Backstepping DTC control of PMSM with robust adaptive law

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Abstract. The traditional direct torque control (DTC) of permanent magnet synchronous motor (PMSM) is characterized by the feature of inconstant switching frequency and large ripples of flux and torque which is due to the hysteresis controllers adopted in the system. Besides, the modification of motor parameters, especially the rise of stator temperature, and load torque disturbance further leads to the speed steady-state error and fluctuation. A novel DTC method of interior PMSM based on the adaptive backstepping control with load torque and stator resistance identification is proposed in this paper. In order to reduce the ripples of the traditional DTC, a speed backstepping controller is designed to replace PI speed controller, and torque and flux backstepping controllers are designed to replace torque and flux hysteresis controllers in this algorithm. Owing to the real-time and accurate estimation of the stator resistance and load torque, the control variables can be instantly and simultaneously modify to ensure the accurate and fast response of the speed. The effectiveness and correctness of the presented method are verified through multiple simulation experiments, and the results indicate that the dynamic and static performance of the PMSM can be significantly improved by using the method.

1. Introduction
Permanent magnet synchronous motor (PMSM) is utilized widely in various industrial applications. The traditional direct torque control (DTC) method of PMSM is proposed by Professor Zhong L. Rahman MF from Australian and Professor Hu Yuwen from Nanjing University of Aeronautics and Astronautics of China[1, 2]. Compared with field oriented control (FOC) which is another important method in the field of motor control, DTC owns the advantages such as simpler implantation, less machine parameter dependence and quicker dynamic torque response[3]. However, the traditional DTC uses flux and torque hysteresis regulator to control the system, which has the disadvantages of large fluctuation of control variables and unstable inverter frequency[4, 5].

Backstepping control is a new nonlinear system control strategy, which can realize the complete decoupling and simplification of controller design, and ensure the system stability by designing Lyapunov function. In [6], the adaptive control of resistance based on backstepping control was realized. Reference [7] improved the system speed tracking performance by the fuzzy controller adjusting backstepping parameters of the system. In [8] an adaptive backstepping control system was proposed to control the rotor position of PMSM drive using recurrent fuzzy neural network. But the methods proposed above were mainly focused on FOC based on backstepping control, the application of DTC based on backstepping control for PMSM[8, 10] was few and the adaptive backstepping control based on DTC with the consideration of deviation of stator resistance and the disturbance of load torque was fewer.
The influence of these factors of the system is relatively large, such as the winding temperature increase of 25 degrees, the resistance will rise 6% when the motor is running, and the performance of system will become degradation owing to the parameters can not adapt to the change. In the high precision control system, the influence of these parameters should be considered. This paper introduce the backstepping control to DTC of PMSM combined with adaptive control algorithm to design the stable function for subsystem on the purpose of the adaptive control of stator resistance and load torque. The algorithm proposed in this paper has 3 advantages: Firstly, The backstepping controller is used instead of the hysteresis controller and the PI controller, which is fast and greatly reduces the ripples of the system. Secondly, the influence of stator resistance change and load mutation on servo precision is solved by adaptive control algorithm. Finally, the SVM modulation method is used to keep the switching frequency of the inverter constant. The method can not only enhance the performance of traditional DTC but also suppress the influence of deviation of parameters to improve the robustness of the system.

2. System Description

2.1. Current Model of Interior PMSM

Define:

\[ \phi_s = \phi_s^2 + \phi_s^\beta, \alpha = \frac{1}{J}, b = \frac{B_m}{J}, \alpha = 1/L_d, \beta = (L_d - L_q)/L_d \]  (1)

A new current model of interior PMSM can be established, as shown in formula (2) and (3):

\[
\begin{aligned}
\left(\begin{array}{c}
\frac{d\phi_\alpha}{dt} \\
\frac{d\phi_\beta}{dt} \\
\frac{dw}{dt}
\end{array}\right) &= \left(\begin{array}{ccc}
-aR & -\beta w & 0 \\
-\beta w & -aR & 0 \\
0 & 0 & -a
\end{array}\right)
\left(\begin{array}{c}
i_\alpha \\
i_\beta \\
e
\end{array}\right) + \left(\begin{array}{c}
E_\alpha \\
E_\beta \\
-\alpha
\end{array}\right) + \alpha \left(\begin{array}{c}
u_\alpha \\
u_\beta \\
e
\end{array}\right)
\end{aligned}
\]  (2)

\[
T_e = \frac{3}{2} n_p (\phi_\alpha i_\beta - \phi_\beta i_\alpha), \frac{dw}{dt} = an_p (T_e - T_L) - bw
\]  (3)

Where \( \phi_s \) is the square of the stator flux linkage, \( \phi_\alpha, \phi_\beta \) are the \( \alpha \) axis and \( \beta \) axis flux linkage of the stator windings, \( J \) is the moment of inertia, \( B_m \) is the viscous friction coefficient, \( L_d \) and \( L_q \) are the equivalent inductances of stator windings in \( d \) axis and \( q \) axis, \( i_\alpha \) and \( i_\beta \) are the components of stator current in \( \alpha \) axis and \( \beta \) axis, \( R \) is the phase resistance of the stator windings, \( \nu \) is mechanical angular velocity of the rotating rotor, \( E \) is the EMF of PMSM, \( u_\alpha \) and \( u_\beta \) are the components of stator voltage in \( \alpha \) axis and \( \beta \) axis, \( n_p \) is the number of rotor pole pairs, \( T_L \) is the load torque, \( T_e \) is the electromagnetic torque.

2.2. Backstepping Control Design

For the PMSM system, \( w^*, T_e^*, \phi_s^* \) are the reference signal, it is assumed that the tracking error \( e_w, e_T, e_\phi \) are:

\[
e_w = w - w^*, e_T = T_e - T_e^*, e_\phi = \phi_s - \phi_s^*
\]  (4)

Lyapunov function \( V_1 \) is selected as follows:

\[
V_1 = \frac{1}{2} e_w^2 + \frac{1}{2} e_T^2 + \frac{1}{2} e_\phi^2
\]  (5)

The estimated value are \( \hat{T}_L, \hat{R} \), the estimations error \( \Delta T_L, \Delta R \) can be expressed as follows:

\[
T_L = \hat{T}_L - \Delta T_L, R = \hat{R} - \Delta R
\]  (6)

The \( \alpha, \beta \) axis voltage of PMSM can be chosen as:

\[
u_\alpha = \frac{2 \phi_\beta}{3n_p [\phi_\beta (i_\beta - \phi_\beta \alpha) + \phi_\alpha (i_\alpha - \phi_\alpha \alpha)]} \left[ 1.5n_p \phi_\alpha \alpha i_\beta + \phi_\beta \alpha i_\alpha \right] \hat{R} - 1.5n_p (w_\beta i_\alpha - \alpha E_\beta) \phi_\alpha - an_p e_w - \frac{1.5n_p \phi_\beta \alpha - i_\alpha}{\phi_\beta} \left( \frac{R\phi_\alpha \alpha i_\beta + \hat{R}i_\beta - k_\phi \alpha}{2 \phi_\beta} \right) - 1.5n_p (w_\beta i_\beta + \alpha E_\alpha) + (b - k_\nu) T_e + (b - k_\nu) \hat{T}_L + \frac{bw(b - k_\nu)}{an_p} + \frac{w^*}{an_p} + \frac{k_\nu w^*}{an_p} + \frac{\hat{T}_L - k_T e_T}{an_p}
\]  (7)
\[ u_\beta = \frac{2\varphi_\alpha}{3n_p\varphi_\beta(\varphi_\beta - \alpha)i_\beta + \varphi_\alpha(\varphi_\beta - i_\omega)} \left[ 1.5n_p\left( \varphi_\alpha \alpha i_\beta + \varphi_\beta \alpha i_\alpha \right) - \frac{2\varphi_\alpha}{2k_\omega} \right] \left( 1.5n_p (w_\beta i_\alpha - \alpha E_\beta) \varphi_\alpha - w_\omega \beta i_\omega \right) \\
- 1.5n_p (w_\beta i_\omega + \alpha E_\omega) \varphi_\beta - an_p e_w - 1.5n_p (i_\beta - \varphi_\beta) \left( \frac{k_\omega e_\omega}{\varphi_\alpha} \hat{R} i_\alpha - \frac{k_\omega e_\omega}{2\varphi_\alpha} \right) + (b - k_w) T_e + \\
(b - k_w) \hat{T}_L + \frac{b w (b - k_w)}{a n_p} + \frac{w^*}{a n_p} + k_w w^* + \hat{T}_L - k_\varphi e_T \]

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

\[ V_2 = -k_w e_\omega^2 - k_\tau e_\tau^2 - k_\varphi e_\varphi^2 + an_p e_w \Delta T_L + (b - k_w) \Delta T_L + 1.5n_p (\varphi_\alpha \alpha i_\beta + \varphi_\beta \alpha i_\alpha) \Delta R + \\
e_\varphi (2 \Delta R \varphi_\alpha i_\alpha + 2 \Delta R \varphi_\beta i_\beta) \]

Where \( k_w, k_\tau, k_\varphi \) represents the positive control gain.

2.3. Adaptive Controller Design

Lyapunov function \( V_2 \) is chosen as follows:

\[ V_2 = V_1 + \frac{\Delta R^2}{2r_1} + \frac{\Delta T_L^2}{2r_2} \]

Where \( r_1, r_2 \) represents positive adaptive gains. Adaptive law is obtained:

\[ \Delta T_L = r_2 (k_w - b - an_p e_w) \]

\[ \Delta R = -1.5n_p (\varphi_\alpha \alpha i_\beta + \varphi_\beta \alpha i_\alpha) - 2 e_\varphi r_1 (\varphi_\alpha i_\alpha + \varphi_\beta i_\beta) \]

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

\[ \lim_{t \to +\infty} e_\omega = 0, \lim_{t \to +\infty} e_\tau = 0, \lim_{t \to +\infty} e_\varphi = 0 \]

For PMSM system model with internal and external disturbances, design of adaptive control laws (11), selection of suitable controller gains \( k_w, k_\tau, k_\varphi \), and adaptive law gains \( r_1, r_2 \), the proposed adaptive robust backstepping controller (7) and (8) based DTC can ensure the tracking error signals (4) of PMSM system are asymptotically stable. That is to say, adaptive robust backstepping control based DTC for PMSM can quickly track the given reference signals and restrain the influence of outside interference at the same time.

3. Simulation Results

First of all, a comparison of steady-state performance with reference speed \( \omega = 20 \text{ rad/s} \) and load torque \( T_e = 28 \text{N-m} \) is carried out among the method in this paper. The backstepping controller parameters of the method in this paper are \( k_\omega = 0.01, k_\tau = 230, k_\varphi = 2000 \), the adaptive identification parameters \( t_1 = 4.52, t_2 = 4.78 \).
The simulation results given in Figure 1 and Figure 3 show the speed, torque and flux ripples are apparent due to hysteresis controllers in traditional DTC. Figure 2 and Figure 4 indicated the speed, torque and flux ripples are dramatically improved, meanwhile, the adjustment time is faster and the overshoot is smaller in proposed method compared to the traditional DTC.

Figure 5 Speed wave of backstepping DTC without adaptive law

Figure 6 Speed wave of backstepping DTC with adaptive law

Figure 5 shows the speed in backstepping DTC without adaptive law for PMSM while stator resistance increases to 0.4Ω at 0.15s and load torque $T_l$ increases to 42N·m at 0.3s. Figure 5 (a) shows that the speed has dropped down to 19 rad/s from 20 rad/s while the stator resistance $R_s$ of PMSM increases to 0.4Ω at 0.15s. Figure 5 (b) shows that the speed has a big spike which reaches 17rad/s while the load torque $T_l$ increases to 42N·m at 0.3s.
Figure 6 shows the speed in backstepping DTC with adaptive law for PMSM while the parameters has the same change as in Figure 5. Figure 6 (a) indicates that the speed can be hold to 20 rad/s due to the estimation of $R_s$. Figure 6 (b) indicates that the speed of the proposed algorithm can be hold to 20 rad/s and only has a tiny spike due to the estimation of $T_L$ by adaptive law used in the method. From Figure 5 and 6, the variation of $R_s$ and $T_L$ could cause steady-state error and a transient and great spike without parameters identification of adaptive law. Using adaptive law, steady-state error of speed can be eliminated and the great spike of can be reduced, then the performance of the system can be improved.

4. Conclusion
Aiming at the problems of traditional DTC, this paper proposes a novel adaptive backstepping DTC strategy for PMSM. The improved method can estimate the change of the motor stator resistance and the load torque of the system in real time, and the tracking error of the system is globally consistent and convergent. The method has a good effect on suppressing the change of parameters, and ensures that the robustness and fast tracking performance of the system are guaranteed. Simulation results show that:

(1) This method can significantly reduce the torque and flux ripples, and make the inverter work at a constant frequency.
(2) This method has excellent dynamic and static performance.
(3) The influence of parameter perturbation on the system is obviously reduced and the method is more robust.

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