Journal of Electronics and Information Science (2022)
Clausius Scientific Press, Canada
DOI: 10.23977/jeis.2022.070309
ISSN 2371-9524 Vol. 7 Num. 3

Simulation Analysis of Permanent Magnet Synchronous Motor for Electric Vehicle Based on Matlab

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Keywords: Electric vehicle, Permanent magnet synchronous motor, Simulation, Matlab

Abstract: The mathematical models of permanent magnet synchronous motors in different coordinate systems are established and analyzed. According to requirement of electric vehicle, an effective motor vector control scheme is proposed, and a PMAM double closed-loop system is established on the basis. Based on the vector control theory of permanent magnet synchronous motor, the various modules in the control system are built in Matlab/Simulink, including coordinate transformation module, SVPWM module, etc. The permanent magnet synchronous motor simulation model is established, and the simulation experiment is carried out. It shows that the double closed-loop control system can effectively improve the response speed and control accuracy of the permanent magnet synchronous motor and has good robustness.

1. Introduction

With the continuous progress and development of society, the awareness of environmental protection in various countries continues to increase, and the role of electric vehicles in energy conservation and emission reduction is becoming more and more important. As the driving device of pure electric vehicle, electric motor is the core part of its driving system, and the control of motor torque seriously affects the performance of the whole vehicle. Therefore, the operation of PMSM need to be study deeply[1], [2].

2. Mathematical Model of Permanent Magnet Synchronous Motor

The permanent magnet synchronous motor is a nonlinear system and is characterized by multivariable, strong coupling[3]. To facilitate its analysis, the following assumptions are made:

(1) The magnetic circuit is a linear one, disregarding remanence, saturation hysteresis and eddy current effects;

(2) The magnetic field of the air gap is distributed in a sinusoidal manner, leaving out the effects

of higher harmonics;

(3) The effects of the stator and rotor surface grooves are not considered;

(4) The motor structure is symmetrical with respect to the straight and cross axes; and

(5) The stator winding is a symmetrical three-phase winding[4].

The mathematical model of the ABC coordinate system of the permanent magnet synchronous motor is shown as follows.

Voltage Formula of stator winding is shown in formula 1.

$$[u_1] = [R][i_1] + \frac{d[\psi_1(\theta,i)]}{dt} \tag{1}$$

Flux linkage equation of three-phase stator winding is shown in formula 2.

$$[\Psi_1(\theta,i)] = [\Psi_{11}(\theta,i)] + [\Psi_{12}(\theta)] \tag{2}$$

Equations of motion is shown in formula 3:

$$T_e - T_l = \frac{J}{n_p}\frac{d\omega}{dt} + \frac{B}{n_p}\omega \tag{3}$$

The mathematical model in the *d-q* coordinate system is obtained from the mathematical model in the ABC coordinate system by transforming the coordinates.

Stator voltage equation is shown in formula 4 after transforming the coordinates.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{d_t}\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} -\omega_e\psi_q \\ \omega_e\psi_p \end{bmatrix} \tag{4}$$

Flux linkage of stator winding is shown in formula 5 after transforming the coordinates.

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi\begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{5}$$

Equations of motion is shown in formula 6 after transforming the coordinates. :

$$\frac{\mathrm{J}}{\mathrm{n_p}}\frac{d_\omega}{d_t} + \frac{B_\omega}{\mathrm{n_p}} = T_e - T_l \tag{6}$$

3. Establishment of control system based on Matlab/Simulink

MATLAB / SIMULINK software developed by Mathworks with powerful matrix operation ability, visual simulation background and drawing function is mainly used for mathematical calculation. SIMULINK has a set of POWER SYSTEM toolbox with complete model, which makes it widely used in the field of electrical engineering. In practical engineering applications, the simulation results are often highly consistent with the experimental results, which greatly improves the efficiency of engineering development[5].

The specific motor parameters in simulation are shown in the Table 1.

Table 1: Simulation motor parameters

Parameter	Value	Unit	Parameter	Value	Unit
Rated power *P*	*3*	*kW*	Rated speed *ω*	*1200*	*rpm*
Stator resistance R_s	*0. 958*	*Ω*	Number of pole-pairs n_P	*4*	-
Damping coefficient *B*	*0. 008*	*N M s*	Sampling time T_s	*1*	*μs*
Busbar voltage U_{dc}	*311*	*V*	d-axis inductance L_d	*5. 25*	*mH*
q-axis inductance L_q	*12*	*mH*	Flux linkage φ_f	*0. 1827*	*wb*

3.1. Coordinate transformation module

The transformation modules used in the control system include Park transformation, Clark transformation and anti-park transformation. Simulation block diagram of Park transformation is shown in Figure 1, simulation block diagram of Clark transformation is shown in Figure 2, simulation block diagram of anti-park transformation is shown in Figure 3.

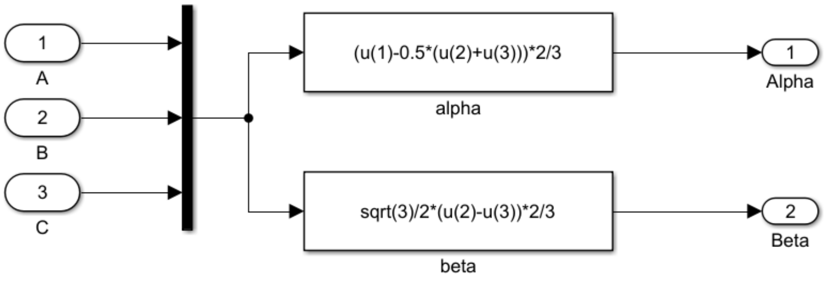


Figure 1: Simulation block of Park transformation

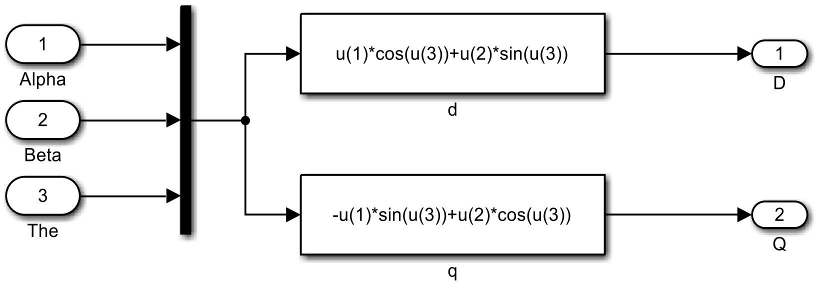


Figure 2: Simulation block of Clark transformation

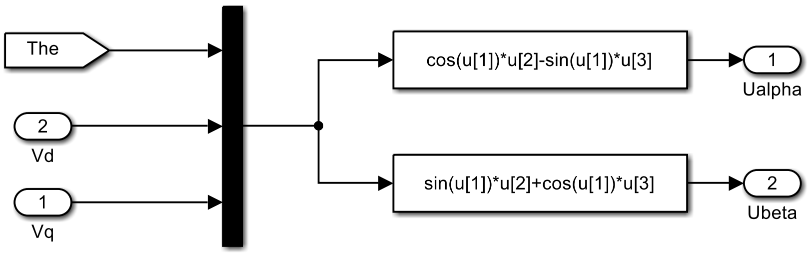


Figure 3: Simulation block of anti-park transformation

3.2. PI regulator module

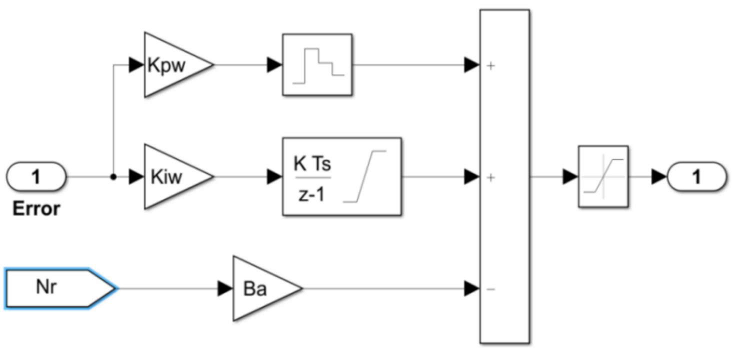


Figure 4: PI regulator module

According to the mathematical principle of PI regulator, PI regulator module is built. It is shown in Figure 4.

3.3. SVPWM simulation module

SVPWM refers to the space vector pulse width modulation, which takes the inverter system and the motor as a whole to control 错误!未找到引用源。. Six voltage vectors and two zero vectors are used to control the motor, so that the circular rotating magnetic field is generated in the motor, and the control of the motor is more efficient[7]. The module of Simulink selected is shown in Figure 5. To determinate Location of reference vector U_{rfe} is shown in Figure 6.

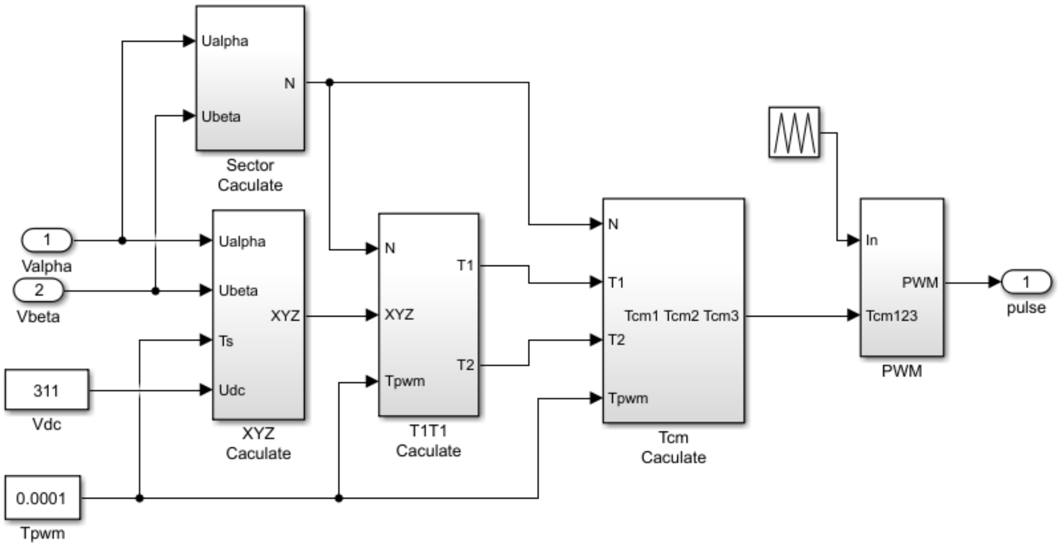


Figure 5: Overall block diagram of SVPWM

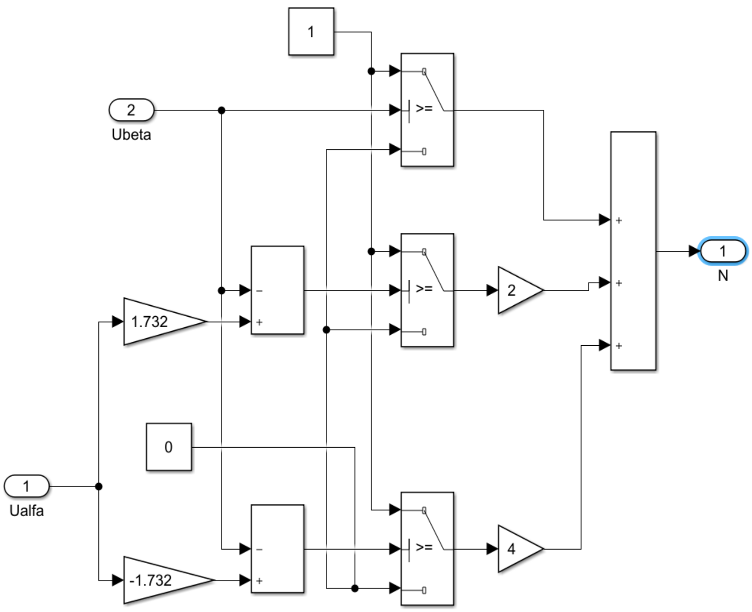


Figure 6: Sector judgement

The action time X, Y, Z of two adjacent nonzero vectors in different sectors are calculated. According to the second-volt principle, the time of basic vector action can be calculated, and the simulation diagram is shown in Figure 7[8], [9].

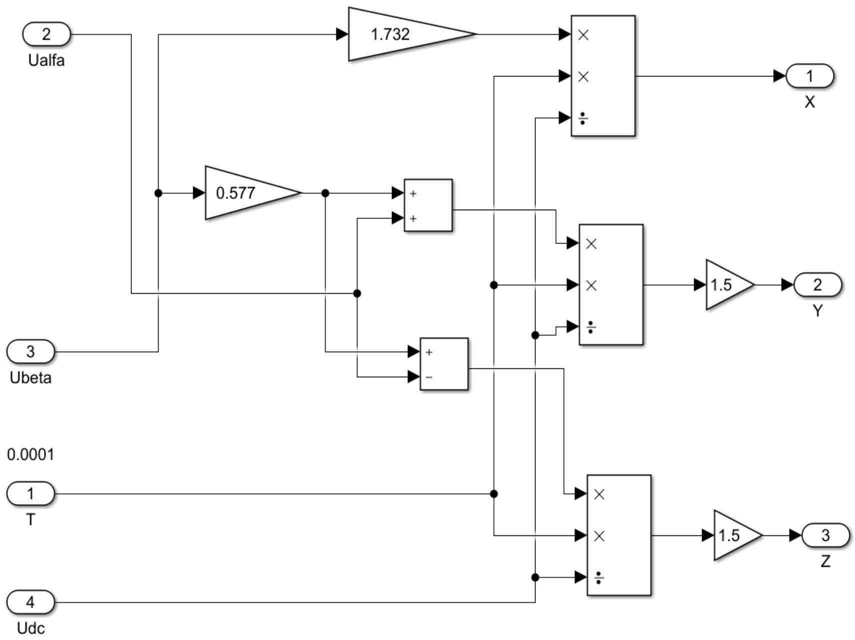


Figure 7: Calculation of vector action time

The action times T_1 and T_2 can be assigned. The values of different sectors T_1 and T_2 are shown in Table 2.

Table 2: Time allocation table for six sector vectors

sector	1	2	3	4	5	6
T_1	Z	Y	-Z	-X	X	-Y
T_2	Y	-X	X	Z	-Y	-Z

The simulation module of vector action time distribution is shown in the figure 8.

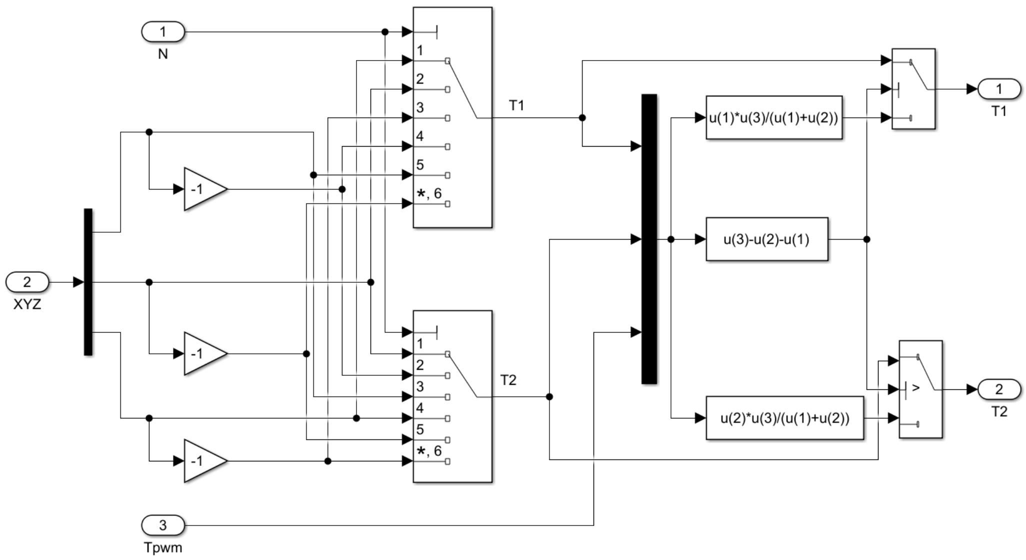


Figure 8: Vector action time distribution diagram

Calculate the conduction time of different switch tube combinations to obtain the vector action switching point, and its calculation equation is shown in formula 7[10].

$$\begin{cases} T_a = \frac{T - T_1 - T_2}{4} \\ T_b = T_a + \frac{T_1}{2} = \frac{T + T_1 - T_2}{4} \\ T_c = T_b + \frac{T_2}{2} = \frac{T + T_1 + T_2}{4} \end{cases} \quad (7)$$

From formula 7, the switching on-time of each tube can be obtained, it is shown in Table 3.

Table 3: Turn-on timetable in different sectors of the switch tube

sector	1	2	3	4	5	6
T_{aon}	T_a	T_b	T_c	T_c	T_b	T_a
T_{bon}	T_b	T_a	T_a	T_b	T_c	T_c
T_{con}	T_c	T_c	T_b	T_a	T_a	T_b

Based on Table 3, a voltage space vector switching point model was constructed, as shown in Figure 9.

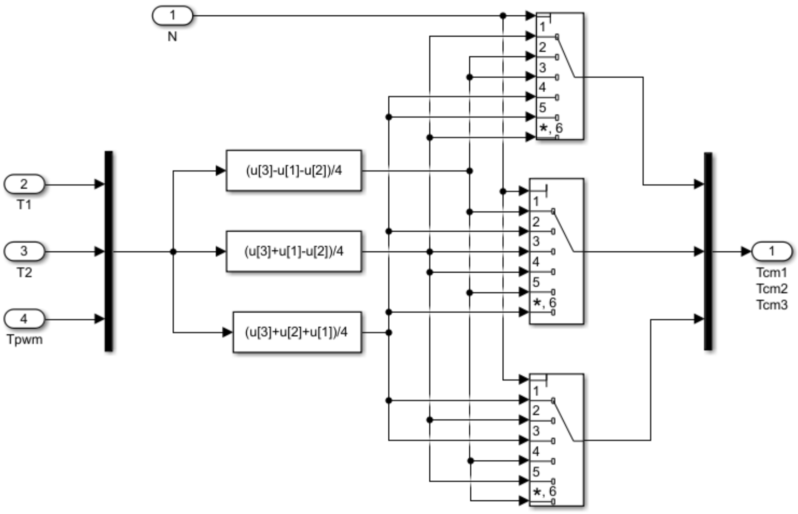


Figure 9: Voltage space vector switching point

After calculating the voltage vector switching point, the generated modulating waveform is converted into PWM pulses, and the pulse output module is built according to the regular sampling method, as shown in Figure 10.

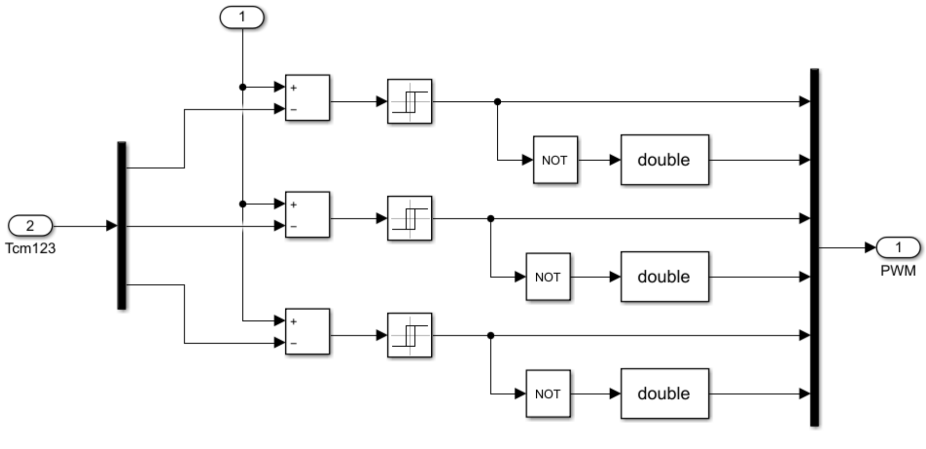


Figure 10: PWM signal generation module

3.4. Simulation model of permanent magnet synchronous motor control system.

After the modules are constructed, the vector transformation system model of permanent magnet synchronous motor based on fuzzy control can be obtained, as shown in Figure 11.

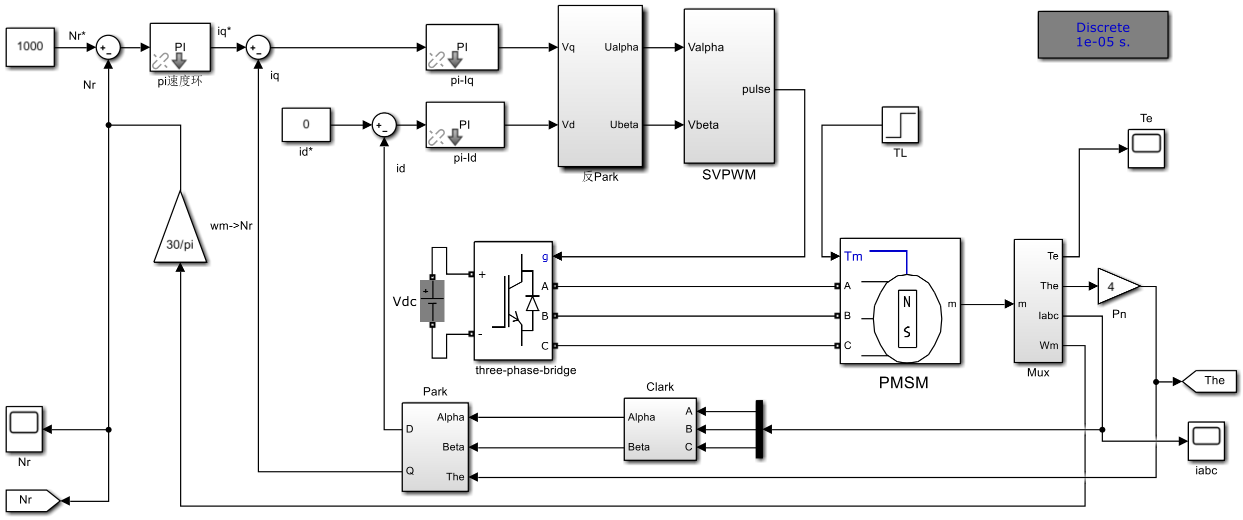
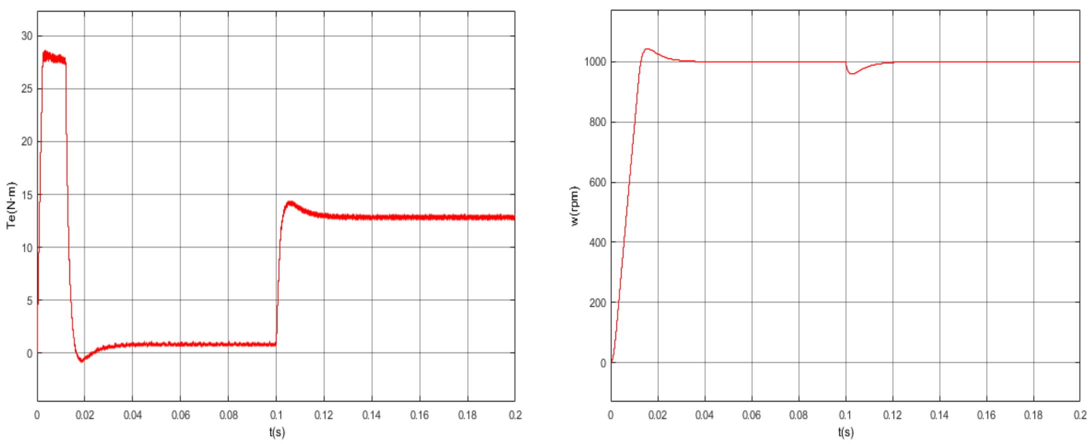


Figure 11: Vector transformation model based on fuzzy control

4. Analysis of simulation results

4.1. Sudden load simulation



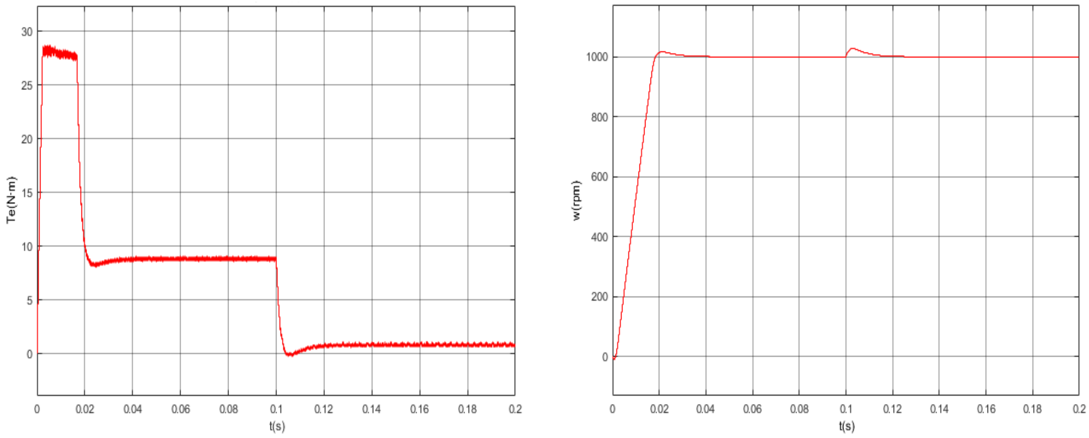
(a) Waveform of the torque (b) Waveform of the speed

Figure 12: Simulation results of sudden load

The waveform of the torque and speed on sudden load is shown in Figure 12. It can be seen that when the no-load starts, the torque of the motor rises rapidly to the limit value and remains and the speed of the motor rises rapidly at the same time. At 0. 03s, the speed of motor reaches the given value of 1000rpm, and after remaining a stable state, the electromagnetic torque decreases rapidly until the torque is equal to the friction torque of 0. 84N ·m.

Load torque rises from 0 to 12N ·m, the electromagnetic torque of the motor rises rapidly, and then quickly stabilizes at 12. 84N ·m, and the motor speed drops slightly and then quickly returns to the given value. After a sudden load is applied, the system can respond quickly, the output torque can quickly follow the load torque, and the speed can quickly follow, the system return to the stable state.

4.2. Dump load simulation



(a) (b)

a. Waveform of the torque, b. Waveform of the speed.

Figure 13: Simulation results of the dump load

The waveform of the motor torque and speed on dump load is shown in Figure 13. It can be seen that when the load is started, the torque of the motor rises rapidly to the limit value and remains, and the speed of the motor rises rapidly at the same time. At 0. 035s, the speed of the motor reaches the given value of 1000rpm, and after entering a stable state, the electromagnetic torque decreases rapidly until the torque is equal to the sum of the load torque and the friction torque 8. 84N·m.

At 0. 1s, the load torque decreases from 8 to 0 N·m, the electromagnetic torque of the motor drops rapidly, and then quickly stabilizes at 0. 84N·m, and the speed rises slightly and quickly returns to the given value. After a sudden load drop, the system can respond quickly, and the output torque quickly follows the load torque, so that the system returns to a stable state.

5. Conclusion

According to the operation characteristics of electric vehicles and the operation characteristics of permanent magnet synchronous motors, the mathematical models in different coordinate systems are analyzed and deduced in detail. Based on Matlab/Simulink, the simulation model of permanent magnet synchronous motor vector control system is built. This paper focuses on the model building process, and expounds how to use the SVPWM algorithm to drive the permanent magnet synchronous motor after vector control, which effectively controls the drive motor and improves the response speed of the motor and the stability of the system.

Acknowledgments

This research was funded by scientific and technological innovation ability cultivation special project for college and middle school students,grant number 22E50218D;Xingtai Youth Talent Plan Project, grant number 2021ZZ034.

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