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ROTATIONAL SPEED OBSERVATION OF A METALLURGICAL LIFTING MOTOR BASED ON THE DELTA OPERATOR

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In metallurgical and mining applications, it is not easy to install speed sensors, so the speed of the lifting motor is usually obtained using a speed observer. To solve the instability problem of traditional speed observers in practical applications when the sampling period is reduced after discretization based on shift operators, a new type of speed observer for discrete-time systems is analyzed and designed. The speed observer introduces the Delta operator, which improves the problem of unstable observation data caused by high-frequency sampling in traditional speed observers. And by establishing a motor speed observation system through simulation, the correctness of the conclusion was verified.

Keyword: speed observer, permanent magnet synchronous motor, delta operator, metallurgical lifting motor

INTRODUCTION

Due to its simple structure, high power density, and fast response speed, permanent magnet synchronous motors (PMSM) are widely used in fields that require high-precision control and fast response, such as metallurgy and mining industries[1]. The speed of PMSM is mostly measured through sensors, but in practical applications, sensors may also have some defects[2]. For example, the working environment and the particularity of the tested object can affect the installation and measurement of sensors; In addition, sensors themselves also have deterministic errors, and their limited response ability can introduce noise into the system, reducing the reliability of system control[3]. Therefore, signals with higher accuracy than sensors can be obtained by using appropriate observers.

Establishment of Mathematical Model for Permanent Magnet Synchronous Motor

In order to facilitate the design of the controller in the later stage, a mathematical model in a synchronous rotating coordinate system is adopted[4].

The stator voltage equation is:

$$\begin{cases} u_d = Ri_d + \dfrac{d}{dt}\psi_d - \omega_e\psi_q \\ u_q = Ri_q + \dfrac{d}{dt}\psi_q + \omega_e\psi_d \end{cases} \tag{1}$$

Where: u_d, u_q is the d-q axis component of the stator voltage; i_d, i_q is the d-q axis component of the stator current; R is the stator resistance; Ψ_d, Ψ_q is the d-q axis component of the stator flux; ω_e is the angular velocity.

The stator flux equation is:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{2}$$

Where: L_d, L_q is the d-q axis component of the stator inductance; ψ_f is the flux of a permanent magnet.

The electromagnetic torque equation is:

$$T_e = \frac{3}{2} p_n i_q \left[i_d \left(L_d - L_q \right) + \psi_f \right] \tag{3}$$

Where: T_e is the electromagnetic torque; p_n is the pole logarithm.

The mechanical motion equation is:

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{4}$$

Where: J is the moment of inertia; ω_m is the mechanical angular velocity; T_L is the load torque; B is the viscous coefficient of friction.

In summary, the state space of the system is expressed as:

$$\begin{gathered} \frac{d}{dt}\begin{bmatrix} i_q \\ \omega_m \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{L_q} & -\dfrac{P_n\psi_f}{L_q} \\ \dfrac{3P_n\psi_f}{2} & -\dfrac{B}{J} \end{bmatrix}\begin{bmatrix} i_q \\ \omega_m \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_q} \\ 0 \end{bmatrix} U_q \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix}\begin{bmatrix} i_q \\ \omega_m \end{bmatrix} \end{gathered} \tag{5}$$

Design of Speed Observer

The Luenberger observer is a method used for observation and control of dynamic systems. It is based on the system state space equation and takes the system output and observer output errors as feedback. When estimating and tracking state variables, the feedback error quickly converges to zero through observer pole configuration. The design purpose of the Longberg observer is to achieve

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better identification and control of the system's dynamic behavior by using system models and sensor data to estimate the system's state in real time[5].

The form of a permanent magnet synchronous motor speed observer with output feedback is as follows.

$$\frac{d}{dt}\begin{bmatrix} i_q \\ \hat{\omega}_m \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_q} - L_1 & -\frac{P_n \psi_f}{L_q} \\ \frac{3P_n \psi_f}{2} - L_2 & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_q \\ \hat{\omega}_m \end{bmatrix}$$

$$+\begin{bmatrix} \frac{1}{L_q} \\ 0 \end{bmatrix} U_q + \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} i_q \qquad (6)$$

$$\hat{y} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_q \\ \hat{\omega}_m \end{bmatrix}$$

Where: $\hat{\omega}_m$ is the observed value of the mechanical angular velocity; L_1, L_2 is the two poles of the observer.

The structure diagram of the PMSM speed observer is as follows Figure 1:

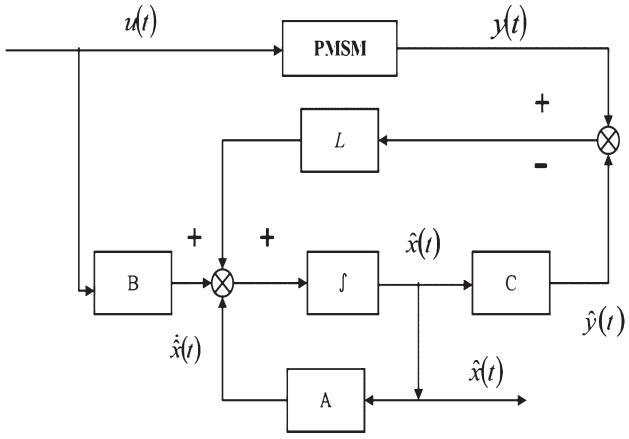

Figure 1 Structural diagram of Luenberger observer

Discretization of observer equations based on Delta operator

Currently, there are two major research areas in control theory: continuous systems and discrete systems. The research theory of discrete systems is more suitable for computer implementation, while the research conclusions of continuous systems are convenient for theoretical research. The conclusions of the two fields appear to have significant differences on the surface, and it is generally difficult to find a connection between them. The Delta operator theory serves as a bridge connecting the two.

Under fast sampling conditions, traditional shift operators can cause the poles of the sampling system to be located at stable boundaries, resulting in numerical instability issues such as quantization errors and limit cycle oscillations. They may also introduce non minimum phase zeros, leading to a decrease in the stability of the discretized system, while the Delta operator system model parameters tend to approach the corresponding continuous time model parameters. The sampling period in the Delta operator model is used as an explicit parameter to facilitate the observation and analysis of system performance under different sampling periods. The PMSM speed observer based on the Delta operator discretization method also shows better performance than the shift operator when the sampling period is reduced.

The Delta operator can also be called an incremental difference operator, and its definition is as follows:

$$\delta(T) = \begin{cases} \frac{dX(t)}{dt}, (T = 0) \\ \frac{X(t+T) - X(t)}{T}, (T \neq 0) \end{cases} \qquad (7)$$

Where: T is the sampling period of the discrete system. When $T = 0$, the system is continuous; when $T \neq 0$, the system is discrete.

Continuous time system state space model:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \qquad (8)$$

Where: A, B, C is the coefficient matrix of the state-space equation.

Z-domain discrete-time system model:

$$\begin{aligned} x(k+1) &= A_Z x(k) + B_Z u(k) \\ y(k) &= C_Z x(k) \end{aligned} \qquad (9)$$

Where: $A_Z = e^{AT}$, $B_Z = \int_0^T e^{A(T-s)} Bds$, $C_Z = C$.

State space model in Delta domain:

$$\begin{aligned} \delta x(k) &= A_\delta x(k) + B_\delta u(k) \\ y(k) &= C_\delta x(k) \end{aligned} \qquad (10)$$

Where: $A_\delta = (A_Z - I)/T$, $B_\delta = B_Z / T$, $C_\delta = C$.

Simulation experiment verification and analysis

To verify the observation accuracy of the new speed observer based on Delta operator discretization, a simulation model is constructed and the discrete system state matrix is calculated. The PMSM control structure diagram is as follows Figure 2.

This model adopts an id = 0 control strategy to achieve dual closed-loop control of current and speed. The parameters in the state space equation of the speed observer are shown in the Table 1.

The observer has two pole configurations of -1, -2.

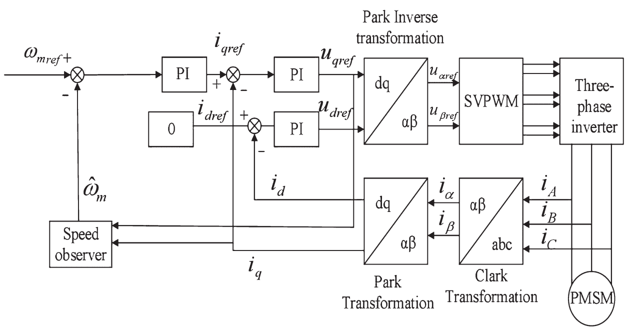

Figure 2 PMSM control structure diagram

Table 1 **Motor simulation parameters**

parameter	numerical value
stator resistance R/Ω	2,6
Q-axis inductance L_q/mH	5,6
Rotor flux ψ_f/W_b	0,065
Coefficient of viscous friction $B/N{\cdot}m{\cdot}s$	0,0002
Moment of inertia $J/kg{\cdot}m^2$	0,003
Polar logarithm P_n	4

The observer feedback matrix L can be obtained as:

$$\begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = \begin{bmatrix} 0,4379 \\ 2,4690 \end{bmatrix}$$

Input the unit step signal to the system, and the Z-domain unit step response is shown in the Figure 3.

The speed observer based on traditional shift operators has a decrease in observation accuracy from 99,4 % to 89,1 % as the sampling period decreases, and the observation accuracy gradually decreases as the sampling period decreases.

The unit step response in the Delta domain is shown in the Figure 4.

The speed observer based on Delta operator improves the observation accuracy from 99,6 % to 99,9 % as the sampling period decreases, and the observation accuracy gradually increases as the sampling period decreases.

By comparison, it can be seen that the new type of speed observer based on Delta operator discretization can observe PMSM speed well, and the observed speed curve is smooth and in line with the actual curve. However, the error of the speed observer based on traditional shift operator discretization gradually increases with the decrease of sampling period.

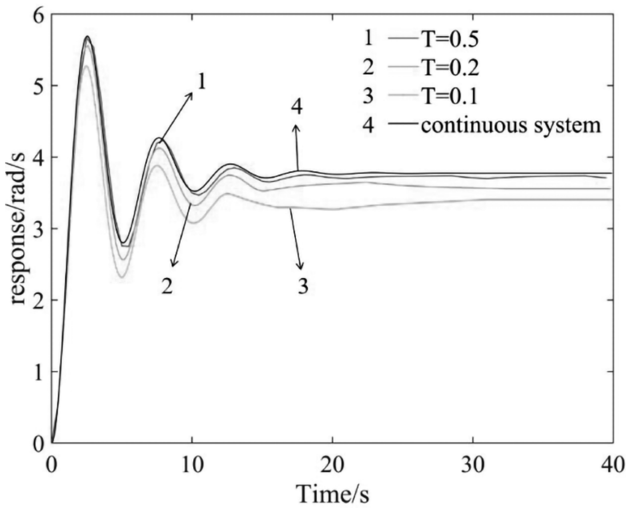

Figure 3 Z-domain response curve graph

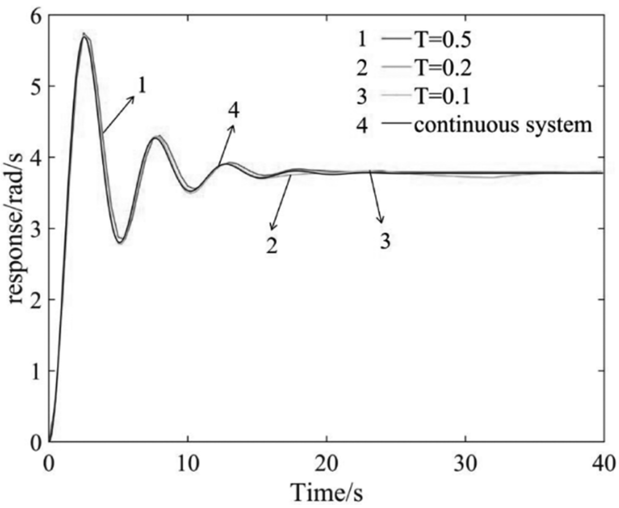

Figure 4 Delta-domain response curve graph

CONCLUSION

The speed observer design problem of PMSM was studied using the Delta operator discretization method. The speed observer designed at high sampling frequencies not only meets the accuracy requirements of the observer while ensuring system stability, but also has higher accuracy compared to traditional shift operators. Therefore, the speed observer design method proposed in this article can also be extended to practical engineering situations for observing other state variables, such as load torque observation of permanent magnet synchronous motors.

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Note: The responsible translator for English language is L. L. Meng