Deadbeat Predictive Current Control with Disturbance Observer for Permanent Magnet Synchronous Motor

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Abstract. Deadbeat predictive current control (DPCC) is a kind of motor control method with excellent dynamic response performance. To increase the parameter robustness of DPCC, a disturbance observer (DO) is designed based on the extended Kalman filter (EKF). Firstly, this paper derives the DPCC method based on the mathematical model of permanent magnet synchronous motor (PMSM). Then, the DO is designed based on the EKF. The voltage disturbances caused by parameters mismatch are selected as the state vector, and the voltage disturbances at each time are calculated by the EKF iteratively. Thus, a novel control algorithm combining DPCC with DO is proposed. The simulation results of DPCC method are compared with the results of DPCC+DO method to verify the effectiveness of the proposed method.

1. Introduction
For permanent magnet synchronous motor (PMSM), the robustness and response speed of internal current loop plays a decisive role in the performance of the whole control system. Deadbeat predictive current control (DPCC) as a non-linear control method has better dynamic response performance than traditional PI control [1]. However, DPCC is based on motor model with accurate parameters. When the parameters of motor changed due to temperature or other factors, the calculated reference voltage will deviate from the expected value. Therefore, how to improve the parameter robustness of DPCC is of great significance to the stable operation of the motor [2]. Some researchers have studied methods of parameter identification to mitigate the performance degradation caused by model uncertainty [3-5]. However, the methods are susceptible to interference and have the shortcomings of large amount of calculation. In addition, approaches that combining the DPCC and disturbance observer (DO) can improve control performance as well [6]. Zhang [7] proposed a DO based on sliding mode exponential reaching law, but the inherent high-frequency chattering of sliding mode control will affect the performance of the motor. It is a relatively effective method to correct the output voltage of DPCC by compensation. However, how to design a simple and accurate DO remains to be studied. In order to overcome the shortcomings of the existing DO, a DO based on extended Kalman filter (EKF) is designed in this paper. The DO can observe the system voltage disturbance caused by parameter mismatch accurately and improve the parameter robustness of DPCC.
2. DPCC and Disturbance Observer

2.1. Mathematical Model of PMSM and DPCC
In this paper, the surface-mounted PMSM is taken as the research object. The voltage equation of the motor in the \( \alpha-\beta \) coordinate system is as follows:

\[
\begin{align*}
\dot{u}_a &= R_i i_a + L_s p_i_a - \omega \psi_r \sin \theta \\
\dot{u}_\beta &= R_i i_\beta + L_s p_i_\beta + \omega \psi_r \cos \theta
\end{align*}
\]  

(1)

In the equation, \( u_a \) and \( u_\beta \) are the stator voltage in the \( \alpha-\beta \) coordinate system; \( i_a \) and \( i_\beta \) are the stator current in the \( \alpha-\beta \) coordinate system; \( \psi_r \) is the rotor flux; \( R_s \) is the stator resistance; \( L_s \) is the stator inductance; \( \omega_c \) is the rotor electrical palstance; \( \theta \) is the rotor position angle; \( p \) is the differential operator.

The model described in equation (1) is ideal, that is, assuming that the parameters of motor remain unchanged. Considering the variation of motor parameters, equation (1) is rewritten as follows:

\[
\begin{align*}
\dot{u}_a &= R_{sc} i_a + L_{sc} p_i_a - \omega \psi_{rc} \sin \theta + f_a \\
\dot{u}_\beta &= R_{sc} i_\beta + L_{sc} p_i_\beta + \omega \psi_{rc} \cos \theta + f_\beta
\end{align*}
\]  

(2)

Where, \( R_{sc}, \ L_{sc}, \ \psi_{sc} \) are the estimated value of motor parameters, and \( f_a, \ f_\beta \) are the voltage disturbance caused by the parameter mismatch. The voltage disturbance \( f_a, \ f_\beta \) are defined as follows:

\[
\begin{align*}
f_a &= \Delta R_i i_a + \Delta L_s p_i_a - \Delta \psi_r \omega_c \sin \theta \\
f_\beta &= \Delta R_i i_\beta + \Delta L_s p_i_\beta + \Delta \psi_r \omega_c \cos \theta
\end{align*}
\]  

(3)

If the sampling time \( T_{sc} \) is short enough, the voltage equation (1) can be discretized by using the first-order Euler equation, and the voltage equation of PMSM in the discrete state can be obtained. Based on the voltage equation in the discrete state, the DPCC can be expressed as follow:

\[
\begin{bmatrix}
i_a(k+1) \\
i_\beta(k+1)
\end{bmatrix} = \left(1 - \frac{T_{sc} R_s}{L_s}\right) \begin{bmatrix}i_a(k) \\i_\beta(k)\end{bmatrix} + \frac{T_{sc}}{L_s} \begin{bmatrix}u_a(k) \\
u_\beta(k)\end{bmatrix} + M(k)
\]

(4)

\[
\begin{bmatrix}
u_a(k+1) \\
u_\beta(k+1)
\end{bmatrix} = \frac{L_s}{T_{sc}} \begin{bmatrix}i_a(k+2) \\i_\beta(k+2)\end{bmatrix} - \left(1 - \frac{T_{sc} R_s}{L_s}\right) \begin{bmatrix}i_a(k+1) \\i_\beta(k+1)\end{bmatrix} - M(k+1)
\]

(5)

Where, \( i_a(\cdot+2) \) and \( i_\beta(\cdot+2) \) represent the reference current values at \( k+2 \) time; \( M \) is defined as follows:

\[
M(k) = \begin{bmatrix}
\frac{T_{sc}}{L_s} \omega_c(k) \sin \theta & -\frac{T_{sc}}{L_s} \omega_c(k) \psi_r \cos \theta
\end{bmatrix}^T
\]

(6)

2.2. Disturbance observer
The calculation process of EKF can be divided into two parts: prior prediction and posterior correction. Based on the EKF algorithm, the state vector \( x \) and the control vector \( u \) can be selected. It is simpler to use the output voltage of DPCC as the control vector than to collect the output voltage of the inverters as the control vector.

\[
x = \begin{bmatrix}i_a & i_\beta & \omega_c & \phi & f_a & f_\beta\end{bmatrix}^T
\]

(7)

\[
u = \begin{bmatrix}u_a & u_\beta\end{bmatrix}^T
\]

(8)

Then, by rewriting equation (2) in the form of current state equation, the corresponding non-linear equation of PMSM can be written out as equation (9). The change of motor parameters are slow relative to the change of current, so it can be considered that the change of voltage disturbances caused by parameter mismatch are slow relative to the change of current, and they remain unchanged during the interval of a sampling period, i.e., the derivative of disturbances are zero.

\[
\dot{x} = f(x) + C u + w
\]

(9)
Where, \( w \) is the system noise, \( C \) is the gain matrix of control variables, and \( f(x) \) is the state transition function.

\[
\begin{bmatrix}
    f_1 \\
    f_2 \\
    f_3 \\
    f_4 \\
    f_5 \\
    f_6
\end{bmatrix} =
\begin{bmatrix}
    \frac{(-R_s i_a + \psi_r \omega_c \sin \theta - f_a)}{L_{ac}} \\
    \frac{(-R_s i_\beta - \psi_r \omega_c \cos \theta - f_\beta)}{L_{ac}} \\
    0 \\
    \omega_e \\
    0 \\
    0
\end{bmatrix}
\tag{10}
\]

\[
C = \begin{bmatrix}
    L_{ac}^{-1} & 0 & 0 & 0 & 0 \\
    0 & L_{ac}^{-1} & 0 & 0 & 0
\end{bmatrix}
\tag{11}
\]

The stator current, rotational speed and rotor position angle are selected as the observation vector. Then the corresponding measurement equation of motor control system can be obtained.

\[
y = \begin{bmatrix}
    i_a \\
    i_\beta \\
    \omega_e \\
    \theta
\end{bmatrix}^T
\tag{12}
\]

\[
y = h(x) + v
\tag{13}
\]

Where, \( v \) is the measurement noise and \( h(x) \) is the measurement function.

\[
h(x) = \begin{bmatrix}
    i_a \\
    i_\beta \\
    \omega_e \\
    \theta
\end{bmatrix}^T
\tag{14}
\]

The DO in this paper has the function of observing the voltage disturbance caused by parameter mismatch in real-time. Using EKF algorithm to linearize the non-linear motor model can minimize the amount of on-line calculation and ensure the good dynamic current tracking characteristics in the process of motor operation. Linearization of \( f(x) \) and \( h(x) \) is carried out as follows:

\[
F(x(t)) = \frac{\partial f}{\partial x} |_{x=x(t)}
\tag{15}
\]

\[
H(x(t)) = \frac{\partial h}{\partial x} |_{x=x(t)}
\tag{16}
\]

2.3. DPCC with DO

Combining the designed DO with DPCC by feed-forward compensation, the output voltage of DPCC can be corrected by the DO, which can effectively improve the parameter robustness of DPCC. The block diagram of DPCC with DO is shown in Fig. 1.

![Figure 1. Block diagram of DPCC with DO.](image)

3. Results and Discussions
In this part, the verification test was carried out on Matlab/Simulink. The test was conducted in a comparative way. Firstly, the traditional DPCC method was simulated for parameter mismatch, and then the DPCC+DO method was simulated for the same parameter mismatch. The effect of DO on improving the parameter robustness is analysed through the different performances of the motor. The parameters of the PMSM used in the simulation are shown in Table 1. As for the initialization of the DO, the initial value of the covariance matrix of the state vector as well as the initial values of the covariance matrix of system noise and measurement noise were set as follows:

\[
P_0 = \begin{bmatrix} 0.1 & 0.1 & 500 & 0.5 & 10 & 10 \end{bmatrix}^T
\]

(17)

\[
Q_d = diag(0.1, 0.1, 300, 0.2, 2, 2)
\]

(18)

\[
R = diag(0.001, 0.001, 0.001, 0.001)
\]

(19)

| Table 1. Parameters of PMSM for Test. |
|---------------------------------------|
| Motor parameters                      |
| Value                                 |
|                                        |
| \(d\)-axis and \(q\)-axis inductances  | 0.001225 mH |
| Stator phase resistance                | 0.365 Ω    |
| Flux linkage of permanent magnet       | 0.1667 Wb  |
| Rotational inertia                    | 0.00194 kg⋅m² |
| Number of pole pairs                  | 4          |

In the simulation, the initial target speed was set to 800 r/min and the motor started without load; the load torque of 10N⋅m was applied to the motor when the test had been carried out to 0.04s; and the target speed of the motor was raised to 1200 r/min when the test had been carried out to 0.1s.

Fig. 2 is the current variation diagram of DPCC under different parameters mismatch. Based on the feed-forward compensation method shown in Fig. 1, a DPCC+DO simulation model was built. The results are shown in Fig. 3. By comparing Fig. 2 with Fig. 3, it is concluded that: the DPCC+DO method can reduce the ripple caused by inductance mismatch effectively and compensate for the deterioration of dynamic characteristics caused by resistance mismatch and flux mismatch to a certain extent.

**Figure 2.** Current variation diagram of DPCC under parameter mismatch.

(a) No mismatch of parameters (b) \(L_{ac}=2L_s\) (c) \(L_{ac}=0.5L_s\) (d) \(R_{sc}=10R_s\) (e) \(R_{sc}=0.1R_s\) (f) \(\psi_{sc}=2\psi_r\)
Considering that only the inductance mismatch has a significant impact on the steady-state of the motor, the amplitude of current ripple in the case of inductance mismatch \((L=2L_0)\) is recorded in Table 2. It can be concluded that when the inductance mismatch occurs, the amplitude of current ripple in \(q\)-axis can be reduced by 80.27\% (0.04s-0.1s) and 79.9\% (0.1s-0.14s) respectively, and the amplitude of current ripple in \(d\)-axis can be reduced by 89.14\% (0.04s-0.1s) and 70.96\% (0.1s-0.14s), respectively. The results reveal that the DO can effectively reduce the ripple caused by the mismatch of inductance.

![Figure 3. Current variation diagram of DPCC+DO under parameter mismatch.](image)

\((a)\) No mismatch of parameters \((b)\) \(L_{ss}=2L_s\), \((c)\) \(L_{ss}=0.5L_s\) \((d)\) \(R_{ss}=10R_s\) \((e)\) \(R_{ss}=0.1R_s\) \((f)\) \(\psi_{se}=2\psi_t\)

Table 2. Quantitative comparison of DPCC and DPCC+DO under inductance mismatch \((L_{ss}=2L_s)\).

| Method | DPCC         | DPCC+DO     |
|--------|--------------|-------------|
| \(i_q\) | 0.04s-0.1s-0.14s | 9.82 A & 7.63 A | 1.94 A & 2.22 A |
| \(i_d\) | 0.04s-0.1s-0.14s | 14.54 A & 7.82 A | 1.58 A & 2.27 A |

4. Conclusion

In this paper, the DO based on EKF is combined with DPCC by feed-forward compensation, and the novel method improves the parameter robustness of DPCC. Using the outputs of the DO, the state of the motor can be monitored in real time. Also we admit it that if the convergence speed of EKF can be faster, e.g. by reducing its dimension, the dynamic characteristics of the observer will be better.

Acknowledgments

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