A Research Of Reducing Torque And Speed Ripple For Pmsm Based On Direct Torque Control

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Abstract

The main topic of this paper is to present a novel switching technique to reduce the torque and speed ripple for permanent magnet synchronous motor (PMSM). Low number of voltage vectors which can be applied to the machine using the basic direct torque control (DTC) scheme may cause undesired torque and current ripple. An improvement of algorithm can be obtained more voltage vectors based on the application of the space vector modulation (SVM) for prefixed time intervals. Due to increase the voltage vectors, the switching table can be expanded. Moreover, simulation and experimental results for the proposed DTC were compared with the conventional DTC. Results show that the proposed DTC has the high control performance than the conventional DTC.

Keyword: Permanent magnet synchronous motor、Direct torque control 、Discrete Space vector modulation

改善永磁式交流同步馬達在DTC下的轉速轉矩漣波

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摘 要

本研究提出減少永磁同步馬達驅動器的轉矩及速度漣波之技術，以新的切換表來減少永磁同步馬達的轉矩漣波，利用離散的空間向量調變（Discrete Space Vector Modulation）可以產生更多的向量以供選擇，如此可以建構出更多的切換表種類，並藉由磁通和轉矩誤差回授的大小，在加上所需的轉矩角大小，可以找出最理想的切換向量表，達到降低轉矩與轉速漣波大小之功效，並以 MATLAB 與實際永磁同步馬達來驗証此方法的可行性與效果。

關鍵字：永磁同步馬達、直接轉矩控制、離散空間向量調變.

1. Introduction

In the past, DC motors have been widely used in the factory automation as high performance drives. However, the mechanical commutators and brush assembly make dc motors much more expensive than ac motors. Moreover, the use of mechanical commutators will result in undesired sparks, which are not allowed in some applications. The inherent disadvantages of dc motors have prompted continual attempts to find better solutions to the problem. An attempt has been made to use induction motors instead of dc motors. However, due to the high nonlinearity and time-varying characteristics of induction motors, to design a high performance ac motor drive is not an easy work.

Permanent magnet synchronous motors (PMSM's) are used in many applications that require rapid torque response and high-performance operation. The torque in PMSM's is usually controlled by controlling the armature current based on the fact that the electromagnetic torque is proportional to the armature current. Recently, with the appearance of high-speed digital signal processors (DSP's), a control method called direct torque control (DTC) has become popular in many commercial industrial applications. The DTC, which was recently developed for induction motors, has now been implemented PMSM's [1, 3]. The DTC technique is different from traditional methods of controlling torque where current controllers in a suitable reference frame are used to control the motor torque and fluxes [4, 5]. The basic principle of DTC is to directly select stator voltage vectors according to the differences between the reference and actual torque and stator flux linkage. The current controller followed by a pulse width modulation (PWM) comparator is not used in DTC systems, and the parameters of the motor are also not used, except the stator resistance. Therefore, it minimizes the use of machine parameters and reduces the complexity of the algorithms involved in field oriented control (FOC) and feedback linearization methods. However, the traditional DTC, because of only six effective and two zero output voltage vectors that could be chosen, it is difficult to produce a sinusoidal voltage to the PMSM. The low number of voltage vectors which can be applied to the machine using the basic DTC scheme may cause undesired torque and current ripple. This paper proposes a novel switching technique that produces more voltage vectors, to overcome the problem of low number voltages vectors and to reduce torque and speed ripples.

2. Machine Equations

The well-known stator flux linkage, voltage, and electromagnetic torque equations in the rotor reference frame are as follows:

$$v_d = R_s i_d + p\varphi_d - \omega_r \phi_q \tag{1a}$$

$$v_q = R_s i_q + p\varphi_q + \omega_r \phi_d \tag{1b}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{2a}$$

$$\lambda_q = L_q i_q \tag{2b}$$

$$T = \frac{3}{2} p(\lambda_d i_q - \lambda_q i_d) \tag{3}$$

where

R_s　　Stator armature resistance, Ω;

L_d, L_q　　Direct and quadrature inductance, H;

ω_r	Rotor speed in electrical, rad/s;
T	Electromagnetic torque, Nm;
p	Pole pairs.

According to [6], the torque equation is as follows:

$$T = \frac{3}{2}\frac{1}{L_s} p|\lambda_s|\lambda_f \sin\delta \tag{4}$$

Equation (4) implies that the torque increases with the increase in δ if the amplitude of the stator flux linkage is kept constant and δ is controlled within the range of is the angle between the stator and magnet flux linkages.

3. Switching-Table Based DTC

The basic DTC structure is shown in Fig. 1, where the inverter is realized in the hardware, other parts are realized by the software (firmware). Torque and stator flux linkage are controlled using two hysteresis comparators which operate independently of each other, as shown in Fig. 2. In Fig. 1, the three-phase variables are transformed into the stationary dq-axis variables. Then the stator and torque can be express as

$$\hat{\lambda}_{qs} = \int (v_{qs} - R_s i_{qs})dt + \lambda_{qs}|_{t=0} \tag{5}$$

$$\hat{\lambda}_s = \sqrt{\hat{\lambda}_{ds}^2 + \hat{\lambda}_{qs}^2} \tag{6}$$

$$\hat{T}_e = \frac{3}{2} p(\lambda_d i_q - \lambda_q i_d) \tag{7}$$

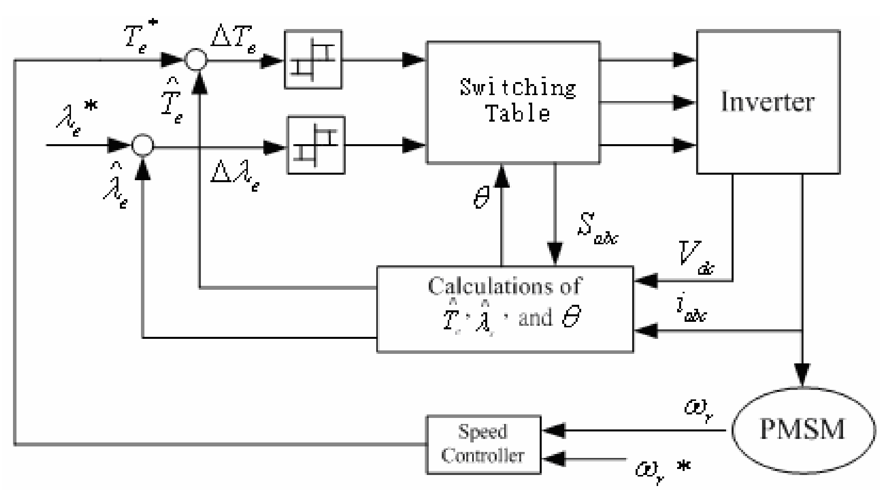


Fig. 1 The block diagram of the PM motor control.

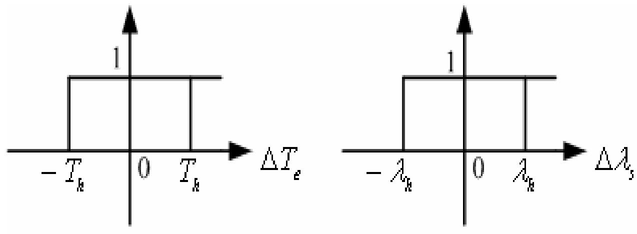


Fig. 2 The torque and flux hysteresis comparators

The stator voltage vector is determined by the status of the power switches. So, there have six nonzero voltage vectors, $V_1,\ldots,V_6$, and two zero voltage vectors, V_0 and V_7.

The six nonzero voltage vectors are 60° apart from each other in voltage vector plane, as show in Fig. 3. These switching states can be expressed S_a, S_b and S_c. Then, the three-phase voltage vector is

$$V_a = \frac{Vdc}{3}(2S_a - S_b - S_c) \tag{8}$$

$$V_b = \frac{Vdc}{3}(-S_a + 2S_b - S_c) \tag{9}$$

$$V_c = \frac{Vdc}{3}(-S_a - S_b + 2S_c) \tag{10}$$

The inverter switching table are selected according to the errors of the torque ΔT_e and flux $\Delta\lambda_s$. Noting that

$$\Delta T_e = T_e^* - \hat{T}_e \tag{11}$$

$$\Delta\lambda_s = \lambda_s^* - \hat{\lambda}_s \tag{12}$$

The switching states selections are indicated in Table 1. In Table 1, ϕ and τ are the output of hysteresis comparators for flux linkage and torque respectively. In the switching table, “1” express increase, and “0” express decrease.

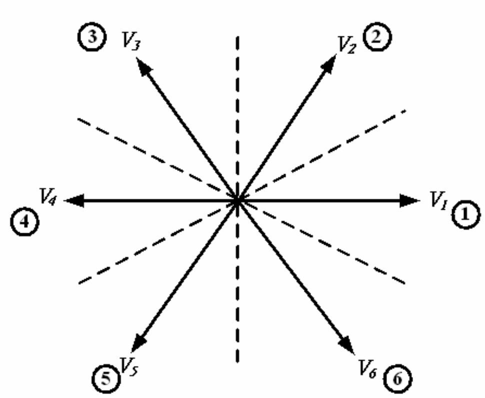


Fig. 3 The six effective voltage vectors.

Table 1 The Switching Table

ϕ	τ	Sector1	Sector2	Sector3	Sector4	Sector5	Sector6
0	0	V_5	V_6	V_1	V_2	V_3	V_4
	1	V_3	V_4	V_5	V_6	V_1	V_2
1	0	V_6	V_1	V_2	V_3	V_4	V_5
	1	V_2	V_3	V_4	V_5	V_6	V_1

4. Novel Switching－Table DTC

In this paper, a new DTC switching technique for PMSM control is presented. In traditional DTC, because there are only six effective and two zero output voltage vectors that could be chosen, it is difficult to produce a sinusoidal voltage to the PMSM. When the motor is controlled by the traditional DTC, it will cause undesired torque and current ripple, and unable to reach smooth-going performance. In order to overcome this drawback, this paper is based on a traditional DTC and match the idea of discrete space voltage modulation (DSVM) [7] that it can produce more voltage vectors. At the result, it can make the motor get more choices of voltage vectors and reduce the speed and torque ripples.

New control architecture for PMSM is shown in Fig. 4, and it can find out both the novel DTC and traditional DTC are need the voltage and current feedback. In order to estimate the electromagnet torque and stator flux linkage, after compare the motor speed ω_r^* with the feedback speed ω_r, it will produce a speed error $\Delta\omega_r$. As well, the estimate value of stator flux and torque will compare with its command value respective, and produce a flux error e_λ and torque error e_T. Then, two error values pass through the torque and stator flux hysterisis controller respectively. Finally, the PWM duty is decided by the switching table and the sector position. Compare with the traditional DTC, the different is the switching table size and the hysterisis controller. Due to voltage vectors are increased, the switching table compare with the traditional switching table has more kind of vectors can be chosen. And because all voltage vectors were presented in the table, the running time of the control algorithm will be saved.

In the novel DTC presented in this paper, the torque hysterisis controller and flux hysterisis controller are shown in Fig. 5. There are four compare levels in the torque comparators and flux comparators respectively. This paper utilizes original six effective voltage vectors to synthesize the other voltage vectors, and it is shown in Fig. 6. The method of vectors synthesis is utilizing the concept of voltage space vector pulse width modulation (SVPWM). We have to judge vectors closed the interval of the six closed intervals that defined by SVPWM. If compare the Fig. 5, the first sector has four vectors (V_1, V_1', V_2, V_2'). Then, use the two near effective vector duty size to synthesize the new vector. The detailed method of voltage vector synthesis can be found out from Fig. 7, where T_1, T_2 and T_z are the near voltage vectors, duty size, and the sample time respectively.

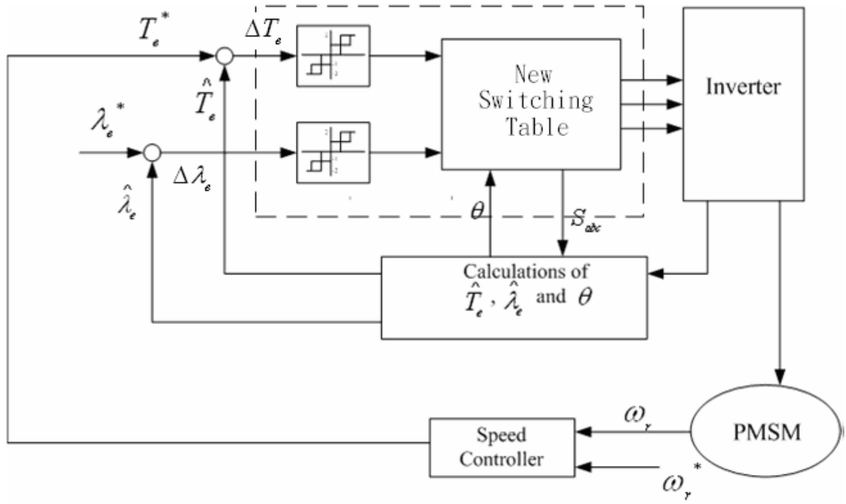


Fig. 4　The new block diagram of the PM motor control.

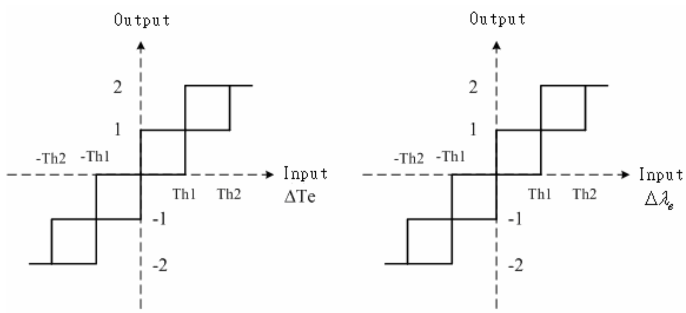


Fig. 5　The new torque and flux hysterisis comparators.

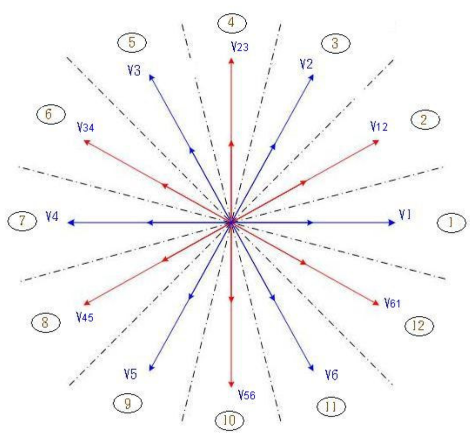


Fig. 6　The new effective voltage vectors.

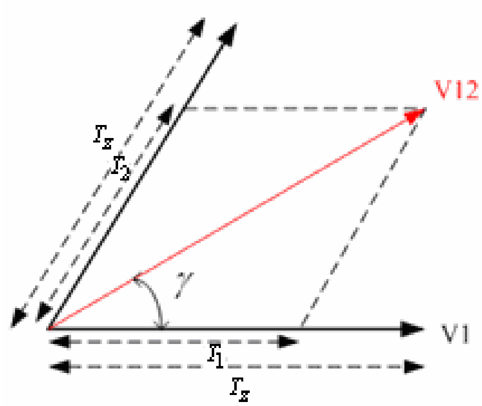


Fig. 7　The method of synthesis.

In Fig. 7, V_{12} is the new vector and it can be synthesized by the vector V_1 and V_2.

The duty size can be obtained from (13)-(15) as follows:

$$T_1 = \frac{V_{ref}}{V_d} \frac{\sin(\frac{\pi}{3} - \gamma)}{\sin(\frac{\pi}{3})} \tag{13}$$

$$T_2 = \frac{V_{ref}}{V_d} \frac{\sin(\gamma)}{\sin(\frac{\pi}{3})} \tag{14}$$

$$T_0 = T_z - T_1 - T_2 \tag{15}$$

After calculating the duty size for the two near vectors, the vector position is decided by the SVPWM. Table 2 is the vector duty size of three phase system U, V and W, where the T_0 is the duty size of the zero voltage vector. Finally, the construct table form for these vectors is shown in Table 3.

Finally, Fig. 8 and Fig. 9 are shown the simulation results for traditional switching table and novel switching table at high speed and low speed command respectively, and all are with the same sampling frequency. From the simulation results shown in Fig. 8 and Fig. 9, we can conclude that the ripple of the speed and torque are reduced by utilizing the novel switching table.

Fig. 10 and Fig. 11 are shows the experimental results for the traditional switching table and novel switching table at high speed and low speed respectively. The motor parameters are the same with the simulations. The experimental results also proved the torque and speed ripple was reducing by the novel switching table

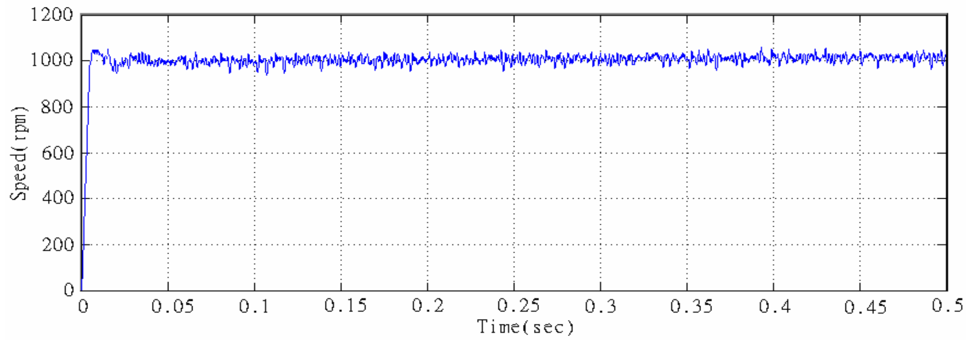
Table 2 Calculation of Three Phase Duty (UVW)

Sector	I	II	III	IV	V	VI
f_a	$\frac{T_0}{2}+T_1+T_2$	$\frac{T_0}{2}+T_1$	$\frac{T_0}{2}$	$\frac{T_0}{2}$	$\frac{T_0}{2}+T_2$	$\frac{T_0}{2}+T_1+T_2$
f_b	$\frac{T_0}{2}+T_2$	$\frac{T_0}{2}+T_1+T_2$	$\frac{T_0}{2}+T_1+T_2$	$\frac{T_0}{2}+T_1$	$\frac{T_0}{2}$	$\frac{T_0}{2}$
f_c	$\frac{T_0}{2}$	$\frac{T_0}{2}$	$\frac{T_0}{2}+T_2$	$\frac{T_0}{2}+T_1+T_2$	$\frac{T_0}{2}+T_1+T_2$	$\frac{T_0}{2}+T_1$

Table 3 New switching table

F	-1				-2				1				2			
T	-1	-2	1	2	-1	-2	1	2	-1	-2	1	2	-1	-2	1	2
vector	V'_{n-4}	V'_{n-3}	V'_{n+4}	V'_{n+3}	V_{n-4}	V_{n-3}	V_{n+4}	V_{n+3}	V'_{n-1}	V'_{n-2}	V'_{n+1}	V'_{n+2}	V_{n-1}	V_{n-2}	V_{n+1}	V_{n+2}

-1:light decrease ; -2:large decrease ; 1:light increase ; 2: large increase



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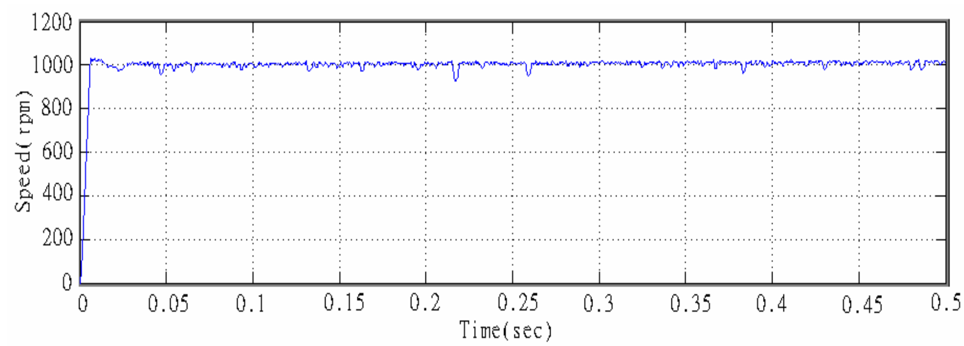

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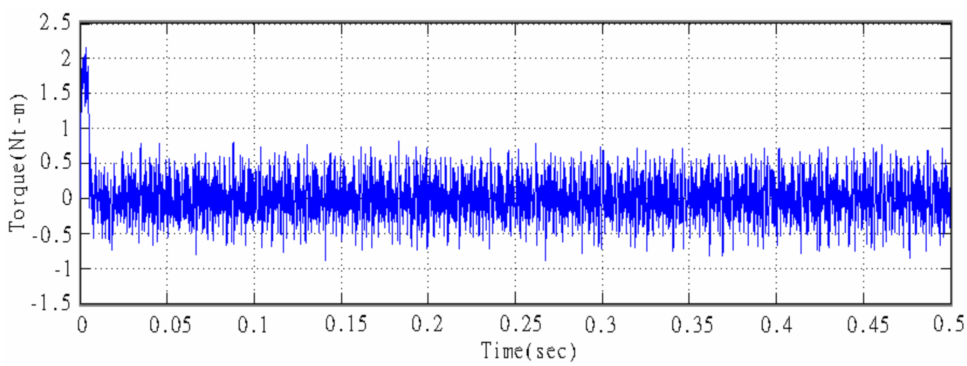

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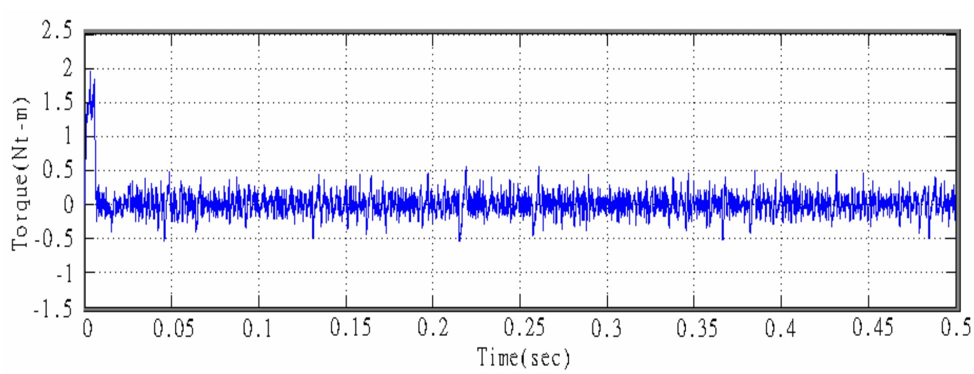
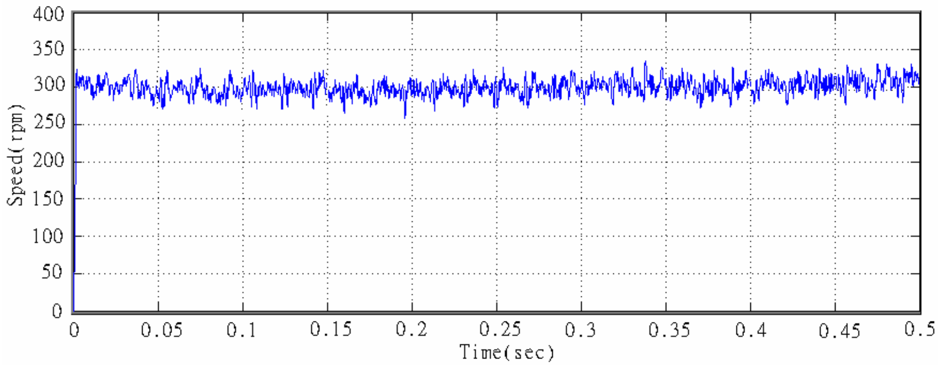


(d)

Fig. 8 (a) Speed of simulation traditional DTC (1000 rpm). (b) Speed of simulation novel DTC (1000 rpm). (c) Torque of simulation traditional DTC. (d) Torque of simulation novel DTC.



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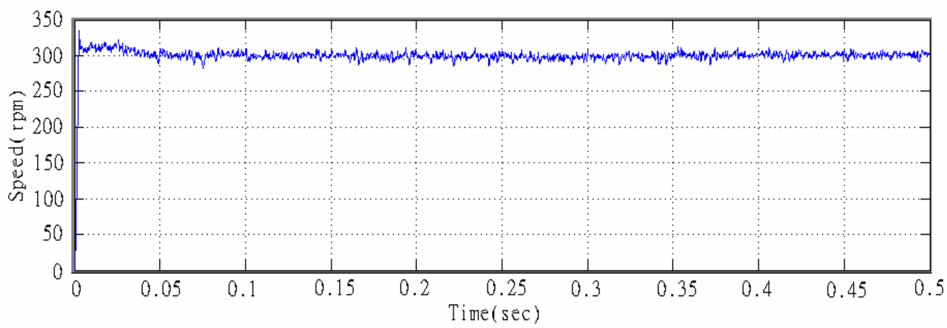

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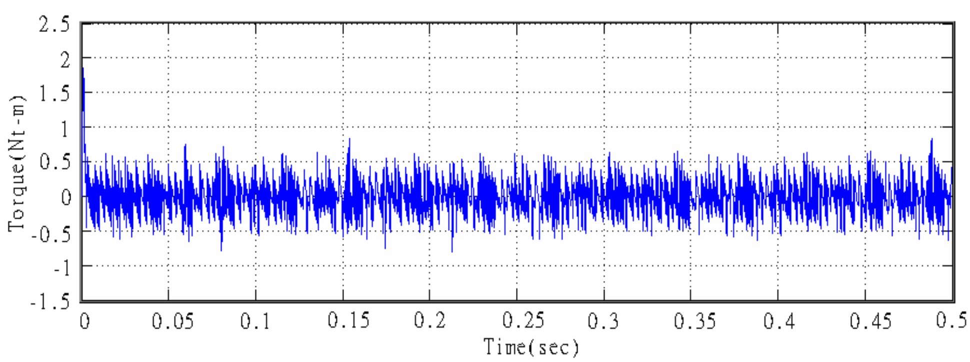

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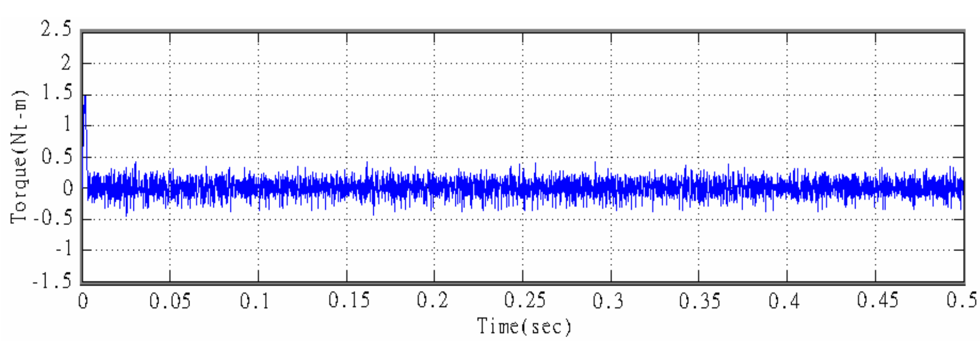

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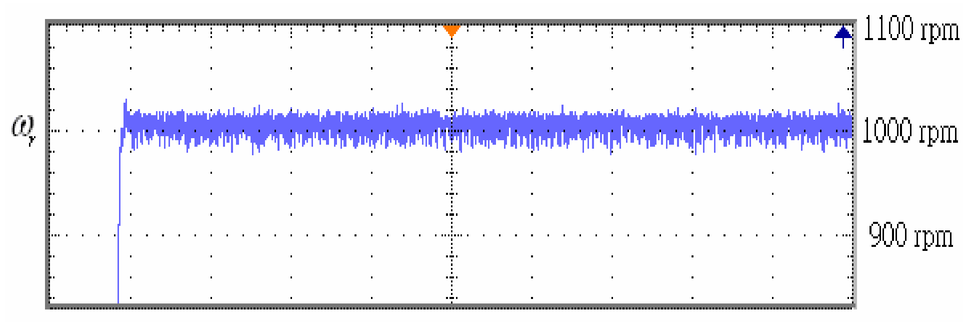
Fig. 9 (a) Speed of simulation traditional DTC (300 rpm). (b) Speed of simulation novel DTC (300 rpm). (c) Torque of simulation traditional DTC. (d) Torque of simulation novel DTC.



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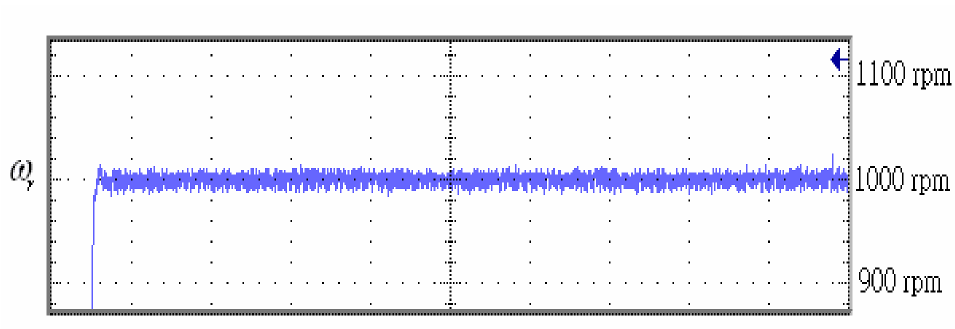

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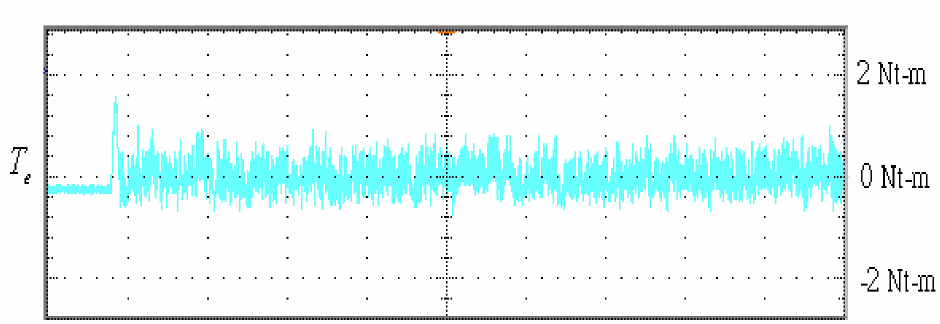

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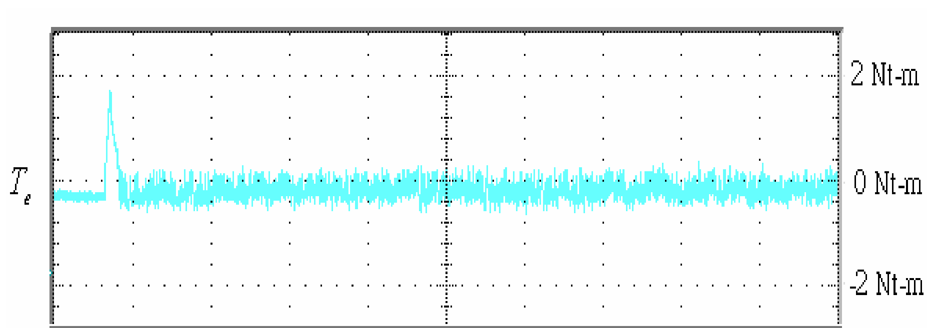
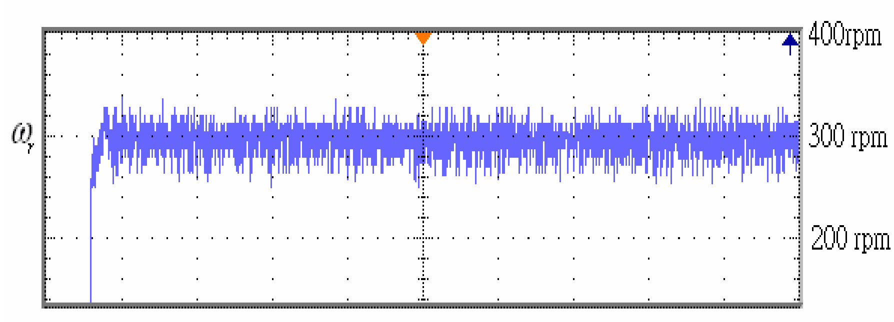


(d)

Fig. 10　(a) Speed of experimental traditional DTC (1000 rpm). (b) Speed of experimental novel DTC (1000 rpm). (c) Torque of experimental traditional DTC. (d) Torque of experimental novel DTC.



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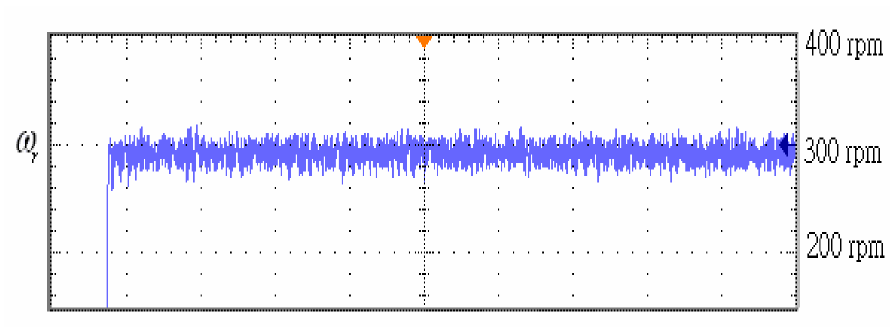

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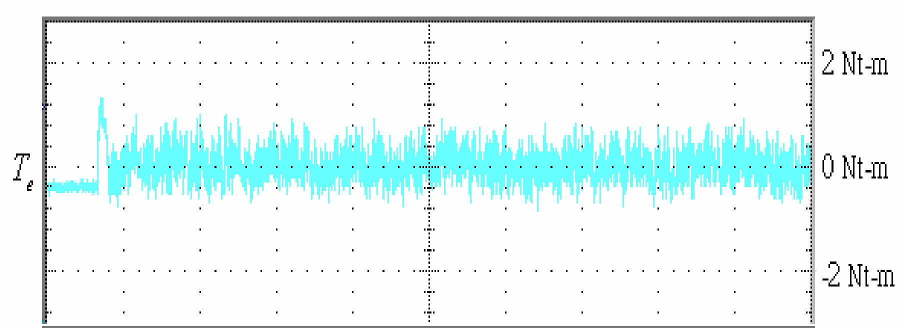

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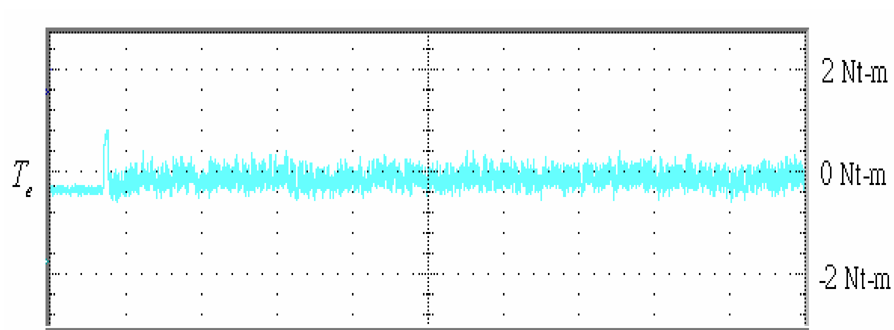

(d)

Fig. 11 (a) Speed of experimental traditional DTC (300 rpm). (b) Speed of experimental novel DTC (300 rpm). (c) Torque of experimental traditional DTC. (d) Torque of experimental novel DTC.

5. Conclusions

In this paper, a modified switching table for the PMSM has been proposed, and it does not spend additional time to produce more effective voltage vectors in the new algorithm. The feasibility and accuracy of the new switching table has been proved by simulation and experimental. Finally, the simulation and experimental results show that both torque and speed ripples are greatly reduced when compared with the traditional DTC.

6. Appendix

Permanent magnet synchronous motor:

110V/3.5A, 0.75KW,4 poles, 2000rpm

R_s	$1.57\,\Omega$
L_S	0.00467mH
J_m	$0.000161 kg-m^2$

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