Research on DPCC Control Strategy of PMSM Based on LESO

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Abstract. In permanent magnet synchronous motor control system, the excellent current control effect is very important to the control performance of the system. In order to eliminate the sampling delay in digital control, the deadbeat predictive current control strategy considering sampling delay is proposed. In order to solve the problem that the predictive current control has low robustness to model parameters, especially motor inductance parameters, combined with active disturbance rejection control technology, the linear extended state observer is introduced into deadbeat predictive current control to observe and compensate the internal and external disturbances of the system. The introduction of linear extended state observer improves the robustness of system parameters and the ability of anti load disturbance. The final designed system has the advantages of good speed tracking performance, strong anti-interference ability and greatly improved parameter robustness. Finally, the feasibility and correctness of the proposed control strategy are verified by simulation.

1. Introduction

In recent years, with the development of modern control technology, more and more advanced control strategies have been applied to the control of Permanent Magnet Synchronous Motor (PMSM). Among them, as a model-based predictive control algorithm, Deadbeat Prediction Current Control (DPCC) not only has the characteristics of fast dynamic response and small current harmonics that are commonly found in predictive control algorithms, but also has the unique advantages of constant switching frequency, high bandwidth and easy digital realization[1].

Since DPCC is fundamentally a model-based control algorithm, it is highly sensitive to model parameters, especially inductance, and parameter mismatch will seriously affect the current control effect[2]. In response to this, on the basis of deadbeat control, a robust current control algorithm based on Luenberger state observer is introduced in literature [3], which compensates inductance error and phase delay caused by current sampling and improves the robustness of the system. Literature [4] uses relaxed current deviation constraints and smooth output voltage prediction methods to keep the system stable when the motor inductance parameters are mismatched. Literature [5] designed a disturbance observer to estimate the disturbance and feed forward compensation, which improved the robustness of the system to parameters. Literature [6] uses the model reference adaptive algorithm to identify the motor parameters online, which reduces the current error caused by the motor parameter deviation.

Based on the foregoing, the PMSM control system with PI controller for speed loop and DPCC controller for current loop is designed. The control system has the advantages of high current control accuracy and low harmonic content of DPCC strategy. In order to overcome the problem of reduced
current control effect caused by parameter mismatch and observation disturbance, combined with the characteristics of strong anti-disturbance ability of linear active disturbance rejection control (LADRC) technology[7], linear extended state observer (LESO) is introduced to observe and compensate for disturbances, which greatly improves the system's parameter robustness and anti-disturbance ability. The simulation results verify the effectiveness of the proposed control strategy.

2. Conventional DPCC control strategy

The basic principle of DPCC algorithm is that according to the mathematical model of PMSM in d-q coordinate system, the optimal reference voltage vector is determined by the actual current value obtained at the current sampling time and the expected current value at the next sampling time, so that the actual current of the motor can track the given current value in a control cycle.

In the d-q coordinate system, the discretization expression of PMSM voltage equation is

\[
\begin{align*}
\delta u_d(k) &= L_d (i_d(k+1) - i_d(k))/T_s + R_{i_d}(k) - \omega_s L_q i_q(k) \\
\delta u_q(k) &= L_q (i_q(k+1) - i_q(k))/T_s + R_{i_q}(k) + \omega_s (L_d i_q(k) + \psi_f)
\end{align*}
\]

(1)

Where, \(L_d\) and \(L_q\) are d-axis and q-axis inductance respectively, \(R\) is stator resistance, \(\omega_s\) is electric angular velocity, \(T_s\) is the sampling time, \(u_{d,q}(k)\) is d-axis and q-axis voltage given at the k\(th\) sampling time, \(i_{d,q}(k)\) and \(i_{d,q}(k+1)\) are current values sampled at the sampling time of \(kT_s\) and \((k+1)T_s\).

In this case, if let \(i_{d,q}(k+1)\) be \(\hat{i}_{d,q}(k+1)\), then \(u_{d,q}(k)\) obtained from equation (1) can make the current value at time \((k+1)T_s\) equal to the given value \(\hat{i}_{d,q}(k+1)\). Therefore, the optimal reference voltage vector can be determined according to equation (1) to achieve fast dynamic response.

3. DPCC controller with sampling delay

The DPCC control strategy described in section 2 is implemented in the ideal control mode, that is, current sampling, optimal reference voltage vector calculation and PWM pulse duty cycle update can be completed simultaneously in a control cycle. But in the actual discrete control system, there is a certain delay from current sampling to duty cycle updating.

The control sequence of discrete system is shown in Fig. 1. Under normal circumstances, the system completes the current sampling at time \(kT_s\), and then completes the determination of the reference voltage vector and the calculation of the duty cycle in \(kT_s\) control cycle, and the update of the duty cycle can only be completed at the beginning of the next sampling cycle. After that, the discrete system needs a cycle to apply the pulse signal to the inverter and complete the tracking of the motor current to the given value. Therefore, it takes two sampling cycles from the current sampling to the end of the control instruction. In order to achieve better control performance, this factor must be taken into account when designing the current loop DPCC controller.

![Fig. 1 Control timing diagram of discrete digital system](image)

Due to the delay effect of sampling, the actual reference voltage vector \(u_{d,q}(k)\) at \(kT_s\) is known, which is calculated in the \((k-1)T_s\) control period. Therefore, by substituting the known \(u_{d,q}(k)\) into equation (1), the current value at the time of \((k+1)T_s\) can be calculated, that is

\[
\begin{align*}
\hat{i}_{d}(k+1) &= T_s \left( u_{d}(k) - R_{i_d}(k) + \omega_s L_q i_q(k) \right)/L_d + i_d(k) \\
\hat{i}_{q}(k+1) &= T_s \left( u_{q}(k) - R_{i_q}(k) + \omega_s \left( L_d i_q(k) + \psi_f \right) \right)/L_q + i_q(k)
\end{align*}
\]

(2)

Where \(\hat{i}_{d,q}(k+1)\) is the predicted current value at time \((k+1)T_s\) under the action of \(u_{d,q}(k)\).
When the predicted value of current at time \((k+1)T_s\) is known, the \(u_{d,q}(k+1)\) actually acting at time \((k+1)T_s\) can be calculated in \(kT_s\) control cycle with reference to equation (1), that is

\[
\left\{
\begin{array}{l}
u_d(k+1) = L_d \left( i_d^* (k+2) - i_d(k+1) \right)/T_s + R_d i_d(k+1) - \omega_e L_{q}\psi_f(k+1) \\
u_q(k+1) = L_q \left( i_q^* (k+2) - i_q(k+1) \right)/T_s + R_q i_q(k+1) + \omega_e \left( L_d i_d(k+1) + \psi_f \right)
\end{array}
\right.
\]

(3)

Where \(i_{d,q}(k+2)\) is the given current value at time \((k+2)T_s\).

The \(u_{d,q}(k+1)\) calculated by equation (3) can act on the inverter in the \((k+1)T_s\) control cycle, so that the current setting value \(i_{d,q}(k+2)\) can be achieved in the motor current tracking at time \((k+2)T_s\). Therefore, the DPCC strategy with this control mode can eliminate the influence of sampling delay in digital control system and realize deadbeat control.

4. Improved Strategy of DPCC Controller Based on LESO

4.1. DPCC Controller Based on LESO

In the DPCC strategy described in the previous section, in order to obtain the accurate reference voltage vector, the accurate current measurement value is needed, and the current measurement error will lead to the calculation deviation. When the motor parameters change due to environmental temperature and other factors, if the nominal value is still used for calculation, it will lead to the deviation of calculation results. Combined with the advantages of LADRC in disturbance suppression, the core module leso of LADRC can be introduced into the control system to compensate the disturbance caused by observation error and parameter change.

When the parameter changes are not considered, the form of equation (1) in the actual control system is

\[
\left\{
\begin{array}{l}
u_d(k+1) = v_d(k) - R_d i_d(k) + \omega_e L_{q}\psi_f(k) \\
u_q(k+1) = v_q(k) - R_q i_q(k) - \omega_e \psi_f(k) - \omega_e L_{d}\psi_f(k)
\end{array}
\right.
\]

(4)

\(R_0, L_{d0}, L_{q0}\) and \(\psi_{f0}\) in equation (4) are nominal parameter values. Considering the variation of parameters, there is a certain error between the predicted current and the actual current. According to the control idea of LADRC, the internal and external disturbances and parameter errors in the control system can be regarded as "total disturbances". Let the total disturbances of d-axis and q-axis are \(f_{d2}\) and \(f_{q2}\) respectively (the current coupling term \(\omega_e L_{q}\psi_f/L_{d0}\) and \(\omega_e L_{d}\psi_f/L_{q0}\) can also be regarded as part of the total disturbances). Let \(b_d=1/L_{d0}, b_q=1/L_{q0}\), then equation (4) can be changed into

\[
\left\{
\begin{array}{l}
u_d(k+1) = f_{d2}(k) + b_d v_d(k) - R_d i_d(k) \\
u_q(k+1) = f_{q2}(k) + b_q v_q(k) - R_q i_q(k)
\end{array}
\right.
\]

(5)

In LADRC control theory, for first-order single input and single output (SISO) systems:

\[
\dot{x} = f(x, w(t), t) + b_0 u \\
y = x_1
\]

(6)

Where \(w(t)\) is the external disturbance and \(f(x_1, w(t), t)\) is the total disturbance; \(b_0\) is the control gain, which can be determined by the controlled system parameters. Its LESO can be expressed as

\[
\begin{align*}
e &= z_1 - y \\
\dot{z}_1 &= z_2 + b_0 u - \beta_{01} e \\
\dot{z}_2 &= -\beta_{02} e
\end{align*}
\]

(7)

Where, \(\beta_{01}, \beta_{02}\) is the controller parameter; \(z_1\) is the tracking value of \(y\) and \(z_2\) is the observation value of total disturbance \(f(x_1, w(t), t)\).

Therefore, from equation (5) and equation (7), the discretized current loop LESO can be obtained as follows:
\[\begin{align*}
    e_d &= z_1(k) - i_d, \quad e_q = z_3(k) - i_q \\
    z_1(k+1) &= z_1(k) + T_e \left( z_1(k) + b_d u_d - R_0 z_1 / L_{d0} \right) - \beta_1 e_d \\
    z_2(k+1) &= z_2(k) - \beta_2 e_d \\
    z_3(k+1) &= z_3(k) + T_e \left( z_3(k) + b_q u_q - R_0 z_3 / L_{q0} \right) - \beta_3 e_q \\
    z_4(k+1) &= z_4(k) - \beta_4 e_q
\end{align*}\] (8)

Where, \(z_1, z_2, z_3, \) and \(z_4\) are respectively the tracking value of d-axis current \(i_d\), the observation value of d-axis total disturbance \(f_{d2}\), the tracking value of q-axis current \(i_q\) and the observation value of q-axis total disturbance \(f_{q2}\). \(\beta_m (m=1, 2, 3, 4)\) is the discrete gain coefficient in the discrete LESO equation of state.

By substituting \(z_1\) and \(z_3\) obtained by leso into equation (3) and feeding back the observed disturbances \(z_2\) and \(z_4\), the reference voltage vector after compensating disturbance can be obtained

\[\begin{align*}
    u_d(k+1) &= L_{d0} \left( \frac{z_1(k+1)}{T_e} + R_0 z_1(k+1) - \omega_0 L_{d0} z_3(k+1) + \frac{z_2(k+1)}{b_d} \right) \\
    u_q(k+1) &= L_{q0} \left( \frac{z_3(k+1)}{T_e} + R_0 z_3(k+1) + \omega_0 L_{d0} z_1(k+1) - \frac{z_4(k+1)}{b_q} \right)
\end{align*}\] (9)

The reference voltage vector \(u_{d,q}(k+1)\) calculated by the above equation comprehensively considers and compensates the errors caused by sampling delay and internal and external disturbances of the system, so it has higher control accuracy and robustness than equation (3). The fig.2 shows the current loop DPCC control structure based on LESO. It can be seen that the d-axis and q-axis current coupling terms of the control system are eliminated, and the decoupling control can be realized. But at the same time, this control method will increase the observation burden of LESO, and has higher requirements for parameter tuning of LESO. If the parameter setting is not appropriate, it will bring more estimation error. Therefore, it is necessary to analyze the parameter range of the designed LESO.

\[G_\zeta(z) = \frac{(\beta_1 - T_e R_0 / L_{d0})(z-1) + T_e \beta_2}{z^2 + (\beta_1 - 2)z + 1 - \beta_4 + T_e \beta_2}\] (10)

According to the direct criterion of stability in z-domain, the stability condition of LESO is obtained as follows

\[\begin{align*}
    T_e \beta_2 &< \beta_4 < (4 + T_e \beta_2^2) / 2 \\
    \beta_2 &> 0
\end{align*}\] (11)

Fig. 2 Control structure of current loop DPCC after decoupling

4.2. Parameter Stability Analysis of LESO

The d-axis and q-axis LESO of PMSM current loop have the same structure, so the parameter stability analysis of LESO is based on d-axis in the following. The structure block diagram of d-axis LESO designed by equation (9) is shown in Fig. 3.

Fig. 3 Block diagram of d-axis LESO structure

The closed loop transfer function of LESO obtained Fig. 3 is

\[G_\zeta(z) = \frac{(\beta_1 - T_e R_0 / L_{d0})(z-1) + T_e \beta_2}{z^2 + (\beta_1 - 2)z + 1 - \beta_4 + T_e \beta_2}\] (10)

According to the direct criterion of stability in z-domain, the stability condition of LESO is obtained as follows

\[\begin{align*}
    T_e \beta_2 &< \beta_4 < (4 + T_e \beta_2^2) / 2 \\
    \beta_2 &> 0
\end{align*}\] (11)
It can be seen that the stability of LESO is closely related to the selection of parameters $\beta_1$ and $\beta_2$. Only when the set values of $\beta_1$ and $\beta_2$ satisfy the condition of equation (12), the poles of LESO transfer function fall in the unit circle, the system can be stable.

Fig. 4 is the pole distribution diagram of LESO closed-loop transfer function drawn by MATLAB (sampling period $T_s = 0.0001$). It can be seen from the figure that when $\beta_1=1.5$, the closed-loop poles can fall in the unit circle when the value of $\beta_2$ is in the range of 0~15000. When $\beta_2=6000$, the closed-loop poles can fall in the unit circle when the value of $\beta_1$ is in the range of 0~2.3. The above results are consistent with the conclusion of equation (12).

Fig. 4 LESO closed-loop pole distribution diagram

In general, the selection principle of discrete system poles is to avoid distributing in the left half of the z-plane unit circle, and it is better to distribute in the right half near the origin. If this, the amplitude of complex poles is small, and the transient process of response is fast, that is, the discrete system has fast response performance to the input.

5. Simulation analysis

5.1. Simulation analysis of sampling delay effect

In order to study the influence of sampling delay on the designed control system, a simulation experiment is designed. The overall structure diagram of PMSM control strategy with PI controller for speed loop and DPCC controller for current loop is shown in Fig. 5 (Using $i_d = 0$ control strategy).

Fig. 5 Block diagram of PMSM control strategy structure

Fig. 6 shows the simulation comparison diagram of the DPCC controller of PMSM control system without considering the sampling delay and considering the sampling delay. In the simulation, the initial speed is given as $n^* = 1000 \text{rpm}$, and the given speed is changed to 2000rpm when $t = 0.1 \text{s}$. The load torque at the initial time is set to zero, the rated load is added when $t = 0.05$, and the load is unloaded when $t = 0.15 \text{s}$.
The simulation results show that the speed stability of the motor is poor without considering the delay effect, the amplitude of the fluctuates about 15rpm in steady-state operation, and the d-axis and q-axis current oscillates obviously. Considering the time delay, the speed stability of the motor is significantly improved, the d-axis current has no obvious oscillation and almost no static error in the steady state, the q-axis current can track the given value quickly and smoothly, and the current ripple is significantly reduced. It can be seen that the effect of sampling delay on discrete control system is obvious, which can greatly reduce the control accuracy of the system.

5.2. Simulation analysis of DPCC controller based on LESO

In order to verify the control performance of the proposed leso based DPCC strategy, simulation experiments are designed. In the simulation, the DPCC controller of current loop in PMSM control system shown in Fig. 5 is replaced by the DPCC controller based on leso.

Fig. 7 shows the simulation curve of speed and current response of the designed control strategy. In the simulation, the initial given speed is 2000rpm, and the given speed drops to 1000rpm when \( t = 0.1 \)s. At the initial moment, the load torque is set to zero, that is, the motor starts at no load, 2.4n.m load is added when \( t = 0.05 \)s, and load is removed when \( t = 0.15 \)s.

It can be seen from the figure that the speed response can quickly track the given value when the motor is started and the speed is given to change, and the steady-state operation is stable without static error. Because PI controller is used in the speed loop, there is a certain overshoot in the starting process. When there is load disturbance, the speed has a certain degree of fluctuation, but can quickly track the given value. The d and q axis current ripple of the motor is small, there is no static error in steady state, the dynamic response is fast, and it can track the given value quickly.

In order to analyze the static and dynamic characteristics of the designed control strategy when the motor parameters have errors, the PMSM control system with DPCC controller and LESO based DPCC controller is simulated and compared when the actual inductance of the motor is 0.5 times the nominal value (\( L = 0.5L_0 \)). The results are shown in Fig. 8.
It can be seen from Fig. 8 that the d-axis current oscillation under DPCC control is very obvious, and the fluctuation amplitude can reach 8A; The Burr phenomenon of q-axis current is very serious, and the fluctuation amplitude is about 5A in stable operation, which will lead to obvious output torque fluctuation. When the improved DPCC control strategy is adopted, the fluctuation amplitude of d-axis current is obviously reduced, and the fluctuation amplitude is nearly 3A only when the given speed changes. The Burr phenomenon of q-axis current is obviously optimized, there is a certain fluctuation in the starting process, and then the operation is relatively stable. It can be seen that the DPCC control strategy based on leso significantly improves the parameter robustness of the control system.

6. Conclusion

In PMSM double closed-loop speed control system, combined with the characteristics of deadbeat control with high current control accuracy and LADRC with strong anti-interference ability, the DPCC strategy based on LESO is designed. This control strategy not only has good speed and current control effect, but also solves the problem that traditional DPCC has strong dependence on model parameters. It can be seen from the simulation results that the strategy has the characteristics of good speed tracking performance, strong anti disturbance ability and strong parameter robustness.

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