MRAS-based Sensorless Speed Estimation of High Speed Section for Interior Permanent Magnet Synchronous Motor

Hanlu Zhou[a], Zhengnai Sun[b], and Yandong Hu[c]

School of New Energy, Harbin Institute of Technology University, Weihai 264200, China

[a]hanluzhou@126.com, [b]bszn@hitwh.edu.cn, [c]chy376@126.com

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Abstract: For the high speed section of IPMSM sensorless operation, this paper mainly studies the Model Reference Adaptive System (MRAS) speed estimation algorithm. Firstly, the basic principle of model reference adaptive algorithm is expressed. Then the reference model and adjustable model of MRAS are constructed, and the adaptive law of speed estimation based on Popov's super stability theorem is designed. Finally, the sensorless control of IPMSM based on MRAS is carried out. The MATLAB modeling simulation of the system verifies the effectiveness of the designed speed estimation algorithm.

1. Introduction

Sensorless drive of interior permanent magnet synchronous motor (IPMSM) has been widely used in many industrial applications thanks to its easiness and technical maturity. In the high speed section of IPMSM, the speed estimation method based on motor mathematical model is mainly adopted, such as the model reference adaptive method, the sliding mode observer method and the Kalman filter method, etc. Compared with other control algorithms, the model reference adaptive method has good dynamic and steady-state performance, and the control structure is relatively simple and easy to implement. The method was first proposed in [2] followed by [3] which consists of a reference model, an adjustable model and an adaptation mechanism as depicted in Fig.1.

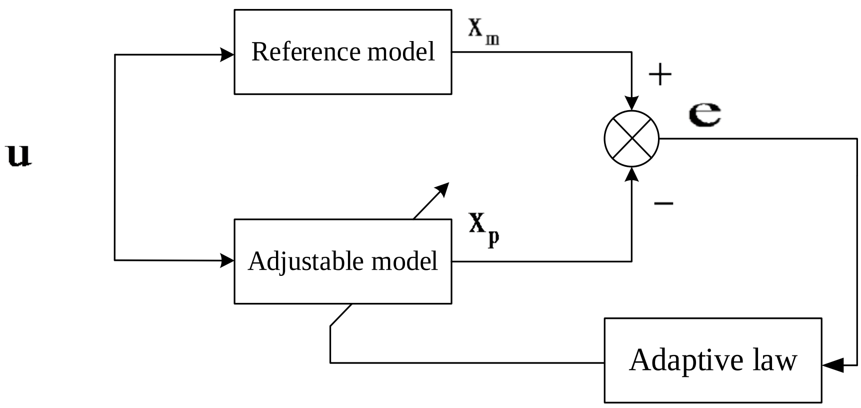

Figure 1. Basic scheme of model reference adaptive method

This paper mainly studies the Model Reference Adaptive System (MRAS) speed estimation algorithm for the high speed area of IPMSM sensorless operation. The effectiveness of the method is verified for a 50-kW position sensorless IPMSM drive.

2. Design of Mras

According to the model reference adaptive theory, transform the voltage equation in rotating coordinate system, MRAS model based on mathematical model of IPMSM is shown as follws:

(a) Reference Model

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R_s}{L_d} i_d + \omega_e \dfrac{L_q}{L_d} + \dfrac{u_d}{L_d} \\ \dfrac{di_q}{dt} = -\dfrac{R_s}{L_q} i_q - \omega_e \dfrac{L_d}{L_q} i_d - \omega_e \dfrac{\psi_f}{L_q} + \dfrac{u_q}{L_q} \end{cases} \tag{1}$$

The equivalent transformation is performed by the equation (1), and it is changed into the following form:

$$\begin{bmatrix} \dfrac{di_d^{'}}{dt} \\ \dfrac{di_q^{'}}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} & \omega_e \dfrac{L_q}{L_d} \\ -\omega_e \dfrac{L_d}{L_q} & -\dfrac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d^{'} \\ i_q^{'} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \end{bmatrix} \begin{bmatrix} u_d^{'} \\ u_q^{'} \end{bmatrix} \tag{2}$$

$$i_d^{'} = i_d + \frac{\psi_f}{L_d};\ \ i_q^{'} = i_q;\ \ u_d^{'} = u_d + \frac{R_s \psi_f}{L_d};\ \ u_q^{'} = u_q \tag{3}$$

Using the estimated value to express equation (2), we can get the following formula:

(b) Adjustable Model

$$\begin{bmatrix} \dfrac{d\hat{i}_d^{'}}{dt} \\ \dfrac{d\hat{i}_q^{'}}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} & \hat{\omega}_e \dfrac{L_q}{L_d} \\ -\hat{\omega}_e \dfrac{L_d}{L_q} & -\dfrac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \end{bmatrix} \begin{bmatrix} u_d^{'} \\ u_q^{'} \end{bmatrix} \tag{4}$$

By subtracting equation (2) from equation (4), the current error equation can be obtained as the following equation:

$$\frac{d}{dt}\begin{bmatrix} i_d^{'} - \hat{i}_d^{'} \\ i_q^{'} - \hat{i}_q^{'} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d} & \omega_e \dfrac{L_q}{L_d} \\ -\omega_e \dfrac{L_d}{L_q} & -\dfrac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d^{'} - \hat{i}_d^{'} \\ i_q^{'} - \hat{i}_q^{'} \end{bmatrix} - (\hat{\omega}_e - \omega_e) \begin{bmatrix} 0 & \dfrac{L_q}{L_d} \\ -\dfrac{L_d}{L_q} & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} \tag{5}$$

The matrix in the above formula can expressed by the following variables:

$$e = \begin{bmatrix} e_d \\ e_q \end{bmatrix} = \begin{bmatrix} i_d^{'} - \hat{i}_d^{'} \\ i_q^{'} - \hat{i}_q^{'} \end{bmatrix} \quad A = \begin{bmatrix} -\dfrac{R_s}{L_d} & \omega_e \dfrac{L_q}{L_d} \\ -\omega_e \dfrac{L_d}{L_q} & -\dfrac{R_s}{L_q} \end{bmatrix} \quad J = \begin{bmatrix} 0 & \dfrac{L_q}{L_d} \\ -\dfrac{L_d}{L_q} & 0 \end{bmatrix} \tag{6}$$

$$W = (\hat{\omega}_e - \omega_e) J \begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} = (\hat{\omega}_e - \omega_e) J \hat{i}_s^{'} \tag{7}$$

Substituting equations (6) and (7) into equation (5), we can obtain the following equation:

$$\frac{de}{dt} = Ae - W \tag{8}$$

According to equation (8), an equivalent nonlinear feedback system as shown in Fig.2 can be constructed.

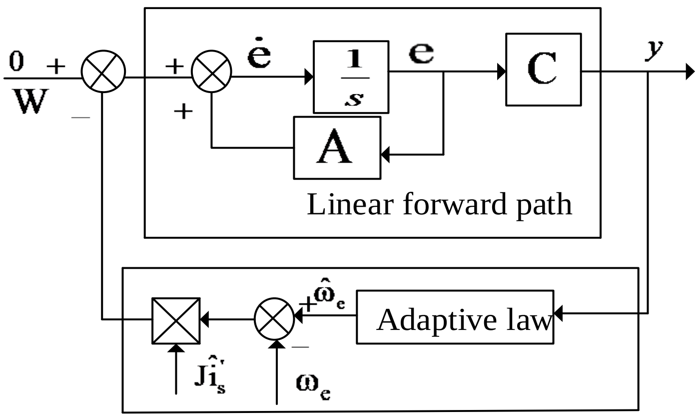

Figure 2. Block diagram of nonlinear feedback system

The linear forward path obtained by equation (9) is as follows:

$$G(s)=\frac{I}{sI-A}=\frac{1}{s^2+\frac{(L_d+L_q)R_s}{L_dL_q}s+\frac{R_s^2}{L_dL_q}+\omega_e^2}\begin{pmatrix} s+\frac{R_s}{L_d} & -\frac{\omega_e L_q}{L_d} \\ \frac{\omega_e L_d}{L_q} & s+\frac{R_s}{L_q} \end{pmatrix} \tag{9}$$

It is easy to prove that the function matrix of the linear forward path is a strictly positive real. According to Popov's hyperstability, the nonlinear system of the feedback path must satisfy the Popov integral inequality shown as equation (10):

$$\forall t_1>0,\eta(0,t_1)=\int_0^{t_1} y^T W dt \ge -r_0^2 \tag{10}$$

According to the above conditions, an adaptive law can be designed as the following equation:

$$\hat{\omega}_e=(K_p+\frac{K_i}{s})\left[i_d\hat{i}_q-\hat{i}_d i_q+\frac{\psi_f}{L_d}(\hat{i}_q-i_q)\right]+\hat{\omega}_e(0) \tag{11}$$

Where K_p and K_i are both greater than zero.

3. Simulation Results

Through the in-depth analysis of the model reference adaptive algorithm, the simulation model of the MRAS-based sensorless speed estimation system is built in MATLAB environment to verify the feasibility of the algorithm. The parameters of the IPMSM are given in Table 1.

Table 1. IPMSM Parameters for Simulation

Parameters	Values	Parameters	Values
Rated voltage	500V	Stator resistance	0.1 Ω
Rated current	223A	Number of pole pairs	4
Rated speed	1600rpm	Per pole flux	0.072 Wb
Rated power	50KW	Rated torque	300 $N\cdot m$
d axis inductance	0.0007H	Momen of inertia	0.084 $kg\cdot m^2$
q axis inductance	0.0022H	Maximum speed	6000rpm

When the speed is given as the initial value of 1600 r/min, the load torque is given the initial value of 150 $N\cdot m$ and abruptly given the value of 250 $N\cdot m$ at 1s, the simulation curve of the actual speed, MRAS estimated speed and the speed error are shown in Fig.3. The MRAS estimated speed reaches a given initial value around 0.8s and enters a stable running state with only a slight overshoot; when a load torque of 250 $N \cdot m$ is added at 1s, the speed only drops slightly and follows the given value about 1.2s, the estimated speed error is less than 35 r/min. But in a short time, the estimated speed error quickly converges to zero. From Fig.3, the MRAS estimated speed can quickly follow the given speed, indicating that the MRAS-based speed estimation method has a good simulation effect.

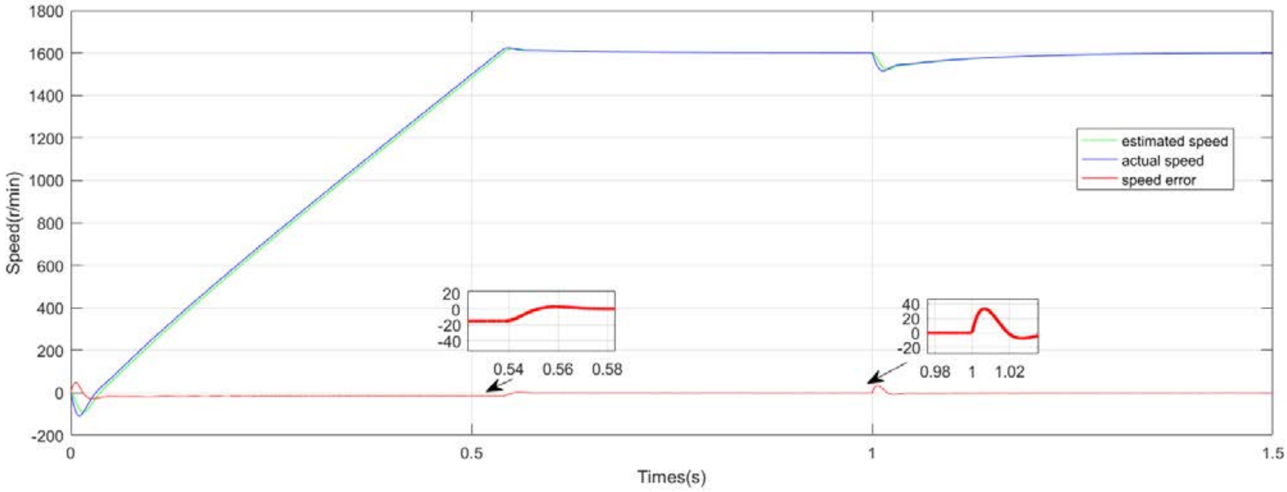

Figure 3. Simulation curve of motor speed and MRAS estimated speed

Fig.4 shows the simulation curve of the motor rotor position error. When the system is stable with load 150 $N \cdot m$, the mechanical angle error is less than 0.0064 rad. When the system is stable with a load of 250 $N \cdot m$, the mechanical angle error is less than 0.0069 rad. When the speed is abruptly changed, the maximum mechanical angle error does not exceed 0.0077rad. As can be seen from Fig.4, the MRAS estimated rotor position is well aligned with the actual rotor position of the motor.

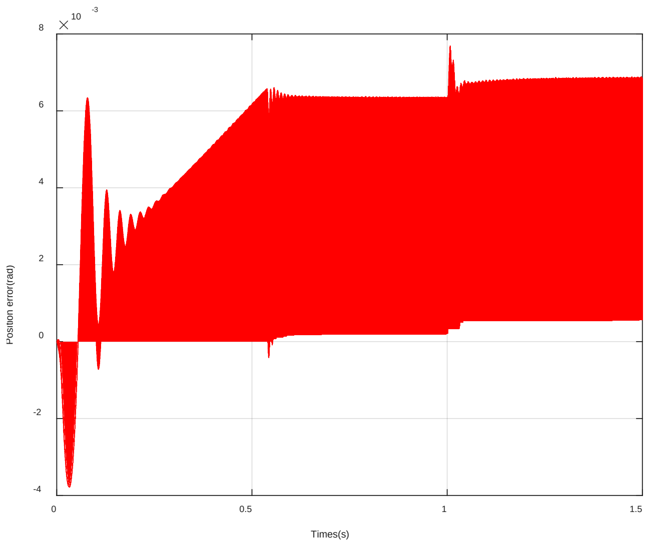

Figure 4. Error simulation curve of motor position and MRAS estimated position

4. Summary

In this paper, MRAS-based sensorless speed estimation of high speed section for IPMSM is studied. Firstly, the basic principle of MRAS is introduced. The appropriate reference model and adjustable model are constructed by motor voltage equation formula deformation. Then, using the Popov's super stability theorem, the adaptive law of rotational speed estimation is derived. Finally, the MRAS-based speed sensorless control system is simulated. The simulation results show that MRAS-based sensorless speed estimation is suitable for IPMSM and meets the stability, dynamics and anti-interference ability of IPMSM at high speed section.

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