Research on Improved Current Predictive Control of Permanent Magnet Synchronous Motor

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Abstract—Aiming at the motion control problem in permanent magnet synchronous motor speed control system, an improved deadbeat current predictive control algorithm based on fuzzy PID control is proposed. In this algorithm, the traditional PID control uses fuzzy control to realize real-time parameter adjustment, it eliminates the overshoot of the system; The improved deadbeat current predictive control is adopted in the current loop, and the control output of the speed loop is taken as the input of the current loop. the output speed of the motor is adjusted, so feedback control is formed to obtain accurate and fast track performance. The simulation results show that the control algorithm is fast and robust under no-load and disturbance conditions, which verifies the feasibility and effectiveness of the algorithm.

1. Introduction
Permanent magnet synchronous motor (PMSM) has been widely used in high-performance electrical drive systems due to its highly power density, strong driving ability, small size and low rotational inertia and have been applied in many fields, such as servo, transportation, aerospace and other key development industries [1]. Although it has excellent characteristics, its system model is complex, which brings some problems such as current ripple, current coupling, parameter uncertainty, internal and external interference, system saturation and so on. The classical PI vector control response speed and overshoot are mutually restricted, and it is difficult to meet the control requirements in the cutting-edge field. Therefore, it is necessary to seek high-performance control methods. However, due to the PMSM itself is a multivariable, nonlinear and strong coupling system, the traditional PI control is difficult to achieve good control results in terms of rapidity and immunity. In this paper, the PID control with parameter self-tuning in the outer ring is proposed to realize the real-time online adjustment of PID control parameters.

In recent years, deadbeat current predictive control (DPC) uses the current cycle current value as the next cycle current prediction value through the PMSM discrete model to accurately calculate the control voltage, thereby achieving deadbeat tracking control [2]. However, the traditional DPC method has control delay, and directly taking the predicted current of k+1 period as the actual value will cause large error. Therefore, this paper proposes an improved deadbeat current predictive control.

In summary, the improved DPC based on parameter self-tuning PID control is proposed in this paper. The current prediction correction link is added to the predictive control to accurately calculate the voltage value, adjust the output speed value of the whole control system, and compare it with the reference speed to form the feedback control, so as to realize the fast response and strong robustness of the control system.
2. Mathematical model of PMSM

The stator of PMSM adopts A, B and C three-phase symmetrical windings, which are 120 degrees apart from each other in space. The stator and rotor are coupled by air gap magnetic field. Analysing the mathematical model of PMSM, the following assumptions are often made [3]: (1) The saturation of magnetic circuit is ignored; the influences of the magnetic hysteresis and the eddy currents are negligible; (2)Three-phase windings are symmetrical, with 120 electrical angle difference in space and no edge effect; (3)There is no damping winding on the rotor, and the permanent magnet has no damping effect; (4)The distribution of the magnetomotive forces is sinusoidal; the influence of cogging effect and higher harmonic.

Define \((i_d, i_q, \omega_m)\) as the state variables of the PMSM system, and the voltage equations can be described as follow [4]:

\[
\begin{align*}
    u_d &= R_i i_d - L_{q} i_q + L_{d} \frac{di_d}{dt} \\
    u_q &= R_i i_q + \omega_m \psi_f + L_{q} i_d + L_{d} \frac{di_q}{dt}
\end{align*}
\]

The magnetic chain equations can be expressed as follows:

\[
\begin{align*}
    \psi_d &= L_d i_d + \psi_f \\
    \psi_q &= L_q i_q
\end{align*}
\]

The torque and motion equations can be expressed as follows:

\[
\begin{align*}
    T_e &= \frac{3}{2} \left[ P_n \psi_f i_q + \left( L_d - L_q \right) i_d i_q \right] \\
    \frac{d\omega_m}{dt} &= \frac{1}{J} \left( T_e - T_L - B \omega_m \right) \\
    \omega_m &= P_n \omega_l
\end{align*}
\]

where \(u_d\) and \(u_q\) are the d- and q-axis stator voltages; \(i_d\) and \(i_q\) are the d- and q-axis currents; \(L_d\) and \(L_q\) are the d- and q-axis stator inductances; \(\psi_d\) and \(\psi_q\) are the d- and q-axis flux linkages; \(R_i\) is the stator resistance; \(\psi_f\) is the flux linkage of permanent magnets; \(J\) is the moment of inertia of the motor; \(P_n\) is the pole pairs; \(B\) is the viscous friction coefficient; \(\omega_m\) is the mechanical angular velocity; \(\omega_l\) is the electrical angular velocity; \(T_L\) and \(T_e\) represent the mechanical load torque and electromagnetic torque. This PMSM studied is a surface mounted permanent motor, such that \(L_d=L_q=L\).

3. Adaptive fuzzy PID control

Traditional PID control is limited by parameter tuning method, inaccurate parameter setting will lead to unsatisfactory performance of the whole system. In this paper, fuzzy control is used to adjust the three parameters of PID controller in real time, which reduces the workload of the system and improves the stability of the system. The Fuzzy-PID controller structure diagram is shown in Figure 1.

The speed tracking error \(e\) is defined as

\[ e = \omega_{ref} - \omega_m \]

PID control parameters : \(k_p=\Delta k_p+k_p0\), \(k_i=\Delta k_i+k_i0\), \(k_d=\Delta k_d+k_d0\), the expression of control is obtained [5]:

\[ m(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt} \]

\[ i_q = i_q^* - B_s \omega_m \]

where \(B_s = \frac{\beta \lambda - J}{1.5 P_n \psi_f} \) is power damping coefficient, \(\beta\) is the expected bandwidth of the speed loop.

Output value of speed loop under traditional PID control
where e and e' are the inputs to the fuzzy controllers, Δk_p, Δk_i, and Δk_d are the outputs of the fuzzy controller.

The q-axis current reference value of the improved PID control is obtained:

\[ i_q^* = k_p e(t) + k_i \int_0^t e(t) \, dt + k_d \frac{de(t)}{dt} - B_\psi \omega_m \]  

(7)

In fuzzy control rules, e, e', Δk_p, Δk_i, and Δk_d are language variables with values taken from the set \{NB, NM, NS, ZO, PS, PM, PB\}. The triangular distribution of membership function is therefore used. The q-axis current reference value of the improved PID control is obtained:

\[ i_q^* = k_p e(t) + k_i \int_0^t e(t) \, dt + k_d \frac{de(t)}{dt} - B_\psi \omega_m \]  

(8)

Figure 1 Fuzzy-PID controller structure diagram

Figure 2 Control structure diagram of PMSM

### 4. Improved deadbeat current predictive control

The traditional DPC takes the reference value as the predicted value at the next moment. However, in the actual control system, due to the influence of sampling delay such as control current and pulse width modulation, the control voltage cannot be immediately loaded into the inverter, but can be executed at the next moment [6]. Therefore, the current value at time \( k+2 \) can track the reference current value at time \( k \). In this paper, an improved DPC is proposed. The predictive current error correction is added to the traditional DPC to realize the deadbeat two-step current predictive control. Figure 3 is the improved DPC flow chart.

From formula (1):

\[
\begin{align*}
\frac{d i_d}{dt} &= \frac{1}{L_d} \left( u_d + \omega_m L_d i_d - R_d i_d \right) \\
\frac{d i_q}{dt} &= \frac{1}{L_q} \left( u_q - R_q i_q - \omega_m \psi_i - \omega_m L_d i_d \right)
\end{align*}
\]

(9)

Formula (9) is discretized:

\[
\begin{bmatrix}
    i_d(k+1) \\
    i_q(k+1)
\end{bmatrix} =
\begin{bmatrix}
    1 - \frac{T R_d}{L} & T_0 \omega_m \\
    - T_0 \omega_m & 1 - \frac{T R_q}{L}
\end{bmatrix}
\begin{bmatrix}
    i_d(k) \\
    i_q(k)
\end{bmatrix} +
\begin{bmatrix}
    T_0 \\
    0
\end{bmatrix}
\begin{bmatrix}
    u_d(k) \\
    u_q(k)
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    - \frac{T \psi_i}{L} \omega_m
\end{bmatrix}
\]

(10)

The discretization equation in synchronous rotating coordinate system can be simplified as:

\[ i(k+1) = Ai(k) + Bu(k) + C \]

(11)
The voltage at k time is derived from formula (12):

\[ u(k) = B^t \left[ i(k + 1) - A \hat{i}(k) - C \right] \tag{12} \]

The control voltage at time k+1:

\[ u(k + 1) = B^t \left[ i(k + 2) - A \hat{i}_q(k + 1) - C \right] \tag{13} \]

where \( \hat{i}_q(k+1) \) is the estimated value of the actual current at k+1, \( \hat{i}_d(k+1) \) is the predicted value of the current at k+1. The default in the above formula is \( \hat{i}_q(k+1) = \hat{i}_d(k+1) \), However, due to the influence of control current and pulse width modulation, \( \hat{i}_q(k+1) \) is not equal to \( \hat{i}_d(k+1) \).

Therefore, the predictive current correction link is introduced to correct the predictive current:

\[ \Delta \hat{i}_c(k) = \hat{i}_c(k) - i(k) \tag{14} \]

\[ \hat{i}_c(k+1) = \hat{i}_c(k + 1) + \beta \Delta \hat{i}_c(k) \tag{15} \]

where \( \beta \) is the correction factor for current error.

\[ u(k + 1) = B^t \left[ i(k + 2) - C \right] - B^t A \left[ A \hat{i}(k) + B \hat{i}_c(k) + C \right] \tag{16} \]

5. Simulation verification and comparison of results

The vector control system of PMSM based on improved DPC algorithm of fuzzy PID control is shown in Figure 2. Traditional PID control, sliding mode control (SMC) and improved DPC based on fuzzy PID control (Fuzzy-PID-IDPC) are applied to the speed control system of PMSM. The PMSM parameters are \( R = 2.875 \Omega, P_n = 4, B = 2 \times 10^{-6}, J = 0.00054 \).

First given fixed speed \( n = 1000 \text{rad/s} \), Figs. 4 is the simulation diagrams of velocity response. It can be seen from the simulation diagram that both the traditional PID control method and the SMC method have large overshoot, and the stable tracking time to the given reference value is longer than that of the control method proposed in this paper.

Given reference speed \( n = 30 \cos(\pi t/2) \), Fig. 5, Fig. 6 and Fig. 7 are the simulation diagrams of velocity response of the three methods in the cosine type. It can be seen from the simulation diagram that the SMC algorithm has obvious chattering phenomenon. The traditional PID control algorithm has obvious overshoot and buffeting phenomenon. Compared with the former two methods, the chattering phenomenon of the proposed control algorithm is obviously weakened, the time to track the given value is short, there is no overshoot and more stable.

Given the speed mutation at \( t = 0.5 \text{s} \). Fig. 8 show the simulation diagram of velocity response of the three methods under the condition of sudden drop of rotational speed, It can be seen from the simulation diagram that the Fuzzy-PID-IDPC can achieve fast and stable tracking in the case of sudden change of rotational speed, PID control and SMC algorithm have large overshoot and obvious chattering phenomenon and long tracking time in the case of sudden change of rotational speed.

In order to improve the disturbance rejection performance of the proposed control method, the external disturbance \( T_L = 20 \text{N.m} \) is added when \( t = 1.5 \text{s} \) in this simulation experiment. Figure 9 is the motor speed tracking response of the three methods in the presence of external disturbances. It can be seen from the simulation diagram that the Fuzzy-PID-IDPC can still achieve fast and smooth tracking in the presence of external disturbances, and the chattering phenomenon is weakened. Both PID control and sliding mode control have large oscillation and long tracking time.
6. Conclusion

Aiming at the motion control problem of PMSM speed control system, an improved DPC algorithm based on fuzzy PID control is proposed. In the outer loop of the motor control system, the fuzzy control algorithm is used to adjust the PID parameters online in real time, and the current predictive control is used in the inner loop, which improves the accuracy and stability of the system. By comparing the
simulation results, the proposed method reduces the chattering phenomenon of the system, speeds up the system to track the given speed time, improves the anti-disturbance ability of the system, and has certain engineering application value in the field of motor speed control.

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