SENSORLESS DTC CONTROL FOR SPMSM APPLIED TO ELECTRIC VEHICLES

ĐIỀU KHIỂN DTC KHÔNG CẢM BIẾN TỐC ĐỘ CHO SPMSM ỨNG DỤNG TRONG LĨNH VỰC XE ĐIỆN

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Ngày nhận bài: 17/12/2022, Ngày chấp nhận đăng: 26/5/2023, Phản biện: PGS.TS. Nguyễn Tùng Lâm

Abstract:

Permanent magnet synchronous motors are widely used in industry, household and especially in the field of electric vehicles. Research on speed sensorless control for PMSM is an important part of synchronous motor drive research. Because the speed sensorless drive with new control algorithms has many advantages compared with the permanent magnet synchronous motor speed sensor drive such as: compact size, economical cost and high reliability. This paper presents the sensorless direct torque control for PMSM, with motor speed is estimated using MRAS method. Matlab/simulink software is used to simulate sensorless DTC drive for PMSM. The simulation results have shown that: the estimated speed tracking real speed and reference speed with small error.

Keywords:

Permanent magnet synchronous motor, direct torque control, motor speed estimation, model reference adaptive system.

Tóm tắt:

Động cơ đồng bộ nam châm vĩnh cửu được sử dụng rộng rãi trong công nghiệp, dân dụng và đặc biệt là trong lĩnh vực xe điện. Nghiên cứu về điều khiển không cảm biến tốc độ cho PMSM là một phần quan trọng của nghiên cứu về truyền động động cơ đồng bộ. Bởi truyền động không cảm biến tốc độ với các thuật toán điều khiển mới có nhiều ưu điểm so với truyền động có cảm biến tốc độ như: kích thước nhỏ gọn, giá thành kinh tế và có tính bền vững cao. Bài báo này trình bày điều khiển trực tiếp mômen cho PMSM, với tốc độ động cơ được ước lượng sử dụng phương pháp MRAS. Phần mềm Matlab/simulink được sử dụng để mô phỏng hệ truyền động DTC không cảm biến tốc độ cho PMSM. Các kết quả mô phỏng đã chỉ ra: tốc độ được ước lượng bám tốc độ thực và tốc độ đặt với sai số bé.

Từ khóa:

Động cơ đồng bộ nam châm vĩnh cửu, điều khiển trực tiếp mômen, ước lượng tốc độ động cơ, hệ thống thích nghi mô hình mẫu.

1. INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) is a special type of synchronous motor. The PMSM rotor is a permanent magnet. Therefore, compared with the rotor of a conventional AC motor, the rotor of PMSM has a smaller inertia, a higher power density and no copper loss, so the efficiency of PMSM is higher than conventional AC motor of the same power. However, the cost of the PMSM is higher than conventional DC and AC motors; In addition, the PMSM can lose its magnetism when the rotor temperature is high [1], [2].

According to rotor structure, the PMSM is classified into 2 types: Surface Permanent Magnet Synchronous Motor (SPMSM) and Interior Permanent Magnet Synchronous Motor (IPMSM) [2], [3]. In addition, belonging to the group of synchronous motors with structures such as the PMSM, there is a brushless DC motor (Brushless DC motor / BLDC motor). The difference between PMSM and BLDC is that: the form of induced emf in the stator winding of BLDC is trapezoidal and PMSM is sinusoidal. Therefore, the PMSM has less pulsating torque and better speed and position accuracy than the BLDC, which is suitable in applications where torque and speed stability is required [1], [2], [3], [4].

The PMSM has many advantages over other types of motors used for AC drive systems such as: small size, high power density, low maintenance cost, easy control, high efficiency and power factor [1], [2],[5]. Therefore, PMSM is widely used in industry, household and especially in the field of electric vehicles [2], [3].

Some studies show that compared with the rotor magnetic control method (Field Oriented Control / FOC), the direct torque control method (Direct Torque Control / DTC) for PMSM has the following advantages: simple structure control, less sensitive to parameters motor (only stator resistance is used to estimate from stator information), faster male model response and eliminates the control PI of dq current [2], [5], [6], [7], [8].

When the PMSM steady-speed control uses the DTC method (DTC-PMSM), the signal of the PMSM speed is one of the information needed for the controller. However, in hot, dusty environments or when high or very low motor speeds are required, using of speed sensors is not suitable. On the other hand, normal speed measuring equipment are bulky and expensive, thus increasing the cost and size of the drive systems [2], [3], [9].

Several studies on speed estimation for PMSM have been shown: The speed estimator using a phase-locked loop has been performed in [10]; an observer based on sliding mode technique for estimating both position and speed is proposed [11]. The speed estimation using the Luenberger observer [12], Extended Kalman Filter [13], Artifical Neural Network [14].

This paper presents the DTC-PMSM speed sensorless drive system with speed estimator using Model Reference

Adaptive System (MRAS). The article is divided into 4 parts. Part 1 presents the advantages of PMSM and the reason for studying the DTC-PMSM speed sensorless drive system. Part 2 shows the construction of a DTC-PMSM speed sensorless drive system. Part 3 presents the PMSM speed estimation algorithm using MRAS. The last part will present the simulation results of the DTC-controlled speed sensorless drive system for the SPMSM motor with the MRAS speed estimator using Matlab/simulink software.

2. SENSORLESS DIRECT TORQUE CONTROL FOR PMSM

Figure 1 shows the block diagram of the DTC-PMSM controlled speed sensorless drive system with a speed estimator using MRAS. On the block diagram Figure 1. The angle of the rotation magnetic field is calculated from equation (2). The conversion of three-phase current or voltage to the αβ static coordinate system is done using equation (3) - also known as the Clark transformation. The conversion of current or voltage in the static coordinate system αβ to the rotational coordinate system dq is done by equation (4)- also known as the Park transformation. The electromagnetic torque estimation stage is shown in equation (5). Figure 1 shows a two-level voltage inverter.

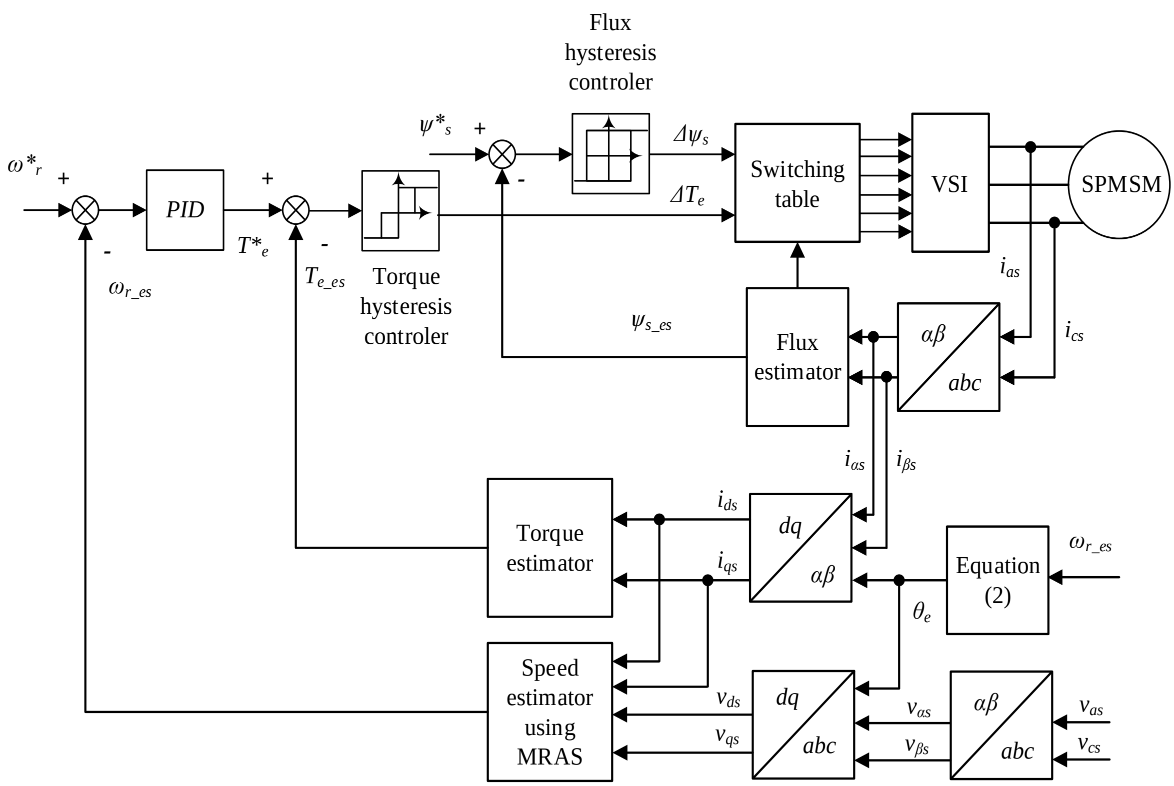


Figure 1. Sensorless torque direct control structure for an SPMSM

Table 1. Optimum voltage vector look-up table

Sector				S_1 ($-30^0 \div 30^0$)	S_2 ($30^0 \div 90^0$)	S_3 ($90^0 \div 150^0$)	S_4 ($150^0 \div 210^0$)	S_5 ($210^0 \div 270^0$)	S_6 ($270^0 \div 330^0$)
$\Delta\psi_s$	1	ΔT_e	1	V_2	V_3	V_4	V_5	V_6	V_1
			0	V_0	V_7	V_0	V_7	V_0	V_7
			-1	V_6	V_1	V_2	V_3	V_4	V_5
	0	ΔT_e	1	V_3	V_4	V_5	V_6	V_1	V_2
			0	V_7	V_0	V_7	V_0	V_7	V_0
			-1	V_5	V_6	V_1	V_2	V_3	V_4

The angular speed of the magnetic field is calculated as follows:

$$\omega_e = \omega_{r\_es}.p_p \quad (1)$$

Magnetic field angle:

$$\theta_e = \int \omega_e dt + \theta_0 \quad (2)$$

Where: θ_0 is the initial angle of the rotation magnetic field.

Stator voltage or current conversion models:

The Clark conversion (from *abc* → *αβ*) is as follows:

$$\begin{bmatrix} x_{\alpha s} \\ x_{\beta s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\,0 & cos(\frac{2\pi}{3}) & cos(\frac{4\pi}{3}) \\ sin\,0 & sin(\frac{2\pi}{3}) & sin(\frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_{as} \\ x_{bs} \\ x_{cs} \end{bmatrix} \quad (3)$$

The Park conversion (from *abc* → *αβ*) is as follows:

$$\begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} = \begin{bmatrix} cos\,\theta_e & sin\,\theta_e \\ -sin\,\theta_e & cos\,\theta_e \end{bmatrix}\begin{bmatrix} x_{\alpha s} \\ x_{\beta s} \end{bmatrix} \quad (4)$$

Model for calculating electromagnetic torque of PMSM:

$$T_e = \frac{3}{2} p_p \psi_r i_{qs} \quad (5)$$

The stator flux estimation using the currents of the static coordinate system *αβ* is written as follows:

$$\begin{cases} \psi_{\alpha s} = L_s.i_{\alpha s} + \psi_r \\ \psi_{\beta s} = L_s.i_{\beta s} \end{cases} \quad (6)$$

Magnitude of stator flux:

$$\psi_{s\_es} = \sqrt{\psi_{\alpha s}^2 + \psi_{\beta s}^2} \quad (7)$$

Stator flux angle:

$$\theta_s = arc\,tan(\frac{\psi_{\beta s}}{\psi_{\alpha s}}) \quad (8)$$

Based on the stator flux angle θ_s, the sectors are shown in Table 1. The voltage space vectors and sectors are shown in Figure 2.

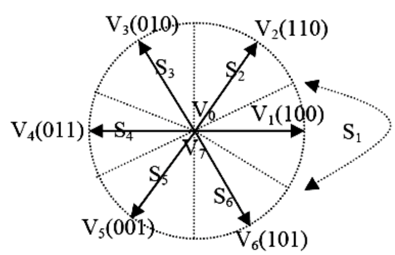


Figure 2. The space and sector vectors of the two-level voltage inverter

The speed estimation stage using MRAS will be presented in Part 3.

(ISSN: 1859 - 4557)

3. SENSORLESS DIRECT TORQUE CONTROL FOR PMSM

Figure 3 shows a block diagram of PMSM speed estimation using MRAS. In Figure 3, the output of the sample model are i_{sd}, i_{sq} currents calculated as equation (4) - Park transform, with i_{sa}, i_{sc} currents measured. The output of the adaptive model is the estimated currents $\hat{i}_{sd}, \hat{i}_{sq}$ shown in equations (9), (10).

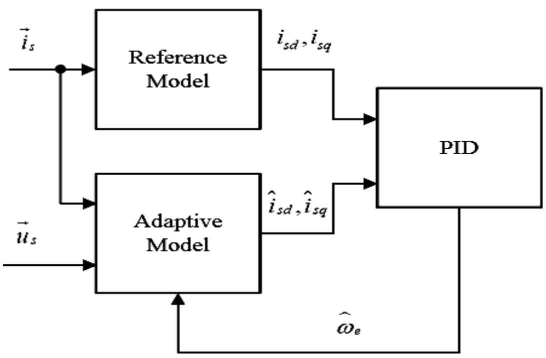


Figure 3. Block diagram of PMSM speed estimator using MRAS

$$\hat{i}_{sd} = \frac{1}{L_s}\int\left(u_{sd} - R_s\hat{i}_{sd} + \omega_e L_s \hat{i}_{sq}\right)dt \qquad (9)$$

$$\hat{i}_{sq} = \frac{1}{L_s}\int\left(\begin{matrix} u_{sq} - R_s\hat{i}_{sq} - \omega_e L_s \hat{i}_{sd} \\ -\omega_e \Psi_r \end{matrix}\right)dt \qquad (10)$$

After the correction, the speed of the rotor magnetic field is estimated as follows [8], [15]:

$$\omega_e = K_{p\omega}\left[\begin{matrix} i_{sd}\hat{i}_{sq} - i_{sq}\hat{i}_{sd} \\ -\frac{\Psi_r}{L_s}(i_{sq} - \hat{i}_{sq}) \end{matrix}\right] \qquad (11)$$
$$+K_{i\omega}\left[i_{sd}\hat{i}_{sq} - i_{sq}\hat{i}_{sd} - \frac{\Psi_r}{L_s}(i_{sq} - \hat{i}_{sq})\right]$$
$$+\omega_e(0)$$

The estimated speed of motor is determined by equation (12):

$$\omega_r = \frac{\omega_e}{p_p} \qquad (12)$$

4. RESULTS AND ANALYSIS

Matlab/Simulink software version 2019a is used to simulate the SPMSM motor speed sensorless DTC transmission system of SPMSM motor. In this simulation, an 11 kW SPMSM motor is used. The engine parameters are shown in Table 2.

Table 2. Parameters of SPMSM

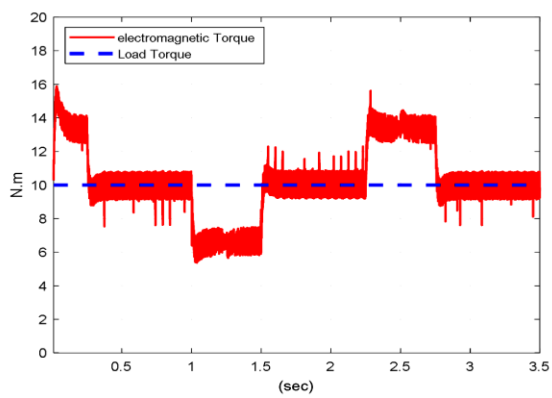
No	Parameter Values	Parameter Values
1	Rated power (P_n)	11 KW
2	Rated speed (n_n)	1500 rpm
3	Rated voltage (V_n)	180 V
4	Rated frequency (f_n)	50 Hz
5	Number of pole pairs (Pp)	4
6	Stator resistance (R_s)	0,0217 Ω
7	Stator inductance (L_s)	0,0007 H
8	Rotor flux (ψ_r)	0,1483 Wb
9	Interia of rotor (J)	0.0281 kgm^2

**** Case 1: load torque is constant, we need to stabilize the motor speed:***

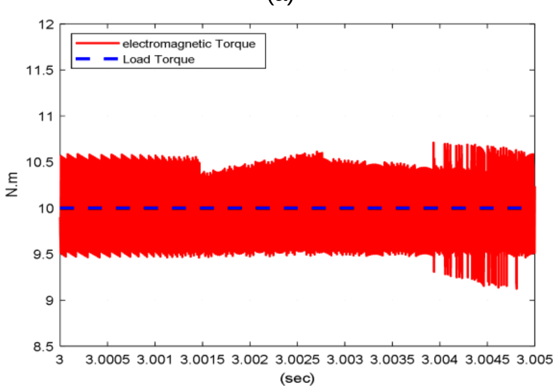
The load torque is set as: T_L^*= 10 (Nm). Sample citation time T_s = 0,00001 (s). Apply one level to the inverter V_{dc}=500 (V). The simulation results of torque and speed amplitudes are shown in Figure 4 and 5.

Figure 4a shows: As the speed increases, the electromagnetic torque increases and is larger than the load torque; when the speed is reduced, the electromagnetic torque decreases and is smaller than the load torque. Figure 4b shows: As the speed is stable, the electromagnetic torque pulses and fluctuates quite large around the load torque. The maximum pulsating electromagnetic torque is about 15% of the load torque.

Figure 5a shows that: After the speed increases, the estimated speed and the real speed follow the reference speed. Figure 5b has shown that: When the speed of the motor is stable, the estimated closely follows the real speed and the error is very small compared to the reference speed.

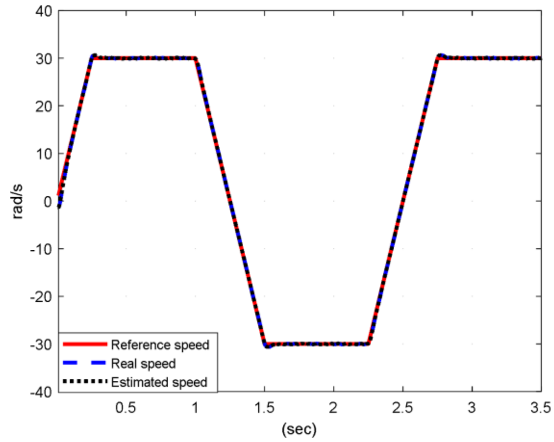


(a)

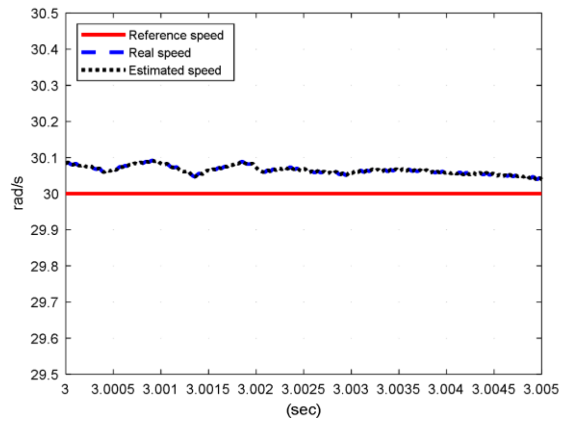


(b)

Figure 4. Response of motor electromagnetic torque and load torque : (a) full time simulation; (b) enlarged image responds to Torque



(a)



(b)

Figure 5. Motor speed responses: (a) full-speed range; (b) enlarged image responds to speed

**** Case 2: load torque is variable, we need to stabilize the motor speed***

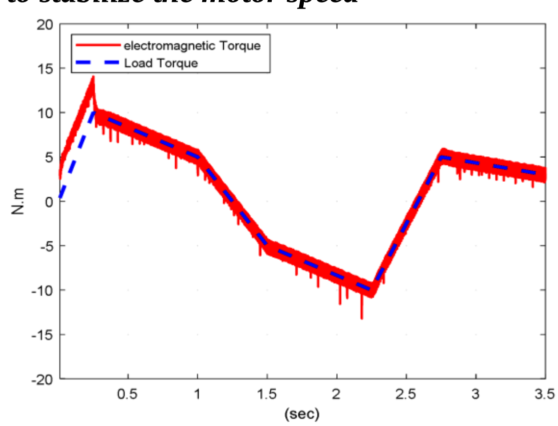


Figure 6. Response of motor electromagnetic torque and load torque

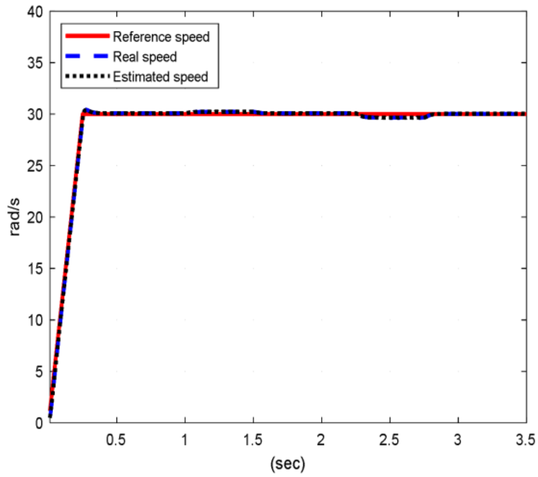


Figure 7. Motor speed includes: set speed, estimated speed, real speed.

In the case of variable load torque:

The electromagnetic torque follows the load torque (Figure 6). The real speed, the estimated speed follows the reference speed (Figure 7).

5. CONCLUSIONS

This paper presents about direct torque control without speed sensor of permanent magnet synchronous motor with speed estimation algorithm using MRAS. Simulations using Matlab/Simulink software have verified for the proposed algorithm, the error between the estimated speed and the real speed is very small. At the same time, both the estimated speed and the real speed follow the reference speed.

The author's next research tendencies are the others of modern speed estimation methods used for speed sensorless drive systems for PMSM such as: Speed estimation using artificial neural networks, SMC sliding controller, Luenberger observer…; study modern PMSM speed control methods, then evaluate the influence of motor parameters in the working process of PMSM drive system.

NOTATIONS

Symbols	Explain the symbols
$v_{\alpha s}$, $v_{\beta s}$	Stator voltages in the stator reference frame (V)
v_{ds} , v_{qs}	Stator voltages in rotor reference frame (V)
ω_{r_es}	Estimated speed of motor (Rad/s)
p_p	Number of pole pairs
ω_e	Magnetic field rotation speed (Rad/s)
$i_{\alpha s}$, $i_{\beta s}$	Stator currents in the stator reference frame (A)
i_{ds} , i_{qs}	Stator current in rotor reference frame (A)
T_e	Electromagnetic torque (Nm)
T_L	Load torque (Nm)
ψ_r	Permanent magnet linkage flux (Wb)
R_s	Stator resistance
L_s	Stator inductance

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