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Rotor Speed and Rotor Position Estimation Based on MRAS

Xueliang Ren [a], Mingjiang Wang [b,*] and Jun Chen [c]
Harbin Institute of Technology, Shenzhen 518000, China
[a] renxueliang@stu.hit.edu.cn [b *]mjwang@hit.edu.cn [c] junchen.time@foxmail.com

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Abstract. In the traditional mechanical equipment, the motor is generally equipped with sensors for measuring the speed and position information of the motor. However, installation of sensors increases the structure burden. In this paper, a sensorless method is proposed for measurement of rotor speed and position. The proposed method is MRAS. It can quickly detect the rotor position information and speed information. As the speed increases and the speed estimation error gradually decreases after stable operation, the estimation error of the rotor position also gradually decreases.

1. Introduction

Due to the complex structure and complicated equation model of the motor, special attention must be paid to the control in the motor control. The design of the method, the speed information and rotor position are indispensable elements in the control process. In this paper, a sensorless method is proposed for measurement of speed and position. However, installation of sensors increases the structure burden. According to past debugging experience, the sensor-mounted motor is susceptible to external factors during operation. In the event of a disturbance in the load torque or a change in the system parameters, the accuracy of the control system will be affected, and the controller cannot well balance between the system's dynamic response and anti-jamming capability. To solve this problem, industrial control experts began to study the possibility of using MRAS to estimate the rotor speed.

The Model Reference Adaptive System (MRAS) was developed from the late 1950s and belongs to a type of adaptive system. From the structure, MRAS can be divided into three parts: adjustable model, reference model and adaptive law. The idea of MRAS identification is to use an expression without an unknown parameter as a desired model, and an expression containing a parameter to be recognized for an adjustable model, and both models have output with the same physical meaning, using the outputs of the two models. The difference in the amount, through the appropriate adaptive law to achieve the identification of synchronous motor parameters. In general, the basic structure of MRAS is as shown in the Figure 1. where, the input of the controller u , and x, $\hat{x}$ are the state vector of the reference model and the adjustable model, respectively.

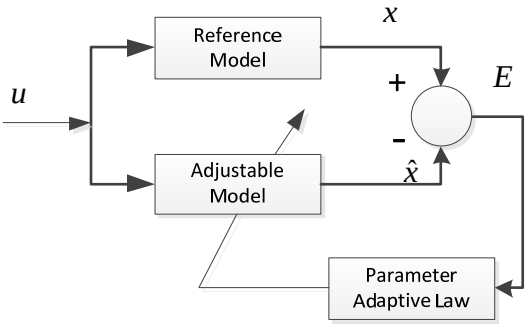


Figure 1. The basic structure of MRAS

Whether MRAS can constitute an excellent adaptive control system, one of the key issues is the determination of the parameter adaptation law. There are usually three basic methods for designing an appropriate adaptive law: a design method based on local parameter optimization theory, a design method based on Lyapunov functions, and a design based on the theory of hyper-stability and positive dynamic systems. method. In view of the advantages and disadvantages of each method, this paper uses a third design method to design the adaptive law.

2. Mras Design

2.1 Determination of Reference Models and Adjustable Models

For surface-mount three-phase PMSM, the voltage equation in the synchronous rotating coordinate system is

$$\begin{cases} u_d = Ri_d + L_s \dfrac{d}{dt} i_d - \omega_e L_s i_q \\ u_q = Ri_q + L_s \dfrac{d}{dt} i_q - \omega_e (L_s i_d + \psi_f) \end{cases} \tag{1}$$

For easy of analysis, formula (1-1) is written as the form of the current equation:

$$\begin{cases} \dfrac{d}{dt} i_d = -\dfrac{R}{L_s} i_d + \omega_e i_q + \dfrac{1}{L_s} u_d \\ \dfrac{d}{dt} i_q = -\dfrac{R}{L_s} i_q - \omega_e i_d - \dfrac{\psi_f}{L_s} \omega_e + \dfrac{1}{L_s} u_q \end{cases} \tag{2}$$

To obtain a tunable model, some transformations are made to equation (1-2):

$$\begin{cases} \dfrac{d}{dt}(i_d + \dfrac{\psi_f}{L_s}) = -\dfrac{R}{L_s}(i_d + \dfrac{\psi_f}{L_s}) + \omega_e i_q + \dfrac{1}{L_s}(u_d + \dfrac{\psi_f}{L_s} R) \\ \dfrac{d}{dt} i_q = -\dfrac{R}{L_s} i_q - \omega_e (i_d + \dfrac{\psi_f}{L_s}) + \dfrac{1}{L_s} u_q \end{cases} \tag{3}$$

Define:

$$\begin{cases} i'_d = i_d + \dfrac{\psi_f}{L_s} \\ i'_q = i_q \\ u'_d = u_d + \dfrac{\psi_f}{L_s} R \\ u'_q = u_q \end{cases} \tag{4}$$

Formula (1-4) can be changed to

$$\begin{cases} \dfrac{d}{dt} i'_d = -\dfrac{R}{L_s} i'_d + \omega_e i'_q + \dfrac{1}{L_s} u'_d \\ \dfrac{d}{dt} i'_q = -\dfrac{R}{L_s} i'_q - \omega_e i'_d + \dfrac{1}{L_s} u'_q \end{cases} \tag{5}$$

Write equation (1-5) as a state space expression, ie

$$\frac{d}{dt} \boldsymbol{i}' = \boldsymbol{A}\boldsymbol{i}' + \boldsymbol{B}\boldsymbol{u}' \tag{6}$$

Where: $\boldsymbol{i}' = \begin{bmatrix} i'_d \\ i'_q \end{bmatrix}$, $\boldsymbol{u}' = \begin{bmatrix} u'_d \\ u'_q \end{bmatrix}$, $\boldsymbol{A} = \begin{bmatrix} -\dfrac{R}{L_s} & \omega_e \\ -\omega_e & -\dfrac{R}{L_s} \end{bmatrix}$, $\boldsymbol{B} = \begin{bmatrix} \dfrac{1}{L_s} & 0 \\ 0 & \dfrac{1}{L_s} \end{bmatrix}$.

The state matrix A in (1-6) contains the rotor speed information, so this can be used as an adjustable model for the adjustable parameters. ω_e is the tunable parameter to be identified. The three-phase PMSM itself serves as a reference model.

2.2 Determination of Reference Adaptive Law

Formula (1-5) is estimated as

$$\begin{cases} \frac{d}{dt}\hat{i}_d^{'} = -\frac{R}{L_s}\hat{i}_d^{'} + \omega_e \hat{i}_q^{'} + \frac{1}{L_s}u_d^{'} \\ \frac{d}{dt}\hat{i}_q^{'} = -\frac{R}{L_s}\hat{i}_q^{'} - \omega_e \hat{i}_d^{'} + \frac{1}{L_s}u_q^{'} \end{cases} \tag{7}$$

Abbreviated as

$$\frac{d}{dt}\hat{\boldsymbol{i}}^{'} = \hat{\boldsymbol{A}}\hat{\boldsymbol{i}}^{'} + \boldsymbol{B}\boldsymbol{u}^{'} \tag{8}$$

Where: $\boldsymbol{i}^{'} = \begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix}, \hat{\mathbf{A}} = \begin{bmatrix} -\frac{R}{L_s} & \hat{\omega}_e \\ -\hat{\omega}_e & -\frac{R}{L_s} \end{bmatrix}$.

Define the generalized error $\boldsymbol{error} = \boldsymbol{i}^{'} - \hat{\boldsymbol{i}}^{'}$,subtract the formulae (1-5) and (1-7) to obtain the following formula:

$$\frac{d}{dt}\begin{bmatrix} \widetilde{error}_d \\ \widetilde{error}_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & \hat{\omega}_e \\ -\hat{\omega}_e & -\frac{R}{L_s} \end{bmatrix}\begin{bmatrix} \widetilde{error}_d \\ \widetilde{error}_q \end{bmatrix} - \boldsymbol{J}(\omega_e - \hat{\omega}_e)\begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} \tag{9}$$

Where: $\widetilde{error}_d = i_d^{'} - \hat{i}_d^{'}, \widetilde{error}_q = i_q^{'} - \hat{i}_q^{'}, \boldsymbol{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

Write formula (1-9) in the following form

$$\frac{d}{dt}\boldsymbol{error} = \boldsymbol{A}_e\boldsymbol{error} - \boldsymbol{W} \tag{10}$$

Where: $\mathbf{A}_e = \begin{bmatrix} -\frac{R}{L_s} & \hat{\omega}_e \\ -\hat{\omega}_e & -\frac{R}{L_s} \end{bmatrix}, \boldsymbol{W} = \boldsymbol{J}(\omega_e - \hat{\omega}_e)\boldsymbol{i}_d^{'}$.

According to Popov's theory of super stability, if the system is stable, it must satisfy:

① the transfer matrix $\boldsymbol{H(s) = (sI - A)}^{-1}$ is a strictly positive definite matrix.

② $\eta(0, t_1) = \int_0^t \boldsymbol{V}^{\boldsymbol{T}}\boldsymbol{W} \geq -\gamma^2_0 \geq 0, \forall t_1 \geq 0, \gamma_0$ is any finite positive number. There is $\lim_{t\to\infty}\boldsymbol{error}(t) = 0$, that is, MARS is gradually stable.

The inverse law of Popov's integral inequality can be solved in an inverse way, and the result is

$$\hat{\omega}_e = \int_0^t K_i(i_d\hat{i}_q^{'} - \hat{i}_d^{'}i_q^{'})d\tau + K_p(i_d\hat{i}_q^{'} - \hat{i}_d^{'}i_q^{'}) \tag{11}$$

Rewrite (1-11) to the following expression:

$$\hat{\omega}_e = (\frac{K_i}{s} + K_p)\,\mathrm{error}_\omega \tag{12}$$

Where: $\mathrm{error}_\omega = i_d\hat{i}_q^{'} - \hat{i}_d^{'}i_q^{'} = \boldsymbol{i}^{'} - \hat{\boldsymbol{i}}^{'}$.

Substituting (1-4) into (1-11),we can get the following formula:

$$\hat{\omega}_e = (\frac{K_i}{s} + K_p)\left[i_d\hat{i}_q^{'} - \hat{i}_d^{'}i_q^{'} - \frac{\psi_f}{L_s}(i_q - i_q^{'})\right] \tag{13}$$

By integrating the formula (1-12), the rotor position estimate can be obtained.

$$\hat{\theta}_e = \int \hat{\omega}_e d\tau \tag{14}$$

The block diagram of MRAS implementation is shown in the Figure 2.

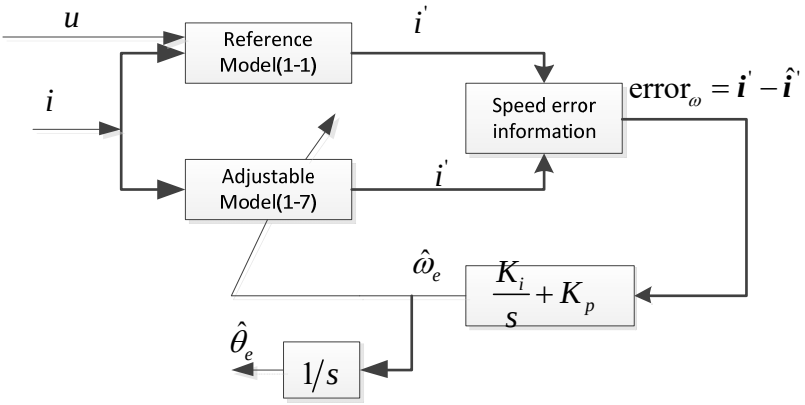


Figure 2. MRAS implementation block diagram

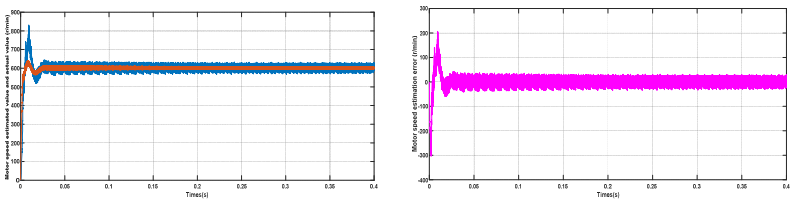
3. Simulation

In this paper, take matalab/simulink for computer simulation experiments to verify MRAS. The $i_d = 0$ control strategy is used in the vector control system. The inputs to the MRAS are u and i, respectively. After the reference model, the adjustable model, and the adaptive law of parameters, the estimated speed of the rotor is obtained. By integrating the estimated rotational speed, the position of the rotor is obtained. The parameters of PMSM are shown in TABLE 1.In order to verify the correctness of the built simulation model, the reference speed is set to 600 r/min. The simulation results under no-load conditions are shown in the figure.

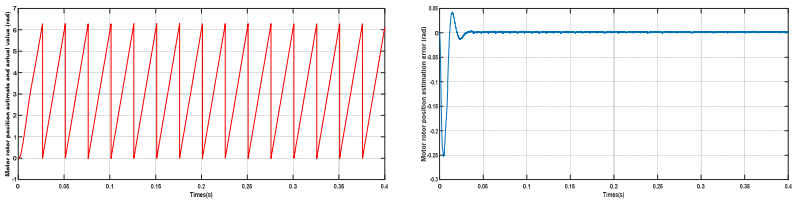
Table 1. PMSM simulation parameters

Parameter	Value
Speed (w)	600[r/min]
Stator Resistor(Rs)	2.875[ohm]
Stator Inductor(Lq,Ld)	0.0085[H]
Rotor Inertia(J)	4.8×10-6 Kg.m2
Poles(P)	4
Flux (∏ f)	0.175[Wb]

The simulation results as shown in the Figure 3, when the motor rises from zero speed to a reference speed of 600 r/min(shown in Figure 3(a)), the speed estimation error has a large value in the rising phase of the speed(shown in Figure 3(b)), but as the speed increases and the speed estimation error gradually decreases after stable operation, the estimation error of the rotor position also gradually decreases(shown in Figure 3(c) and Figure 3(d)). Therefore, it can be demonstrated that the sensorless control technology based on MRAS can meet the needs of actual motor control performance.



(a) Rotor speed estimated and actual value (b) Rotor position estimated error



(c)Rotor position estimated and actual value (d) Rotor position estimated error

Figure 3. Simulation results of rotor speed and position

4. Conclusion

This paper has proposed a MRAS to achieve the sensorless control for PMSM. MRAS can quickly detect the rotor position information and speed information, and from the results of inspection, the motor can quickly reach steady state. The stability of the MRAS has been proved by a Popov's theory of super stability analysis. And it can eliminate the chattering that makes the results smoother.

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