisfactory control characteristics (Chen et al., 2016). The control performance of the drive motor has great influence on manoeuvrability, safety and riding comfort of the whole vehicle. Although the actual operating condition of PMSM is complicated, it is easily affected by the change of motor parameters and environment, so the study of improving dynamic response and robustness of the drive motor has become a research focus.

In order to improve the control performance of drive motor, many scholars have done a lot of research on PMSM speed vector control. A digital hardware was proposed to realise speed sensorless control of PMSM, extended Kalman filter was used to estimate rotor flux angle and rotor speed, which were fed back to current control loop and speed control loop respectively, in which PI controller acts on the speed loop, although the designed control system is complex (Zheng and Pi, 2016).

A space vector pulse width modulation (SVPWM) control algorithm based on back propagation (BP) neural network was proposed, and a BP neural network with strong nonlinear approximation ability was used to modulate SVPWM modulation wave of the triangular carrier, and control signal of three-phase inverter was obtained, but the learning speed of BP neural network is slow (Ji and Li, 2016). An integrated control method of position and speed based on dynamic sliding mode was proposed, which solves the speed control problem of traditional sliding mode variable structure control, but which causes high frequency noise and reduces the performance of controller when obtained speed differential (Xu and Lin, 2014). An online estimation system based on radial basis function (RBF) neural network was proposed, which improves the servo performance of drive motor system, but the design of performance index function is more complicated (Zhu et al., 2016). Combining fuzzy control with sliding mode control can reduce the chattering problem of drive motor control system, but it has the defect of weak practicality (Yuan and Lin, 2009).
A vector control system of PMSM for electric vehicles based on fuzzy PI is proposed. A mathematical model of PMSM in \(d-q\) reference frame is established, fuzzy PI speed controller and sliding mode speed controller are analysed and designed, simulation models of driving motor system based on fuzzy PI control theory and sliding mode control theory are constructed in Simulink environment, and simulation waveform of speed, torque and three-phase current are obtained through simulation experiments. Simulation results show that fuzzy PI speed controller for PMSM vector control has advantages of feasibility and excellent robustness.

2 Mathematical model of PMSM

As the driving part of electric vehicle, PMSM converts electrical energy into mechanical energy, which is a nonlinear, strong coupling multivariable system (Li, 2017). In order to establish the mathematical model of PMSM and simplify analysis process, it is assumed that PMSM is a linear system, motor parameters not change with temperature, without eddy current, hysteresis loss and rotor damper winding. Based on this simplified method, mathematical model of PMSM in \(d-q\) reference frame is established. Stator voltage can be defined by equation (1).

\[
\begin{align*}
    \mathbf{u}_d &= \mathbf{R}_s + \mathbf{L}_d \frac{d\mathbf{i}_d}{dt} - p_s \omega_n \mathbf{L}_d \mathbf{i}_q \\
    \mathbf{u}_q &= \mathbf{R}_s + \mathbf{L}_q \frac{d\mathbf{i}_q}{dt} + p_s \omega_n \mathbf{L}_q \mathbf{i}_d + p_s \omega_n \mathbf{\phi}_f
\end{align*}
\]

Here, \(R\) is stator resistance, \(i_d\) is current of \(d\) axis, \(i_q\) is current of \(q\) axis, \(L_d\) is stator inductance, \(p_n\) is extreme logarithm, \(\omega_n\) is electric angular velocity of motor, and \(\phi_f\) is permanent magnet flux linkage.

Electromagnetic torque of PMSM can be defined by equation (2).

\[
T_e = \frac{3}{2} \rho_n [i_d \phi_f + i_d i_q (L_d - L_q)]
\]

Here, \(L_d\) is the inductor of \(d\) axis, \(L_q\) is the inductor of \(q\) axis.

Motion equation of PMSM can be defined by equation (3).

\[
J \frac{d\omega_n}{dt} = T_e - T_L - B \omega_n
\]

Here, \(J\) is moment of inertia, \(B\) is damping coefficient, and \(T_L\) is load torque.

In order to get better control results, the rotor flux oriented control method of \(i_d = 0\) is adopted (Lu et al., 2016), then stator voltage of PMSM can be defined by equation (4).

\[
\begin{align*}
    \mathbf{u}_d &= -p_s \omega_n \mathbf{L}_d \mathbf{i}_q \\
    \mathbf{u}_q &= \mathbf{R}_s + \mathbf{L}_q \frac{d\mathbf{i}_q}{dt} + p_s \omega_n \mathbf{\phi}_f
\end{align*}
\]

The electromagnetic torque equation and motion equation of PMSM can be defined by equations (5) and (6) respectively.
3 Analysis and design of speed controller for PMSM

3.1 Analysis and design of fuzzy PI speed controller

Fuzzy control is widely applied in modern control systems based on expert knowledge and experience; it does not need precise mathematical model of controlled objects. Fuzzy control is an intelligent control method based on fuzzy set theory, fuzzy rule and fuzzy logic inference (Opresnik et al., 2017). Fuzzy controller usually includes fuzzy interface, knowledge base, and reasoning machine (Zhang et al., 2016). The schematic diagram of fuzzy control is shown in Figure 1.

The fuzzy interface converts the values of each input parameter into suitable fuzzy linguistic variables, values of linguistic variables can be determined by membership function (Aissaoui et al., 2016), error $e$ and error rate $e_c$ as input variables of fuzzy controller. The fuzzy control algorithm in form of ‘if’ and ‘then’ is a control rule library that expresses expert knowledge and experience in actual control process. The fuzzy decision module judges the input variables of fuzzy controller through fuzzy control algorithm then outputs corresponding decision variable (Lai et al., 2016). The defuzzification interface transforms fuzzy value generated in fuzzy decision into corresponding precise value, which is the important part of fuzzy control system (Fan et al., 2016).

In order to restrain speed pulsation and enhance anti-disturbance ability of PMSM, double closed-loop control is adopted, where current loop is inner loop and speed loop is outer loop (Yi et al., 2016). The current loop adopts general PI control, and speed loop adopts fuzzy PI control. The fuzzy controller adopts double input-double output structure. The input variables are speed error $e$ and speed error rate $e_c$. Speed error $e$ and speed error rate $e_c$ are mapped into fuzzy universes $E$ and $E_c$ by quantification factors $K_1$ and $K_2$, where $E = E_c = [-6,6]$, output variable $K_p = [-2,2]$ and $K_i = [-1,1]$. 

$$T_c = \frac{3}{2} p_s i_s \varphi_f$$

$$J \frac{d \omega}{dt} = T_e - T_L - B \omega_m$$

$$3 Analysis and design of speed controller for PMSM$$

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To determine the fuzzy subset of input and output variables, seven linguistic variables, which are negative large (NB), negative middle (NM), negative small (NS), zero (0), positive small (PS), positive median (PM) and positive large (PB) are taken. In order to realise the fuzzification of precise value, membership degree function is used to express membership degree of precise value to fuzzy subsets \( E, E_c, K_p \), and \( K_i \). Commonly used membership functions include Gaussian membership functions, triangular membership functions, trapezoidal membership functions, etc. (Voskoglou et al., 2015). The triangular membership function has advantages of simplified calculation and easy realisation of good control performance. It is widely used in fuzzy control. Therefore, all linguistic variables of fuzzy controller in this paper adopt triangular membership function.

To determine fuzzy control rules, when control system deviation is large, selected control variable should speed up system's response speed and prevent saturation; when control system deviation is normal, selected control variable should reduce the overshoot of control system and ensure response speed of control system; when control system deviation is small, selected control variable should be larger, reducing control system's steady-state error (Cui et al., 2016). Based on such theory, 3D diagrams of input and output are obtained as shown in Figure 2.

**Figure 2** Relationship of output and input for fuzzy controller: (a) \( K_p \) and (b) \( K_i \) (see online version for colours)

![Figure 2](image_url)

Centroid method defuzzification has advantages of high accuracy, smooth output control, and so on (Verbenko and Tkachenko, 2015). Therefore, centroid method is used in this paper. The calculation formula of centroid method can be defined by equation (7).

\[
v_0 = \frac{\sum_{i=1}^{m} v_i \mu_i(v_i)}{\sum_{i=1}^{m} \mu_i(v_i)}
\]  

(7)

Here, \( v_0 \) is precise output of defuzzification, \( v_i \) is fuzzy value of output variable, \( \mu_i(v_i) \) is membership function of fuzzy value of output variable \( v_i \), and \( m \) is the number of output variables.

Based on above control principle, simulation model of PMSM for electric vehicle based on fuzzy PI speed controller is shown in Figure 3.
3.2 Analysis and design of sliding mode speed controller

Sliding mode control is a control strategy of variable structure control system. It is insensitive to system parameter changes and has fast response speed, allowing control system structure to change over time (Zhang et al., 2017). The state variables of PMSM can be defined by equation (8).

\[
\begin{align*}
    x_1 &= \omega_r - \dot{\omega}_r \\
    x_2 &= x_1 = -\dot{\omega}_r 
\end{align*}
\]  

(8)

The selected sliding mode surface function can be defined by equation (9).

\[
    s = cx_1 + x_2 
\]

(9)

The derivation of equation (9) is equation (10).

\[
    \dot{s} = c x_1 + x_2 = cx_2 - Du 
\]

(10)

The exponential approach law was selected to ensure PMSM has better dynamic quality, and by equation (10) the expression of controller was obtained.

\[
    u = \frac{1}{D} \{cx_2 + \epsilon \text{sgn}(s) + qs \} 
\]

(11)
According to sliding mode control principle, simulation model of PMSM for electric vehicle based on sliding mode speed control is shown in Figure 4.

4 Simulation and result analysis

Simulated and analysed established simulation model of PMSM based on fuzzy PI speed controller and sliding mode speed controller, the key parameters of PMSM used in simulation experiment are shown in Table 1.

<table>
<thead>
<tr>
<th>Motor parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole-pairs number $P_n$</td>
<td>4</td>
</tr>
<tr>
<td>Stator inductance $L_s$ (mH)</td>
<td>8.5</td>
</tr>
<tr>
<td>Stator resistance $R_s$ (Ω)</td>
<td>2.875</td>
</tr>
<tr>
<td>Magnetic linkage $\phi_f$ (wb)</td>
<td>0.175</td>
</tr>
<tr>
<td>Rotation inertia $J$ (kg·m$^2$)</td>
<td>0.003</td>
</tr>
<tr>
<td>Reference speed $N_{ref}$ (r/min)</td>
<td>1000</td>
</tr>
<tr>
<td>Load torque $T_L$ (N·m)</td>
<td>10</td>
</tr>
</tbody>
</table>

Simulation conditions were set as follows: simulation time $T_s = 0.6$ s, adopted variable step size-ode 23tb, when simulation time is 0.2 s, added load torque $T_L = 10$ N·m. Under above simulation conditions, simulation experiments are taken. Simulation results are shown in Figures 5–8.

**Figure 5** Speed waveforms (see online version for colours)

The speed waveforms of PMSM under fuzzy PI control and sliding mode control are shown in Figure 5. It can be seen from Figure 5 that under fuzzy PI control, motor speed reaches maximum value of 1195 r/min at 0.01475 s, and at 0.14 s reaches reference speed
of 1000 r/min. After added emergency load of 10 N·m at 0.2 s, motor speed drops to 936.68 r/min and reaches reference speed again at 0.3 s. The maximum motor speed under sliding mode control condition is 1318 r/min, and reaches reference speed at 0.095s. After added emergency load, motor speed drops to 899.49 r/min and reaches reference speed again at 0.252 s. It can be seen from the change of motor speed that speed overshoot in starting process under fuzzy PI control is small, and speed variation of motor after added emergency load is small. Therefore the anti-disturbance capability of fuzzy PI control is stronger than sliding mode control, but speed of reaching reference speed is slower than sliding mode control.

The torque dynamic diagram of PMSM under fuzzy PI control and sliding mode control is shown in Figure 6. As shown in Figure 6, motor torque under fuzzy PI control condition rises from 0 N·m to 33.76 N·m, then drops to –2.411 N·m, and reaches steady-state value at 0.065 s. After added emergency load, motor torque begins to rise to 12.34 N·m and reaches a new steady state value at 0.24 s. Under sliding mode control, motor torque rises from 0 N·m to 35.42 N·m, then drops to –4.935 N·m, and reaches steady-state value at 0.084 s. The torque fluctuates after added emergency load, motor torque rises to 13.2 N·m and reached new steady state value at 0.2357 s. From motor torque change, motor torque overshoot under fuzzy PI control is small, motor torque change is small after added emergency load, and it has better anti-disturbance capability.

Figure 6  Torque waveform (see online version for colours)

The three-phase current variation curves of PMSM under fuzzy PI control and sliding mode control are shown in Figures 7 and 8 respectively. From Figures 7 and 8, it is known that three-phase current appears abrupt in motor starting stage. Three-phase current amplitude under fuzzy PI control condition is more symmetrical than under sliding mode control, and enters the steady state time sooner. After added emergency load, three-phase current of PMSM appears to fluctuate. It is known from Figure 7 that the amplitude of three-phase current fluctuation is smaller and three-phase current is more ideal under fuzzy PI control.
5 Conclusions

The mathematical model of PMSM in $d$-$q$ reference frame is established, and the fuzzy PI speed controller is designed based on fuzzy control theory. The simulation models of PMSM based on fuzzy PI control and sliding mode control are built, and simulation analysis is carried out by Simulink.

Simulation results show that fuzzy PI speed controller designed in this paper can effectively restrain the overshoot of PMSM speed, torque and three-phase current. Fuzzy PI control system can better restrain the change of motor parameters with added emergency load, and fuzzy PI control system is insensitive to disturbance and parameter change, which has a fast state response speed, better dynamic performance and better anti-interference ability.
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