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Original Article

Direct Torque Control of an Interior Permanent Magnet Synchronous Motor

Pham Van Tuan[1], Nguyen Quang Huy[2], Nguyen Thanh Long[3], Ha Huy Cong[4], Vo Thanh Ha[5]

[1,2,3,4]*Vinh University of Technology Education, Vinh city, Vietnam*
[5]*Electrical and Electrical Engineering, University of Transport and Communications, Vietnam*

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Abstract *- The interior permanent magnet synchronous motors are widely used in industry, households,s and especially in electric vehicles. The research problem of direct torque control for PMSM is essential to synchronous motor transmission. This paper presents modeling and simulation of inverter system - IPMSM with a direct torque control method. Matlab/Simulink software was used to verify the research results.*

Keywords *- PMSM, DTC, IPMSM, PMSM.*

1. Introduction

The Permanent Magnet Synchronous Motor (PMSM) is a particular type of synchronous motor. A winding-excited synchronous motor generates a magnetic field on the rotor by supplying a D.C. motor. Excitation source through brushes (sliding rings), where the magnetic field of the permanent-magnet synchronous motor is caused by permanent magnets placed on the rotor. Therefore, the PMSM is also called a brushless motor. They are more efficient than asynchronous copper because the PMSM has no rotor copper loss. However, the cost of the PMSM is higher than the D.C. motor and asynchronous motors. In addition, the PMSM can lose its magnetism at high temperatures [1], [2].

According to rotor structure, the IPMSM is classified into two types such as Surface Permanent Magnet Synchronous Motor (SPMSM) and Internal Permanent Magnet Synchronous Motor (SPMSM) 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 D.C. motor (Brushless DC motor / BLDC motor). The difference between the PMSM and the BLDC is that the form of electromotive force induced in the stator winding of the BLDC is trapezoidal, while the PMSM is sinusoidal [1], [3]. Therefore, the PMSM has less pulsating torque and better speed and position accuracy than the BLDC, which is suitable for applications requiring torque and speed stability.

Compared with the SPMSM, the IPMSM has a higher power density and smaller harmonic field on a permanent magnet ratio $\boldsymbol{\zeta = \frac{L_q}{L_d} > 1}$. The IPMSM can operate in a weak magnetic field, which is impossible with an SPMSM motor. The IPMSM motor is often preferred in industrial applications such as variable speed drives as an alternative to squirrel-cage rotor asynchronous motors to improve transmission efficiency. In contrast to the I.M. motor, the IPMSM provides a precise position control loop without needing an encoder mounted on the motor shaft. Standard asynchronous motors, typically designed to run at speeds of 750÷3000 rpm, are unsuitable for low-speed operation. The gearboxes reduce speed, for example, from 1500 rpm to 600 rpm. A 600rpm gearless IPMSM drivetrain is an alternative, as opposed to a conventional 1500rpm asynchronous motor. The gearbox takes up space and needs maintenance like replacing/adding lubricating oil. Eliminating the gearbox saves space and installation costs and improves transmission efficiency [4], [5], [6], and [7].

In addition, some different studies have shown that compared with the rotor flux-based control method, the Direct Torque Control (DTC) method for IPMSM has the following advantages such as simple control structure, fewer jump sensitivity to motor parameters (only stator resistance is used to estimate stator flux), faster torque response and eliminate P.I. controls of shaft current *dq* [8], [9], [10], and [12].

This paper presents the DTC method for IPMSM. Part I gives the advantages of the PMSM and the reason for studying the DTC method for the IPMSM. In Part II, the mathematical model of IPMSM is presented. Part III presents the DTC method for an IPMSM. Finally, the rest will deliver the simulation results of the DTC - IPMSM inverter system using MATLAB/Simulink software.

2. Mathematical Model of IPMSM

The general dynamics model of an IPMSM includes the following sub-models [1], [2], [3], [4], [5], and [6]:

- Voltage calculation model.
- Math model to calculate the current.
- Math models for converting three-phase voltage or current to two-phase, two-phase *dq* to *αβ* coordinate, and vice versa.
- Math model to calculate electromagnetic torque.
- Math model to calculate engine speed.

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

$$\omega_e = \omega_r . p_p \qquad (1)$$

The angle of the rotating magnetic field:

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

Where: ω_e, ω_r are mechanical rotor velocity, rotor; p_p is a number of pole pairs; $\theta_e; \theta_0$ are flux angle, initial flux angle.

The model for voltage calculation for IPMSM is shown:

$$\begin{cases} u_{ds} = R_s i_{ds} + L_{ds}\frac{di_{ds}}{dt} - \omega_e L_{qs} i_{qs} \\ u_{qs} = R_s i_{qs} + L_{qs}\frac{di_{qs}}{dt} + \omega_e L_{ds} i_{ds} + \omega_e \psi_r \end{cases} \qquad (3)$$

The current calculation model for IPMSM is shown in Eq. (4):

$$\begin{cases} i_{ds} = \frac{1}{L_{ds}}\int\left(u_{ds} - R_s i_{ds} + \omega_e L_{qs} i_{qs}\right)dt \\ i_{qs} = \frac{1}{L_{qs}}\int\left(u_{qs} - R_s i_{qs} - \omega_e L_{ds} i_{ds} - \omega_e \psi_r\right)dt \end{cases} \qquad (4)$$

Where: i_{sd}, i_{sq} dq components of the stator, rotor current; $L_{ds}; L_{qs}$ are d axis, q axis inductance; R_s is stator resistance; ψ_r is rotor flux; $u_{ds}; u_{qs}$ are stator voltage.

Mathematical models of stator voltage or current conversion are shown:

Convert Park (from *αβ* to *dq*) is shown by Eq. (5) & (6):

$$\begin{bmatrix} \boldsymbol{x_{\alpha s}} \\ \boldsymbol{x_{\beta s}} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \boldsymbol{\cos 0} & \boldsymbol{\cos(\frac{2\pi}{3})} & \boldsymbol{\cos(\frac{4\pi}{3})} \\ \boldsymbol{\sin 0} & \boldsymbol{\sin(\frac{2\pi}{3})} & \boldsymbol{\sin(\frac{4\pi}{3})} \end{bmatrix}\begin{bmatrix} \boldsymbol{x_{as}} \\ \boldsymbol{x_{bs}} \\ \boldsymbol{x_{cs}} \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} x_{\alpha s} \\ x_{\beta s} \end{bmatrix} \qquad (6)$$

Convert Park (from *dq* to *αβ*):

$$\begin{bmatrix} x_{\alpha s} \\ x_{\beta s} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} x_{ds} \\ x_{qs} \end{bmatrix} \qquad (7)$$

The IPMSM electromagnetic torque calculation model is written as Eq. (7):

$$T_e = \frac{3}{2} p_p\left[\psi_r i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds} i_{qs}\right] \qquad (8)$$

The moment equilibrium equation is written as Eq. (8):

$$J\frac{d\omega_r}{dt} + f_d\omega_r = T_e - T_L \qquad (9)$$

Where: J is the torque of inertia; f_d is the viscous friction coefficient, and $T_{L.}$ is the loading moment.

From the torque balance Eq. (8) and ignoring viscous friction, the rotor speed is calculated as follows:

$$\omega_r = \int \frac{T_e - T_L}{J} dt \qquad (10)$$

3. Direct Torque Control for an IPMSM

The DTC method for permanent magnet synchronous motors was proposed in the 1990s. The basic principle of DTC is the direct selection of the stator voltage vectors based on the error between the set and actual stator torque and flux values. Torque and flux are controlled directly using hysteresis controllers without performing coordinate transformations of the stator currents. A two-level hysteresis controller manages the stator flux, and a three-level delay controller is used for torque control [7]. The DTC method diagram for IPMSM is shown in Fig. (1)

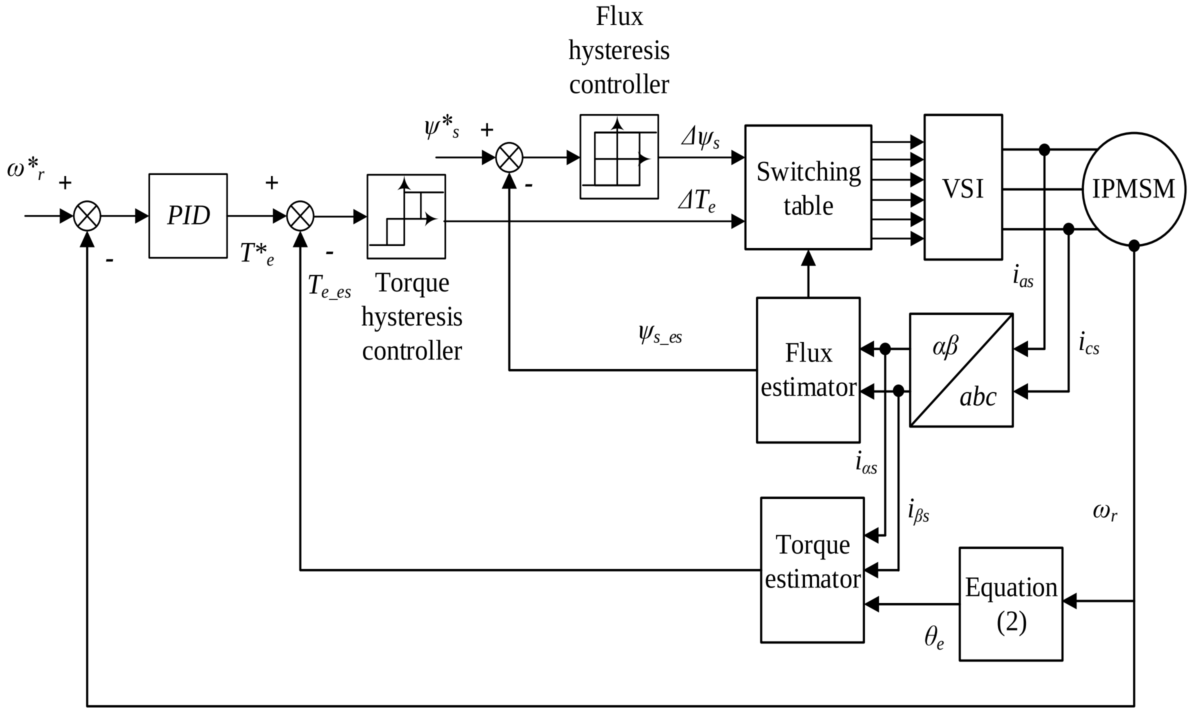


Fig. 1 Torque direct control structure for an IPMSM

Fig. 1 shows that the angle of the rotating magnetic field is calculated from Eq. (2). The conversion of the three-phase (measured) current to the current in the coordinate system attached to the stator-static coordinate system (αβ) is done by Eq. (5).

In addition, the conversion of the current in the static coordinate system αβ to the rotational coordinate system dq is done by Eq. (6). The conversion of the current in the rotating coordinate system *dq* to the static coordinate system αβ (called the inverse Park transform) is shown in Eq. (7). Finally, the electromagnetic moment estimation stage is shown in Eq. (7).

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

$$\begin{cases}\psi_{\alpha s} = L_{ds}.\, i_{\alpha s} + \psi_r \\ \psi_{\beta s} = L_{\mathrm{qs}}.\, i_{\beta s}\end{cases} \tag{11}$$

The magnitude of the stator flux:

$$\psi_{s\_es} = \sqrt{\psi_{\alpha s}^2 + \psi_{\beta s}^2} \tag{12}$$

The stator flux angle:

$$\theta_s = \mathrm{arc}\, tan\, g\, (\frac{\psi_{\beta s}}{\psi_{\alpha s}}) \tag{13}$$

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

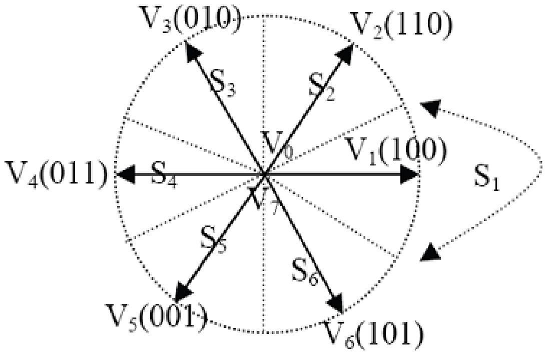


Fig. 2 The space and sector vectors of the two-level voltage inverter

Table 1. Optimum voltage vector look-up table

Sector				**S_1** **$(-30^0\div30^0)$**	**S_2** **$(30^0\div90^0)$**	**S_3** **$(90^0\div150^0)$**	**S_4** **$(150^0\div210^0)$**	**S_5** **$(210^0\div270^0)$**	**S_6** **$(270^0\div330^0)$**
$\Delta\psi_s$	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

4. Results and Analysis

MATLAB/Simulink 2019a software simulates the DTC - IPMSM inverter system. In this simulation, an 11 kW IPMSM motor is used. The motor parameters are given in Table 2.

Table 2. Parameters of IPMSM

No	**Parameter Values**	**Parameter Values**
1	Rated power (P_n)	11 KW
2	Rated speed (n_n)	1750 rpm
3	Rated voltage (V_n)	220
4	Max speed (n_{max})	3000 g/m
5	Max frequency (f_n)	50Hz
6	Number of pole pairs (p_p)	3
7	Stator resistance (R_s)	0,15 Ω
8	d Axis stator inductance (Lds)	0,0036 H
9	q Axis stator inductance (Lqs)	0,005 H
10	Rotor flux (ψ_r)	0,254 Wb
11	Loading moment (J)	0.05 kgm2

This simulation's potential load torque is set to T_L*= 10 Nm. After several tests with different values of the sampling interval, the final deal was chosen to be 0.0001 sec. Finally, the simulation will observe the engine speed.

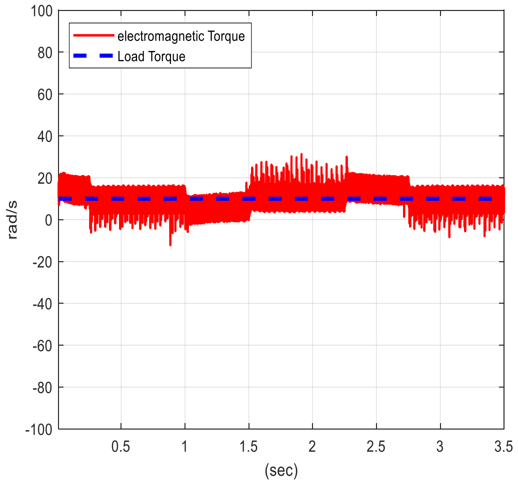
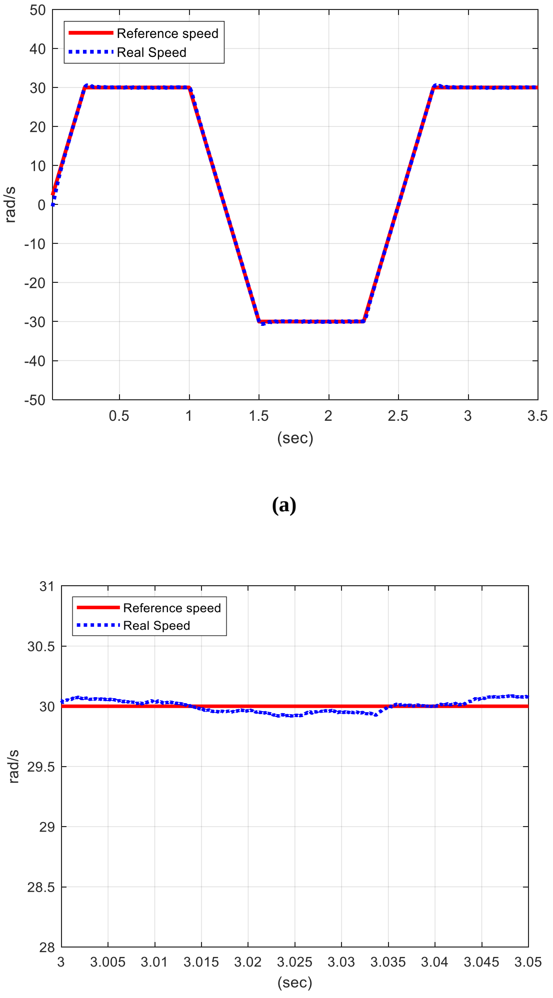


Fig. 3. Response of electromagnetic motor torque and load torque



(a)

(b)

Fig. 4. Motor speed responses: (a) full-speed range; (b) enlarged image responds to speed

Fig. 3 showed ample pulsating electromagnetic torque. When the speed is stable, the average value of the electromagnetic torque adheres to the load torque. This is the DTC method's disadvantage, such as the semiconductor valve's switching frequency is large and uncontrolled, leading to the pulsation of ample motor torque.

In addition, Fig. 4a: After the acceleration time, the actual speed follows the set speed of the engine.

Fig. 4b shows when the speed of the motor has stabilized. The actual rate has a maximum pulse amplitude of ≈ 1.0% of the reference speed.

5. Conclusion

This paper presented the DTC method for an IPMSM. The simulations using MATLAB/Simulink software have verified the proposed control algorithm. The motor speed follows the actual rate with minimal error. The disadvantage of this method is significant torque pulsation because this method has a large and uncontrolled switching frequency of the semiconductor valve. Thus, the following research direction of the authors is to study reducing the torque pulse for the DTC method by using a multi-level voltage invertor or using an artificial neural network in sector selection to generate pulses to control the voltage inverter.

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