Parameters adaptive backstepping control of PMSM using DTC method

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Abstract. The torque and flux ripple of traditional DTC control of PMSM is large, and due to the lack of adaptive control system, the change of the system parameters has a great impact on the steady and transient control performance of the motor speed. Based on the traditional DTC control algorithm, a parameter identification adaptive backstepping DTC control algorithm is proposed in this paper. Because the backstepping controller is used to replace PI controller and flux hysteresis controller, the steady-state and transient performance of the system is obviously improved. At the same time, a parameter identification adaptive controller is designed, which can effectively suppress the influence of parameter changes on the speed control performance. The simulation results verify the correctness and effectiveness of the control algorithm. The control algorithm can significantly improve the steady-state and transient performance of the system under the condition of parameter mutation.

1 Introduction

The traditional direct torque control (DTC) of permanent magnet synchronous motor (PMSM) [1,2] has the advantages of less parameter dependence and faster response speed. However, due to the hysteresis controller used in the torque and flux control, the flux and torque ripple is too large [3]. At the same time, the PI controller is used in the speed loop, resulting in a slow speed response. The backstepping control is a kind of nonlinear system control strategy and the decoupling and order reduction of control system are realized by Lyapunov function. In reference [4], a multi-stage hysteresis controller is proposed to improve the torque and flux ripple of traditional DTC. In reference [5], a novel sliding mode controller is designed, which combined with space vector modulation, can effectively reduce the torque and flux ripple of traditional DTC. Based on the backstepping control algorithm [6-7], reference [8] proposed a control strategy based on space vector modulation, which has the same response speed as the traditional DTC, while significantly reducing the torque and flux ripple.

However, the above control methods do not consider the system response optimization under the condition of system parameter mutation. In high precision control system, the influence of these parameters should be considered. In this paper, the backstepping control of PMSM using DTC method is proposed by combining the backstepping control with adaptive control algorithm. This method can not only improve the performance of traditional DTC, but also suppress the influence of parameter deviation and improve the robustness of the system.

2 System Description

2.1 Mathematical model of PMSM

\[
\begin{align*}
\phi_\mu &= \phi_\alpha^2 + \phi_\beta^2, \quad i_\alpha = \frac{1}{J}, \quad \kappa = \frac{B}{J}, \quad \nu = \frac{1}{L_d}, \quad \sigma = \frac{L_d}{L_d - L_q} \quad (1) \\
T_e &= 1.5n_p (\phi_\beta i_\alpha + \phi_\alpha i_\beta) \quad \frac{d\omega}{dt} = \eta n_p (T_e - T_L) - \kappa \omega \\
\frac{di_\alpha}{dt} &= vRi_\alpha - \sigma \omega i_\beta - vE_\alpha + vu_\alpha \\
\frac{di_\beta}{dt} &= -\sigma \omega i_\alpha - vRi_\beta - vE_\beta + vu_\beta
\end{align*}
\]

Where \(\phi_\mu\) is the stator flux linkage, \(\phi_\alpha, \phi_\beta\) are the \(\alpha\) axis and \(\beta\) axis flux linkage, \(J\) is the inertia, \(B\) is the viscous friction coefficient, \(i_\alpha\) and \(i_\beta\) are the components of stator current in \(\alpha\) axis and \(\beta\) axis, \(R\) is the phase resistance, \(\omega\) is mechanical angular velocity, \(L_d\) and \(L_q\) are the equivalent inductances in \(d\) axis and \(q\) axis, \(E_\alpha\) and \(E_\beta\) are the EMF in \(d\) axis and \(q\) axis, \(T_L\) is the electromagnetic torque, \(n_p\) is the number of rotor pole pairs.

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2.2 Control strategy design

\[
\dot{\xi}_i = \omega - \omega_{ref}, \dot{\xi}_r = T_c - T_{ref}, \dot{\xi}_p = \varphi_s - \varphi_{ref}
\]  
(4)

\[
\eta_1 = \frac{1}{2} \xi_{\omega}^2 + \frac{1}{2} \xi_{\varphi}^2 + \frac{1}{2} \xi_{\alpha}^2
\]  
(5)

\[
T_L = T^*_L - \Delta T_L, R = R^* - \Delta R
\]  
(6)

\[
u = \frac{2\varphi_p}{3n_p} \left[ \varphi_p (i_o - \varphi_o v) + \varphi_x (i_x - \varphi_o v) \right]
\]

\[
- m_p \xi_{\omega} - 1.5n_p (\varphi_o v - i_o) \left( R^* \varphi_o i_o + R^* i_o - \frac{k_e \xi_{\omega}}{2 \varphi_p} \right)
- 1.5n_p (\omega i_o + v E_o) + (\kappa - k_o) T_c
\]

(7)

\[
u = \frac{2\varphi_p}{3n_p} \left[ \varphi_p (\varphi_o v - i_o) + \varphi_x (\varphi_o v - i_x) \right]
\]

\[
- m_p \xi_{\omega} - 1.5n_p (i_o - \varphi_o v) \left( R^* \varphi_o i_o + R^* i_o - \frac{k_e \xi_{\omega}}{2 \varphi_p} \right)
- 1.5n_p (\omega i_o + v E_o) \varphi_x + (\kappa - k_o) T_c
\]

(8)

By substitution of (6), (7) and (8) into the derivative of (5), we can obtain

\[
\eta_2 = -k_\omega \xi_{\omega}^2 - k_r \xi_r^2 - k_\varphi \xi_p^2 + m_p e_c \Delta T_L + (\kappa - k_o) \Delta R
\]

+ 1.5n_p (\varphi_o v_i_o + \varphi_o v_i_x) \Delta R + \xi_p (2 \Delta R \varphi_o i_o + 2 \Delta R \varphi_o i_x)

(9)

Lyapunov function is chosen as follows

\[
\eta_2 = \eta_1 + \frac{\Delta R^2}{2 \lambda_1} + \frac{\Delta T_L^2}{2 \lambda_2}
\]  
(10)

Where \(\lambda_1, \lambda_2\) represents positive adaptive gains.

Adaptive law is obtained:

\[
\Delta T_L = \lambda_2 \left( k_o - \kappa - m_p \xi_{\omega} \right)
\]  
(11)

\[
\Delta R = -1.5n_p (\varphi_o v_i_o + \varphi_o v_i_x) - 2 \xi_p \lambda_1 (\varphi_o i_o + \varphi_o i_x)
\]  
(12)

By substitution of (11), (12) into the derivative of (10), we can obtain

\[
\frac{d\eta_2}{dt} = -k_\omega \xi_{\omega}^2 - k_r \xi_r^2 - k_\varphi \xi_p^2 \leq 0
\]  
(13)

\[
\lim_{t \to \infty} \xi_{\omega} = \lim_{t \to \infty} \xi_r = \lim_{t \to \infty} \xi_p = 0
\]  
(14)

Selection of suitable controller gains \(k_o, k_r, k_\varphi\) and adaptive law gains \(r_1, r_2\) can ensure the tracking error signals of system are asymptotically stable. That is to say, the control method proposed in this paper can quickly track the given reference signals and restrain the influence of outside interference at the same time.

3 Simulation Results

The controller gains value are \(k_o = 0.02, k_r = 100, k_\varphi = 1000\). The adaptive identification parameters are \(t_1 = 4.12, t_2 = 5.58\). The results of comparative experiments with reference speed \(\omega = 20 \text{ rad/s}\) and load torque \(T_L = 28 \text{N-m}\) are shown below.

![Fig 1. Speed wave of the general DTC algorithm.](image1)

![Fig 2. Speed wave of the algorithm in this paper.](image2)
From the above comparison, it can be seen that through the algorithm optimization, the speed and torque ripple are significantly improved, and the response time is also significantly improved.

In order to verify the suppression of stator resistance and load mutation, comparative experiments are carried out. The stator resistance $R_s$ is increased to 0.4 Ω in 0.15s, and the load torque $T_L$ is increased to 42N·m in 0.3s. The speed change of PMSM is analyzed under the condition of parameter mutation.

The simulation results show that in the traditional algorithm, the speed deviates from the reference value about 1rad/ s in 0.15s, and there is an obvious jitter peak at 0.3s. The control algorithm in this paper only has a small amplitude peak at 0.15s and 0.3s, which can quickly recover to the reference value.

### 4 Conclusion

The traditional DTC control has large torque and speed ripple, and the steady state value of speed will shift when the parameter changes suddenly, which will affect the accuracy and robustness of the control system. The control algorithm proposed in this paper can solve the above problems. From the simulation results, it can be seen that the proposed control algorithm not only significantly reduces the torque and speed ripple, but also significantly shortens the response time. At the same time, there is no
static error in the speed tracking under the condition of parameter drift, which significantly improves the accuracy and robustness of the control system. The proposed control algorithm in this paper is of great significance to the precise control of the PMSM.

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