Research on UDE control based on load torque compensation of PMSM

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Abstract: In order to solve the problem that the traditional uncertainty and disturbance estimator (UDE) control needs to increase the filter order to keep good performance when facing rapid disturbance changes, thus lead to cost increase in implementing the system, a speed control strategy of permanent magnet synchronous motor (PMSM) driver based on reduced order observer compensation is proposed. The designed control strategy is robust to the system with internal parameter variation and external torque disturbance. Through the compensation of load torque, the pressure of UDE controller is relieved, and then the tracking error of high-frequency component in load torque is eliminated, and the control performance of the system is improved more effectively. This paper proves the superiority of the new compound controller through comparison of simulation results.

1. Introduction
Permanent magnet synchronous motor has many advantages, such as compact structure, high power density and high air gap flux density. Therefore, researches on permanent magnet synchronous motor servo system is conducted by more and more scholars [1]. However, in practical application, there are unknown system parameters, unpredictable parameter changes and unexpected disturbances. It is particularly important to design a controller with high robust in PMSM drive system.

Uncertain interference estimator (UDE) is an estimation method for model uncertainty and interference proposed by Qing Chang Zhong et al in 2004 [2]. The core of UDE control is to estimate the internal uncertainty and external disturbance of the system by designing appropriate filters, so as to compensate the error between the actual model and the reference model. Therefore, when using UDE theory to design robust controller, it is no need to know the specific model of parameter uncertainty and external disturbance. The design process is simple and the calculation is convenient. At present, it has been successfully applied to uncertain linear time invariant systems [2] [3]. In Zhong [2] suggests that the GF(s) of bandwidth filter should adopt a simple form, and puts forward a practical first-order low-pass filter: the results show that the low-pass filter has better tracking performance when the time constant is small. However, its value is limited by the system sampling time. In Shendge P D [4], the UDE controller based on SMC is applied to linearized load frequency control. It is considered that the proposed method can provide excellent tracking result under up to 98% parameter changes. Literature [5] proposes a PMSM speed loop controller based on UDE, However, it is set in the control law that the disturbance must maintain a constant value and change slowly. Aiming at the problem of poor observation effect under time-varying load in reviewed references, this paper adds a reduced order with traditional UDE to compensate the load torque, improves the speed tracking effect of the speed loop.
both in facing constant and changing disturbance, and improves the anti-interference ability of the system.

2. Mathematical model of PMSM

The stator side voltage equation of MSM in d-q rotating coordinate system is

\[
\begin{align*}
L_d \frac{di_d}{dt} &= -R_i + u_d + \omega \frac{L_q}{c} i_q \\
L_q \frac{di_q}{dt} &= -R_i + u_q - \omega \left( \psi_f + L_d i_d \right) \\
T_e - T_L - B \omega &= \frac{J}{c} \frac{d\omega}{dt} \\
T_e &= \frac{3}{2} P \psi_f i_q
\end{align*}
\]

Where: \(i_d, i_q\) is the motor stator current; \(R\) is the stator resistance; \(u_d, u_q, L_q, L_d\) are voltage and inductance of d-axis and q-axis respectively; \(\omega\) is the electrical angular velocity; \(\psi_f\) is permanent magnet flux linkage; \(n_p\) is the mechanical angular velocity; \(T_e\) is electromagnetic torque; \(P\) is the number of poles; \(B\) is the friction constant; \(J\) is the moment of inertia of the system; \(T_L\) is the load torque.

3. UDE controller design

Using UDE to estimate the disturbance, a disturbance estimation speed tracking controller is designed. The velocity loop equation is as follows

\[
\frac{d\omega_r}{dt} = \frac{3}{2J} \left( \frac{P}{2} \right)^2 i_q \lambda_{af} - \frac{B}{J} \omega_r - \frac{1}{J} T_L
\]

Rewrite equation (2) as

\[
x = a_i x + b_i u + d
\]

where \(a_i = -\frac{B}{J}, \quad b_i = \frac{3}{2J} \left( \frac{P}{2} \right)^2 \lambda_{af}, \quad d\) is external interference

In UDE control, it is necessary to establish a stable reference model to realize the quantitative tracking of the actual state variables to the reference model. For PMSM, in order to realize the good tracking of the actual speed of speed loop to the given speed, the desired reference model is selected and defined as follows

\[
x_m(t) = A_m x_m(t) + B_m c(t)
\]

Here \(x_m = \omega_m\) is the reference state vector, \(c = \omega^*\) refers to a given instruction. For PMSM, the design factor is \(A_m = -\alpha, B_m = \alpha, \quad \alpha\) is a positive real number.

In order to realize the asymptotically stable speed following of the speed loop, the state vector \(x(t)\) needs to converge to the reference state vector \(x_m(t)\), that is, the tracking error converges to 0.

The tracking error is defined as follows

\[
e(t) = x_m(t) - x(t)
\]

Select the appropriate \(u(t)\) to make the formula valid:
By using Lyapunov stability criterion, $A_m < 0$, it can be obtained that the error equation is asymptotically stable. So

$$u(t) = B^{-1}(A_m x(t) + B_m c(t) - Ax(t) - D(t))$$

(7)

Thus can ensure that the actual speed of PMSM can track its reference speed stably.

The core of UDE control theory is to use a suitable filter to estimate the total disturbance, so as to establish the voltage control law of the reference model which can make the actual model accurately track and stabilize. For the step disturbance signal in the motor control system, a first-order low-pass filter is used to estimate the total disturbance, and the transfer function is shown in the formula

$$\hat{D}(s) = D(s) * W(s)$$

(8)

Where, first-order low-pass filter $W(s)$

$$W(s) = \frac{\omega_p}{s + \omega_p}$$

(9)

Where, $\omega_p$ is the cut-off frequency of the first-order low-pass filter,

Substitute (8),(9) into (7)

$$U(s) = B^{-1}\left[ \frac{1}{1-W(s)} (A_m X(s) + B_m C(s)) - AX(s) - \frac{W(s)}{1-W(s)} X(s) \right]$$

$$= B^{-1}\left[ A_m X_m(s) + B_m C(s) - (A_m - \omega_p) E(s) - \frac{\omega_p E(s)}{s} - \frac{AX(s)}{s} \right]$$

(10)

Here $B^{-1} = \frac{1}{b_0}$, $A_m = -B_m = -\alpha$, $A = a_1$.

It can be seen from equation (10) that the UDE controller with the new control rate mainly includes reference model differentiation, error tracking regulator and actual model inversion. The differential feedforward part of reference model improves the speed of error convergence; The PI regulator accurately estimates the total disturbance to compensate the tracking error between the actual model and the reference model; The model inverse module cancels the model part of the controlled PMSM. Compared with PI control, UDE controller has better control effect than PI controller because it contains reference model differential feedforward part.

4. Observer based compound control

The error equation of the actual closed-loop system is

$$e + Ke = \tilde{d}$$

(11)

Among $e = x - x^*$, $\tilde{d} = d - \hat{d}$.

The actual state error can be changed by adjusting the reference model and filter $W(s)$. From equation (11), the error function is

$$E(s) = \frac{1-W(s)}{s + a_m} U_d(s)$$

(12)

Therefore, for the traditional UDE speed loop PMSM control, when the disturbance is constant or slowly changing, the tracking error gradually attenuates to 0, so a satisfactory speed tracking effect can be obtained. However, in the face of rapidly changing disturbances, the order of the filter can not accurately estimate the high-frequency load, and can not obtain a good speed tracking effect. Therefore, when facing rapid change disturbance, the order of the filter needs to be increased. However, the higher
the order, the more complex the filter is and the higher the cost. Therefore, in view of the above situation, a reduced order disturbance observer is designed to accurately obtain the load torque, so that the UDE controller can reduce the estimation pressure of the filter in the face of fast disturbance. Therefore, we take the disturbance caused by time-varying load torque as the observation body and design a reduced order observer

\[
\frac{d\tilde{\omega}_m}{dt} = -\frac{b_m}{J}\tilde{\omega}_m - \frac{1}{J}\tilde{T}_L + \frac{1}{J}T_e
\]

\[
\frac{dT_L}{dt} = k_2(\omega_m - \tilde{\omega}_m) + k_4\frac{d(\omega_m - \tilde{\omega}_m)}{dt}
\]

Value of state feedback coefficient:

\[
k_2 = -\alpha\beta
\]

\[
k_4 = J(\alpha + \beta)
\]

The control schematic diagram is as follows:

Figure.1 Schematic diagram of simulation control

5 Simulation Verification
In order to verify the exception of the composite UDE control strategy based on the down-order observer, the controller of the current loop of three control policies is the same, but the speed loop is used by UDE control policies and downside. The composite UDE control strategy for the observer. The motor parameter is 2.875Ω, the polar log is 4, and the vertical shaft inductance is 0.085MH, and the rotation is 0.03 kg.m².

5.1 When the motor is airborne starts, a given speed 1000R / min, 0.2s surplus 10N.m load, 0.3S suddenly the 10N.m load.

As seen from the simulation results, the control system is basically no over-tuning when the motor is started. By as viewed on the speed response, the speed adjustment time of the UDE controller compensated based on the down-order observer is the shortest, and the dynamic speed is lowered. At the 0.3S sudden load, the speed of the UDE controller compensated for the reduction observer is minimized.
Figure. 2 Motor response overall comparison

Figure. 3 Tracking performance results of reduced order observer

5.2 When the motor is not loaded, a given speed 1000R / min, 0.21s is given a sinusoidal load of 10 amplitude 10.

As seen from the simulation results, under the sinusoidal load input, the motor speed of the UDE control based on the conventional UDE speed loop is lower, the recovery time is short, and the restriction of the change is faster. Higher compensation accuracy, better tracking performance.

Figure. 4 Motor response overall comparison
Figure 5 Tracking performance results of reduced order observer

Comprehensive analysis, the UDE controller based on the compensation of the down-order observer is superior to the traditional UDE control in the face of step load and time variable load, because the traditional UDE controller needs to track the comprehensive disturbance of the change in change, the tracking accuracy is not high, and the UDE controller compensated based on the down-order observer has excellent anti-disturbance performance under load torque compensation, which can make the motor still have good operating performance in the presence of time.

6. Conclusion
In the PMSM speed control system, when the UDE speed loop is controlled, when the speed is facing rapid disturbance, it is necessary to increase the order of the filter, thereby increasing the cost, and this paper proposes a UDE controller based on the downgrade observer compensation, passed the downgrade observer further reduces the bandwidth of the total perturbation, which in turn reduces the observation pressure of the UDE filter while maintaining the original UDE advantage, thereby improving the observation performance.

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