Novel Design for Direct Torque Control System of PMSM

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Abstract
   Nowadays, with the rapid development of high-performance servo system, The conventional permanent magnet synchronous motor (PMSM) Direct Torque Control (DTC) system has large torque ripple in low speed which cannot be well adapted to today`s development. The main reason is because the number of voltage vectors provided by the two-level inverter is only six and the relationship between voltage vector and torque is not clear [1-5.10-12]. In this paper, the basic concept of direct torque control of permanent magnet synchronous motor is investigated in order to emphasize the effects produced by a given voltage vector on stator and torque variations in this paper. Modified the voltage sector switching table, a novel DTC scheme for the permanent magnet synchronous motor is proposed which is using a novel three-level inverter. An improvement of the drive performance can be obtained by using the novel DTC scheme. The simulation results showed that the scheme could reduce the torque ripple in low speed and improved the stability of the motor under the condition of keeping the system dynamic performance.

Keywords: permanent magnet synchronous motor, direct torque control, torque ripple, sector subdivision, voltage vector switching table

1. Introduction

   The conventional direct torque control used stator flux orientation, and used two-level (Bang-Bang) comparator to modify the torque and flux of the motor directly what made the torque responded very fast [1]. It is fed by two-level inverter which can provide six effective and two zero voltage vectors. We can select appropriate voltage vector to control the stator flux and torque in the two hysteresis bands by developing voltage switching table. Nowadays, People usually used voltage switching table, torque self-control strategy and space vector modulation method to achieve voltage vector selection in direct torque control system. Voltage switching table is relatively simple and easy to achieve, therefore, this scheme is more common in practice and research. However, using the conventional voltage switching table and hysteresis controller will bring a range of other issues. In the case of the torque difference is small, the selected voltage vector will make the toque to reach the reference value in a relatively short time in a switching cycle, and the inverter switching state will not change in the remaining time. The selected voltage vector is still acting on the motor, so that torque will continue changing along the direction of the original, what makes the torque ripple. In order to improve the torque characteristics of direct torque control, we must analyze the torque conversion rule. This paper improved the conventional voltage switching table and used a new three-level voltage source inverter to generate voltage vector on the basis of conventional inverter topology, optimized the DTC control strategy further [6].

2.The Proposed Method

   Permanent magnet synchronous motor direct torque control block diagram is shown in Figure 1. By sampling the stator voltage and current, motor flux and torque can directly observe in the stator coordinate system, and comparing this observation value with the given flux and torque, obtained differences are the input to the flux or torque hysteresis comparator respectively. According to the outputs of the two hysteresis controllers and the position of the flux linkage, looked up the novel voltage vector switching table, we can get the right voltage vector.
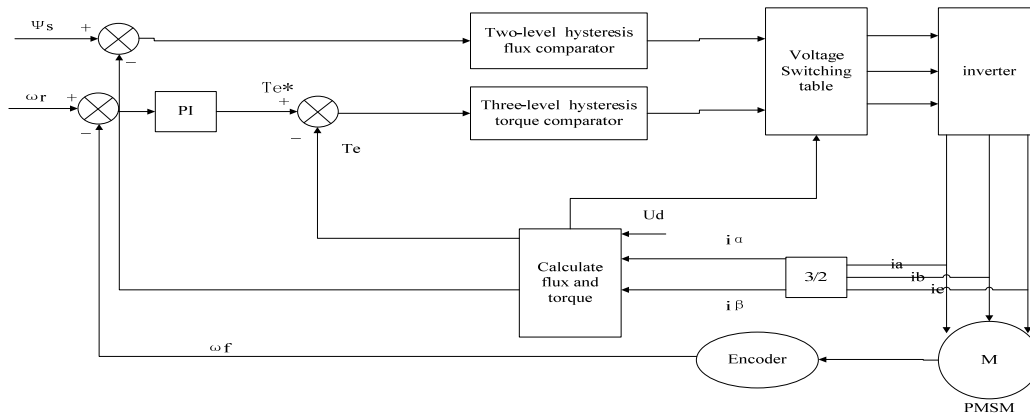
Figure 1. PMSM DTC block diagram

The conventional DTC control system uses a three-phase two-level voltage source inverter. Flux comparator is usually two-level hysteresis comparator where the output is Φ. The torque comparator is usually three-level hysteresis comparator where the output is τ. Φ=1 and Φ=0 indicate the flux linkage increases and decreases respectively. $\tau = 1$ and $\tau = -1$ indicate the torque increases and decreases respectively. $\tau = 0$ denotes that the torque keeps unchanged, thus we got the voltage switching table shown in Table 1:

Table 1. Permanent Magnet Synchronous Motor Direct Torque Control Voltage Switching Table

ϕ	τ	$\theta1$	$\theta2$	$\theta3$	$\theta4$	$\theta5$	$\theta6$
	1	U2	U3	U4	U5	U6	U1
1	0	U7	U0	U7	U0	U7	U0
	-1	U6	U1	U2	U3	U4	U5
	1	U3	U4	U5	U6	U1	U2
0	0	U0	U7	U0	U7	U0	U7
	-1	U5	U6	U1	U2	U3	U4

Wherein the voltage vector and the flux linkage division shown in Figure 2:
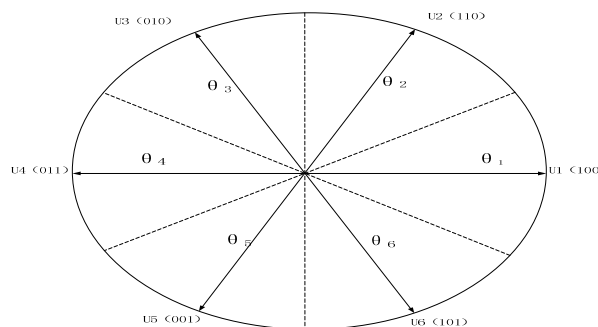

Figure 2. Voltage Vector and the Flux Linkage Division

2.1. DTC Theories for the PMSM
Dynamic mathematical model of PMSM vector form can be described using the d-q transformation as follows:

$$U_{sd} = R_s i_{sd} + p\psi_{sd} - \omega_r \psi_{sq} \tag{1}$$

$$U_{sq} = R_s i_{sq} + p\psi_{sq} + \omega_r \psi_{sd} \tag{2}$$

$$\psi_{sd} = L_d i_{sd} + \psi_f \tag{3}$$

$$\psi_{sq} = L_q i_{sq} \tag{4}$$

Where Usd, Usq are the stator voltage of the d and q axis, respectively; isd, isq are stator current of the d and q axis, respectively; Ψsd, Ψsq are the stator flux linkage of the d and q axis, respectively; p is the differential operator; Rs is the stator resistance; Ld, Lq are the winding inductance of the d and q axis, respectively; In this paper, the PMSM is the surface permanent magnet synchronous motor, so Ld= Lq=Ls.

Substituting (3) and (4) in (1) and (2), respectively. The flux differential can be written as:

$$p\psi_{sd} = -\frac{R_s}{L_s}\psi_{sd} + \omega_r \psi_{sq} + \frac{R_s}{L_s}\psi_f + U_{sd} \tag{5}$$

$$p\psi_{sq} = -\frac{R_s}{L_s}\psi_{sq} - \omega_r \psi_{sd} + U_{sq} \tag{6}$$

Assuming the direct torque control system`s control cycle *Ts* is small enough. We can get the discrete flux equation from Equation (5) and (6):

$$\psi_{sd(k+1)} = \left(1 - \frac{R_s}{L_s}T_s\right)\psi_{sd(k)} + \omega_r \psi_{sq(k)}T_s + \frac{R_s}{L_s}\psi_f T_s + U_{sd}T_s \tag{7}$$

$$\psi_{sq(k+1)} = \left(1 - \frac{R_s}{L_s}T_s\right)\psi_{sq(k)} - \omega_r \psi_{sd(k)}T_s + U_{sq}T_s \tag{8}$$

The torque of the SPMSM (surface permanent magnet synchronous motor) is shown as:

$$T_e = \frac{3p}{2L_s}|\psi_s|\psi_f \sin\delta = \frac{3p}{2L_s}\psi_f \psi_{sq} \tag{9}$$

Where δ can be considered as the angle between the stator flux linkage vector and rotor flux linkage vector, namely the torque angle.

From the formula (9), we can obtain the relationship between the torque angle and torque as follows:

$$\frac{dT_e}{d\delta} = \frac{3p}{2L_s}|\psi_s|\psi_f \cos\delta \tag{10}$$

The formula (10) shows that the electromagnet torque is controllable by adjusting the torque angle under the condition of keeping the amplitude of the stator flux linkage constant.

Substituting (8) in (9):

$$T_{e(k+1)} = \frac{3p}{2L_s}\psi_f\left[\left(1 - \frac{R_s}{L_s}T_s\right)\psi_{sqk} - \omega_r \psi_{sdk}T_s + jU_{sq}T_s\right] \tag{11}$$

We can write the torque expression at time T_{k+1} as:

$$T_{e(k+1)} = T_{e(k)} + \Delta T_{e(k)1} + \Delta T_{e(k)2} \qquad (12)$$

And the detail expression is written as:

$$T_{e(k)} = \frac{3p}{2L_s}\psi_f\psi_{sqk} \qquad (13)$$

$$\Delta T_{e(k)1} = -\frac{3p}{2L_s}\psi_f\psi_{sqk}\frac{R_s}{L_s}T_s = -T_{e(k)}\frac{R_s}{L_s}T_s \qquad (14)$$

$$\Delta T_{e(k)2} = \frac{3p}{2L_s}\psi_f\left(U_{sq} - \omega_r\psi_{sdk}\right)T_s \qquad (15)$$

From the three formulas shown above, the torque increment ΔTe(k)1 due to the electromagnetic torque attenuation caused by the stator resistance effect. The item is proportion to the electromagnetic torque Te(k), and unrelated to the voltage vector and speed. The torque increment ΔTe(k)2 reflects the role of the voltage vector for the influence of the torque change, and it`s influenced by the electromotive force ωrΨsdk [7].

2.2. Analysis of The Electromagnetic Torque Ripple
When the PMSM is in stable state (Te(k)>0), the torque variation caused by the zero vector, forward vector and inverse vector, respectively, can be deduced as follow:

2.2.1. The Torque Increment caused by the Zero Vector:

$$\Delta T^0_{e(k)} = -T_{e(k)}\frac{R_s}{L_s}T_s - \frac{3p}{2L_s}\psi_f\omega_r\psi_{sdk}T_s \qquad (16)$$

Equation (16) indicates thatΔTe(k)1 is the electromagnetic torque attenuation caused by stator resistance, the rest parts absolute value (3PΨfωrΨsdkTs/2Ls) of the negative torque becomes larger with the speed increasing.

2.2.2. The Torque Increment caused by the Forward Vector:

$$\Delta T^+_{e(k)} = -T_{e(k)}\frac{R_s}{L_s}T_s + \frac{3p}{2L_s}\psi_f\left(U_{sq} - \omega_r\psi_{sdk}\right)T_s \qquad (17)$$

From the formula we can see that 3PΨfωrΨsdkTs/2Ls >0. The portion can be understood to be the torque incremental generated by the q-axis component of the forward vector. In addition, the formula above also contains the inverse vector generated by the zero vector.

2.2.3. The Torque Increment caused by the Inverse Vector:

$$\Delta T^-_{e(k)} = -T_{e(k)}\frac{R_s}{L_s}T_s + \frac{3p}{2L_s}\psi_f\left(U_{sq} - \omega_r\psi_{sdk}\right)T_s \qquad (18)$$

From the formula we can see that 3PΨfωrΨsdkTs/2Ls <0. The portion is the inverse torque generated by the inverse vector. In addition, the formula above also contains the inverse vector generated by the zero vector.

Therefore, we can get a conclusion from formula (16) to (18). The size of the inverse torque generated by the zero vector is associated with the motor speed, the higher the motor speed is, the bigger the inverse torque is. The torque variation caused by the forward vector and inverse vector is influenced by the motor speed at the same time. However, with the growth of the speed, forward vector and inverse vector produced a very different effect: on contrast to the

low speed, the torque increment caused by the forward vector is smaller; the inverse torque caused by the inverse vector is further reduced [8].

3. Research Method

From the analysis above, we can see that the inverse vector in high speed could make large torque attenuation, which is a direct result of the torque ripple. Therefore, replace the inverse vector in the conventional voltage vector switching table with the zero vector, thus can reduce the torque fluctuation. When $\tau = 0$, if Φ=1, replace zero vector with forward chopping vector, so that the flux amplitude remains not like using the zero vector as reduce in the case of torque without increasing. If Φ=0, replace zero vector with inverse chopping vector, so that the flux amplitude reduces in the case of torque without increasing, this could fulfill the modulation requirements; Conventional DTC system used two-level inverter. Taking into account that increasing the number of effective voltage vector, so as to achieve the purpose of reducing torque ripple, however, changing the inverter topology will increase the costs. This paper proposes a novel sector subdivision and improves switching table on the basis of conventional two-level inverter reference the paper [6, 8, 9]. Novel voltage vector and flux linkage sector is shown in Figure 3 below:
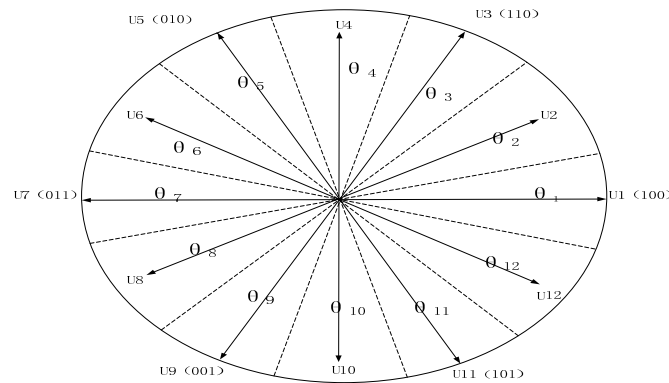

Figure 3. Novel Voltage Sector and Flux Linkage Sector Map

Wherein the even-numbered voltage vector Ui (i = 2, 4, 6 ...) is synthesized by its adjacent two voltage vectors, amplitude value is Ud/√3 and the direction of the new vector is the angle bisector. After synthesis, we get another six voltage vectors, and we divide the flux linkage sector into 12 what makes the selection of voltage vector more sophisticated. SA, SB, SC represent three-phase bridge output of the inverter respectively, $Si = 1$ indicates that the up bridge on and the down off, $Si = 0$ indicates that the up bridge off and the down on, $Si = -1$ indicates that the up and down bridges off all. For example, U2 is synthesized by U1 and U3, and the inverter switching state of U2 is (1 -1 0), and so on. The novel voltage vector switching table is shown in Table 2.

Table 2. Novel Voltage Vector Switching Table

ϕ	τ	$\theta1$	$\theta2$	$\theta3$	$\theta4$	$\theta5$	$\theta6$	$\theta7$	$\theta8$	$\theta9$	$\theta10$	$\theta11$	$\theta12$
	1	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U1	U2
1	0	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12
	-1	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12
	1	U4	U5	U6	U7	U8	U9	U10	U11	U12	U1	U2	U3
0	0	U7	U8	U9	U10	U11	U12	U1	U2	U3	U4	U5	U6
	-1	U0	U13	U0	U13	U0	U13	U0	U13	U0	U13	U0	U13

4. Results and Discussion

The simulation of the DTC PMSM drive system is performed using Matlab/Simulink 7.8 simulation package. Motor parameter: rated power PN=1.5kW, number of poles: P=4, rated speed n=2500rpm, stator resistance Rs=1.18Ω, inductance Ls=3.85mH, rotor inertia J=1.26×10-3kg·m2, Torque coefficient 1N·m /A2.

Chosen algorithm ode23tb where relative error is 1e-3 and given flux linkage is 0.3Wb. The hysteresis band of torque controller is $0.4N \cdot m$, and the hysteresis band of flux linkage controller is 0.02Wb. System is performed by applying torque $10N \cdot m$, $5N \cdot m$ at $0.2s$, $0.4s$. The simulation time is $0.5s$. After starting, sample the voltage and current to estimate the motor flux and torque. Sample the speed to compare with the given speed, the difference of which is the input of the PI controller (Kp=2.1, Ki=150). Compared the output of PI controller with the given torque, the difference of which is the input of torque hysteresis comparator; on the other side, compare the value of stator flux observation with the given flux, the difference of which is the input of the flux hysteresis controller. According to the outputs of the two hysteresis controllers and the position of the flux linkage, looked up the novel voltage vector switching table, we can get the right voltage vector.

The stator flux linkage waveforms of the novel DTC system is shown in Figure 4. It`s obvious that the stator flux linkage keeps constant throughout the running. The flux linkage used about $0.0067s$ to reach $0.3\text{Wb}$. It`s visible that the flux response is very fast and system has a very short transient time.
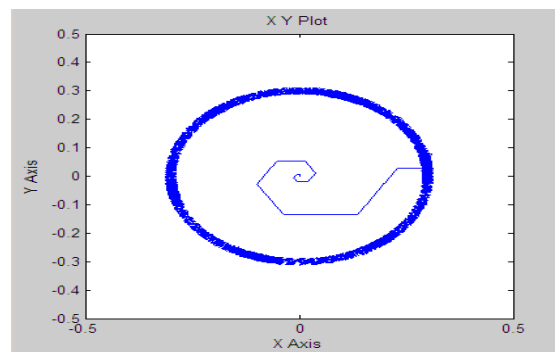

Figure 4. The Stator Flux Linkage Waveforms of the Novel DTC System

The simulation result of torque response of conventional DTC switching table is shown in Figure 5. It clearly shows that the torque is fluctuating between $8N \cdot m$ and $12N \cdot m$. The pulsating quantity is about $4N \cdot m$. From the analysis above, we can see that this is due to the inverse voltage vector generated larger torque ripple, furthermore, due to a single vector working within the entire sampling time.
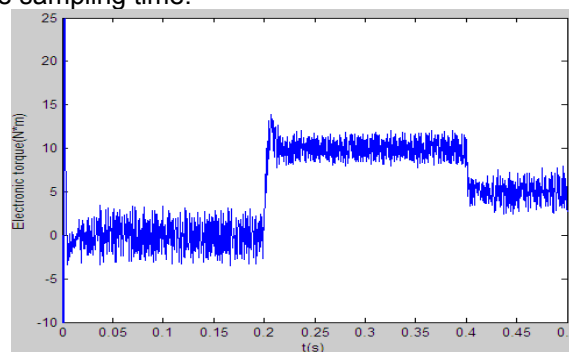

Figure 5. Conventional DTC Torque Response

The torque response of the novel DTC PMSM is shown in Figure 6. We can see that the torque is fluctuating between $9N \cdot m$ to $11N \cdot m$. The pulsating quantity is about $2N \cdot m$. Reduced by about half compared with the previous. So we can get a conclusion that sector subdivision and novel switching table has a positive effect that reduces the torque ripple.
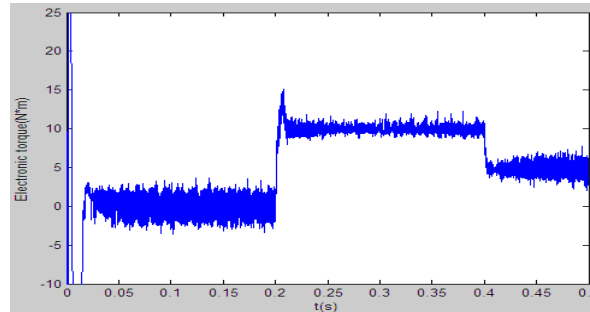

Figure 6. Novel DTC Torque Response

Figure 7 and Figure 8 is the three-phase current waveform diagram. In 0.2s applying a torque and the current tend to normal within 0.03s. System has a quick response, good dynamic performance and less current distortion.
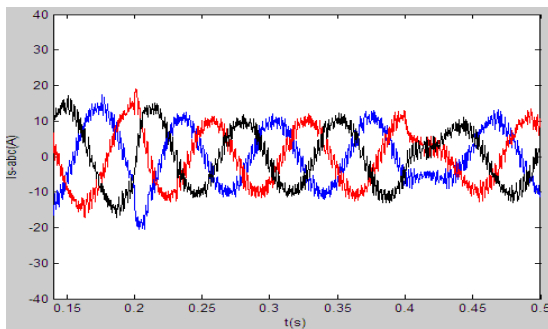

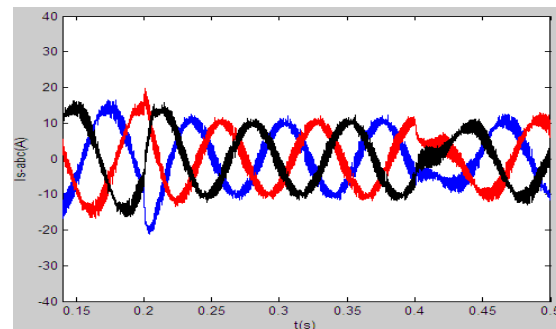Figure 7. Conventional DTC three-phase current waveform

Figure 8. Novel DTC three-phase current waveform

From the simulation results, it is clearly shown that after adopting the novel voltage vector switching table, the linearity of the current of the SPMSM is better than the current using the conventional DTC strategy. When the load torque changes, the system is able to timely overcome changes in the load torque, while reducing the torque ripple of the motor and being able to run smoothly at a given speed condition (200rpm).

5. Conclusion

For the phenomenon of large torque ripple for PMSM in low speed. This paper studies the different voltage vector for PMSM torque influence and proposes a novel PMSM DTC system. Without any increase in hardware cost, only through the software, can get extra six voltage vectors. Furthermore, the sector subdivision of the flux linkage also makes higher control precision. System inherits the conventional DTC system`s simple structure and is easy to implement. Compared to the vector control, eliminated the need for complex calculations and coordinate changes. Due to the system directly control the flux and torque of the PMSM, relatively speaking, the performance is not vulnerable to the effects of changes in motor parameters. The simulation results show that using this scheme can reduce the torque ripple and improve the stability of the motor.

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