Improved Discrete Space Vector Modulation Scheme for DTC Controlled PMSM

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ABSTRACT

The basic direct torque control (DTC) scheme may cause undesired torque, flux and current ripples because of the small number of voltage vectors which can be applied to the machine. Discrete space vector modulation (DSVM) method was proposed for DTC to overcome this problem by applying more vectors in one interval without increasing the switching frequency. On the other hand, in the typical DTC scheme, the voltage vector is applied without considering the influence of motor speed and the absolute value of the torque error, and this also causes undesired torque and flux ripples.

In this paper, after reviewing the primary ideas of DSVM DTC technique, a new scheme for the DSVM-DTC of PMSM is proposed with a new set of switching tables considering the motor speed and the absolute value of torque and flux feedback error. In one fixed time interval, three vectors are applied to the motor including the two zero vectors. The vector applying sequence is investigated. Theoretical development and simulation results for the improved DSVM-DTC are carried out and compared with the basic DTC scheme. The switching frequency of DSVM DTC is obtained based on different sampling periods and compared with the basic scheme. Results show that the DSVM DTC can achieve better steady state and transition performance.

1 INTRODUCTION

Permanent magnet synchronous motor (PMSM) has found wide applications due to its high power density (compactness), high efficiency, ease of control, high torque-to-inertia ratio, and high reliability. A very widely used drive strategy for PMSM is the field oriented control (FOC), which was proposed by Blaschke in 1971 for induction motors (IMs) [1]. However, the FOC scheme is quite complex due to reference frame transformation and it is highly dependent upon the motor parameters and mechanical shaft speed. To mitigate these problems, a new control strategy for the torque control of induction motor was developed by Takahashi as direct torque control (DTC) [2] and by Depenbrock as direct self control (DSC) [3]. The basic idea of DTC for induction motor is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque.

It has been proven that the DTC scheme for induction motors could be modified for PMSM drive. Since it does not require any current regulator, coordinate transformation and PWM signal generator, the DTC scheme has the advantages of simplicity, good dynamic performance, and insensitivity to motor parameters except the stator winding resistance.

Compared with the FOC, the major drawback of the DTC method is the large ripples of torque and flux linkage. The switching state of the inverter is updated only once in every sampling interval. The inverter keeps the same state until the output of the hysteresis controller changes state, resulting in relatively large torque and flux ripples. Another unwanted feature is the non-constant inverter switching frequency, which changes with the rotor speed, load torque and bandwidth of the two hysteresis controllers. In the past few years, many attempts were carried out to overcome these problems. Fixed switching frequency and the reduction of torque ripple could be obtained by calculation of the stator flux vector variation required to exactly compensate the flux and torque errors. The control system should be able to generate any voltage vector, implying the use of space vector modulation (SVM) which complicates the control scheme. On the other hand, a discrete SVM (DSVM) method was proposed to improve the DTC scheme, which replaces the simple switching table by several switching tables, obtaining a combination of three voltage vectors into the same sampling period [4]. The torque and flux ripple could be reduced with small calculation cost although the switching frequency of inverter is still variable.

In this paper, the DSVM DTC of PMSM is reviewed and the zero-vector chosen and the vector selection sequence are modified to improve the performance and reduce the inverter switching loss. Comparisons of the basic DTC and DSVM DTC are made based on the system performance and switching frequency.

2 PMSM MODEL AND DIRECT TORQUE CONTROL

2.1 Machine equations

As to the widely known three-phase PMSM, the voltage equations for the stator windings in the stationary reference frame (*a*, *b*, *c*) can be written in the matrix form as

$$V_{abcs} = R_s I_{abcs} + \frac{d}{dt}\lambda_{abcs} \tag{1}$$

where V_{abcs} is the stator phase voltage, R_s the phase winding resistance, I_{abcs} the phase current, and λ_{abcs} the flux linkage of phase winding.

Usually, the motor equations are transferred to *d*-*q* rotor frame rotating with the rotor, so the inductances no longer depend on the rotor position. Then the voltage and flux linkage for a PMSM in the rotor *d*-*q* reference frame are

$$\begin{cases} v_q = r_s i_q + w_r \lambda_d + \dfrac{d\lambda_q}{dt} \\ v_d = r_s i_d - w_r \lambda_q + \dfrac{d\lambda_d}{dt} \end{cases} \tag{2}$$

$$\begin{cases} \lambda_d = L_d i_d + \lambda_M \\ \lambda_q = L_q i_q \end{cases} \tag{3}$$

and the electromagnetic torque and mechanical equations are

$$T_e = \frac{3P}{4}\lambda_M i_q \tag{4}$$

$$J\frac{dw_r}{dt} = \frac{P}{2}(T_e - T_L) \tag{5}$$

where v_q is the *q*-axis voltage, v_d the *d*-axis voltage, i_q the *q*-axis current, i_d the *d*-axis current, r_s the stator resistance, $L_d = L_q$ the inductance, w_r the electrical angular velocity, λ_d , λ_q are the *d*-*q* components of the stator flux linkage, respectively, λ_M is the permanent magnet rotor flux linkage, *P* the number of poles, *J* the mechanical inertia of motor and load, and T_L the load torque.

2.2 Basic DTC principle

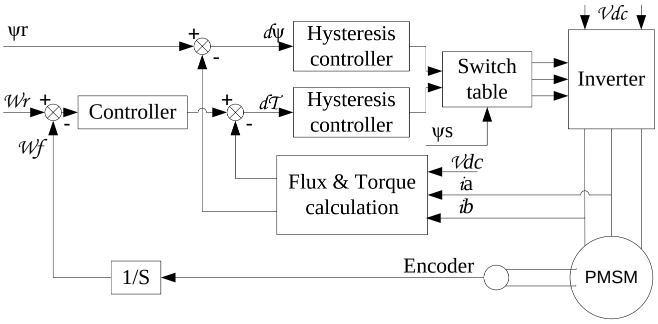
The basic functional blocks used to implement the DTC scheme are illustrated in Fig. 1 (a). The instantaneous values of flux and torque are calculated from stator variable by using a closed loop estimator, in which the flux linkage and torque are calculated in the stator reference frame, α-β frame. The stator flux linkage of a PMSM can be expressed as

$$\varphi_s = \int (v_s - Ri_s)dt \tag{6}$$

and the torque can be written as

$$T_e = \frac{3}{2} p(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \tag{7}$$

Then the errors of torque and flux between reference and feedback values are input to hysteresis controllers to select a proper vector with the help of a look-up table as shown in Fig. 1 (b).



Δφ	ΔT	Sector 1	2	3	4	5	6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_5	V_6	V_1	V_2	V_3	V_4

(b)

Fig. 1-(a) Block diagram of basic DTC scheme; (b) Voltage vector switching table

3 IMPROVED DSVM DTC SCHEME

In voltage source inverters, eight switching combinations can be selected, two of which determine zero voltage vectors and the remaining generate six equally spaced voltage vectors having the same magnitude. Fig. 2 (a) shows the voltage vectors that are usually employed in the DTC scheme when the stator flux vector lies in sector 1.

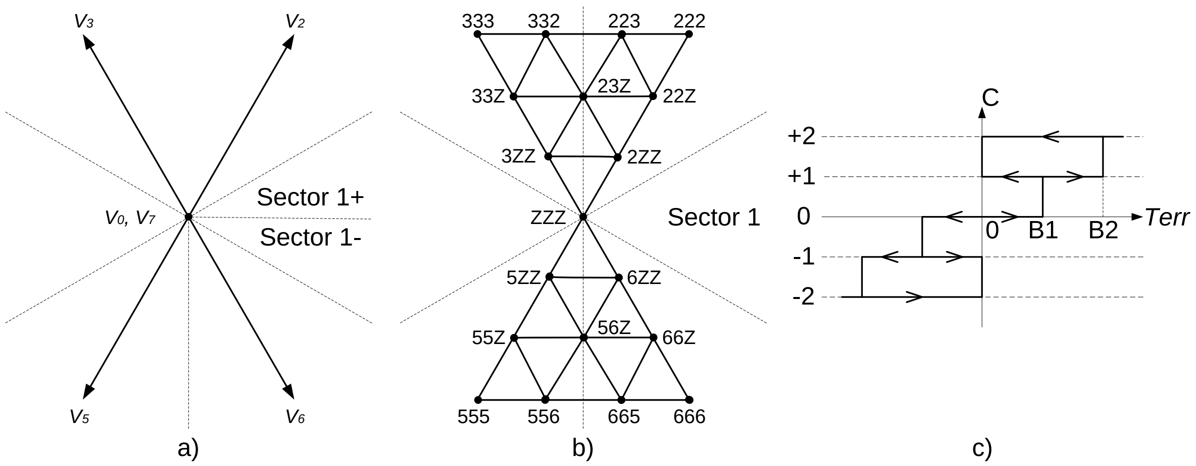


Fig. 2-(a) Voltage vectors utilised in the basic DTC when the stator flux is in sector 1; (b) Voltage vectors obtained by using DSVM; (c) The five-level hysteresis controller

It has been reported that the torque control effect of applying the same voltage vector highly depends on the working condition of the motor [5]. The motor operation status of

DSVM could be classified based on the torque error value and the emf, which is related to the rotor speed. Fig. 2 (b) shows the available voltage vectors that can be chosen in a sampling cycle with three equal time intervals when the stator flux is in sector 1. When the resistance loss is negligible, the torque is maintained at its actual value if the applied voltage vector effect coincides with the induced emf. If the feedback torque is close to the reference value a voltage space vector indicating approximately the emf voltage should be chosen. The space vectors next to the emf voltage levels are used for small torque corrections. When a large torque error is observed, the vectors as V_{333}, V_{222}, V_{555} and V_{666} are selected in order to compensation for the deviation as fast as possible. The different levels of torque error are obtained by a new five-level hysteresis controller as shown in Fig. 2 (c).

Therefore, several switching tables are carried out depending on the value of emf voltage or rotor speed. Table 1 is a set of switching tables for DSVM DTC method when the stator flux is in sector 1 for different speed region.

Table 1-New switching table of DSVM DTC for sector 1

Speed	Sector	Flux	Torque				
			-2	-1	0	+1	+2
Low	1	-1	555	5ZZ	ZZZ	3ZZ	333
		+1	666	6ZZ	ZZZ	2ZZ	222
Medium	1	-1	555	ZZZ	3ZZ	33Z	333
		+1	666	ZZZ	2ZZ	22Z	222
High	1-	-1	555	3ZZ	23Z	332	333
		+1	666	2ZZ	22Z	222	222
	1+	-1	555	3ZZ	33Z	333	333
		+1	666	2ZZ	22Z	222	222

Same as basic DTC scheme, the inverter switching frequency is non-constant in DSVM DTC system. More vectors are applied in one sampling cycle, so there is higher switching frequency. To minimise this, another vector selection algorithm is developed. The inverter status of previous cycle is recorded as a feedback to the vector selector. After a vector set is chosen from Table 1, the applying sequence of these three vectors is adjusted based on the previous inverter output. The order of the three vectors is changed to try to maintain the inverter status or minimise the switching number of the bridges if possible. Because in one fixed sampling period, the system operates as an open loop system without any feedback from the motor. So the same torque control effect could be obtained by any applying sequence of the three vectors. Therefore, this algorithm can reduce the switching frequency and the dead-time cost of the inverter.

4 SIMULATION RESULTS

In order to show the effectiveness of the proposed DSVM technique a set of comparative simulation has been carried out based on a 4-pole PMSM model. The sampling period has been chosen equal to 30 μs for both basic DTC and DSVM DTC. Fig. 3 shows the torque and speed performance of basic DTC and DSVM DTC at steady state of different speed regions for the same sampling period $\Delta t=30\ \mu s$. The reference values are 10 *Nm* for torque and 0.182 *Wb* for the stator flux. The rotor speed is set to 100 *rpm* in Fig. 3 (a) and (b) and 1000 *rpm* in Fig. 3 (c) and (d). An appreciable reduction of torque and speed ripple has been obtained by using the DSVM technique.

In basic DTC and DSVM DTC schemes, the number of switching times per second is observed to identify the inverter operation because the switching frequency is non-constant. As three vectors are chosen for one sampling cycle, the switching frequency of the inverter is increased in DSVM DTC method for same sampling period as shown in Fig. 4. This frequency is related to the sampling time interval and the hysteresis controller band width. In this paper, the band value of the torque hysteresis controller in basic DTC is set to ±0.2 while the five-level controller band in DSVM scheme is set to ±0.1 and ±0.2. Fig. 4 shows the switching frequency of different sampling time intervals for both basic DTC and DSVM DTC schemes.

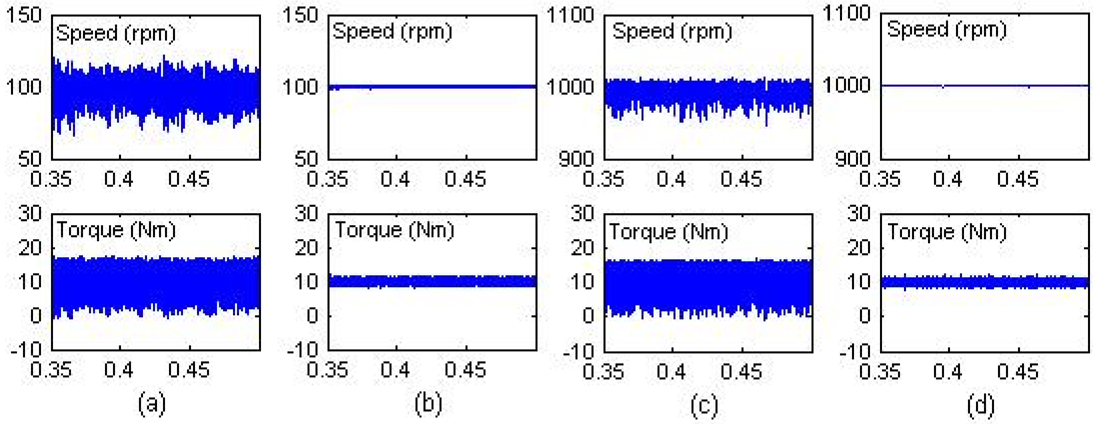


Fig. 3-Steady state performance of basic DTC (BDTC) and DSVM DTC for PMSM (a) BDTC, 100 *rpm*; (b) DSVM DTC, 100 *rpm*; (c) BDTC, 1000 *rpm*; (d) DSVM DTC, 1000 *rpm*.

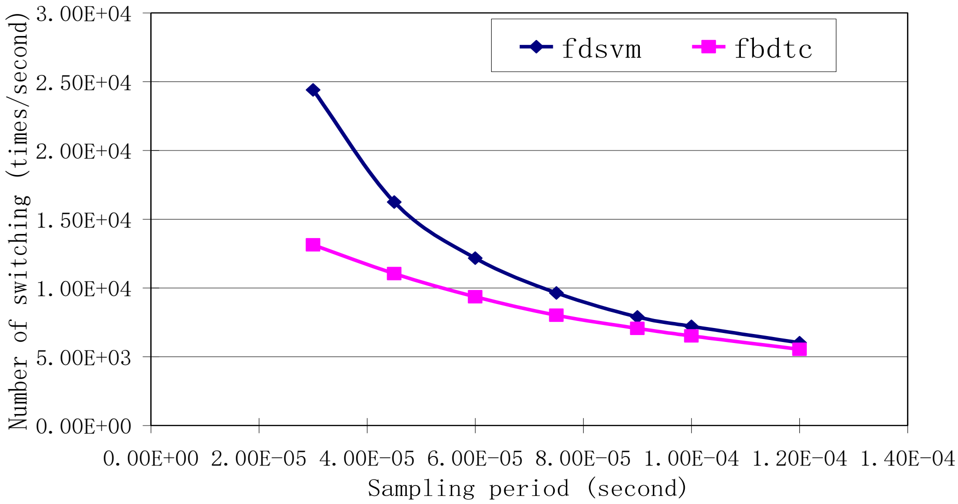


Fig. 4-The number of switching per second by using BDTC and DSVM DTC

In Fig. 4, ‘fdsvm’ and ‘fbdtc’ represent the switching frequency of basic DTC and DSVM DTC respectively. The switching frequency of DSVM DTC reduces closer to the basic DTC scheme when bigger sampling period is applied. When the sampling interval of DSVM DTC is bigger than 40 μs, the sampling period do not need to be doubled in order to achieve a mean switching frequency practically equal to that obtained with the basic switching table as mentioned in [4].

Therefore, another comparison is made to demonstrate that the DSVM DTC method could achieve better performance at the same inverter switching frequency as the basic DTC scheme. In Fig. 5, the sampling period of basic DTC is set to 60 μs and that of DSVM scheme is set to 75 μs so that a approximately same switching frequency could be obtained. The steady state performance is simulated at the speed of 1000 *rpm* with a 10 *Nm* load. Then the dynamic response of load change is simulated assuming a 10 *Nm* load is added to the rotor shaft at *t=0.2 s*. As shown in Fig. 5, the modified DSVM DTC scheme could achieve better steady and dynamic performance.

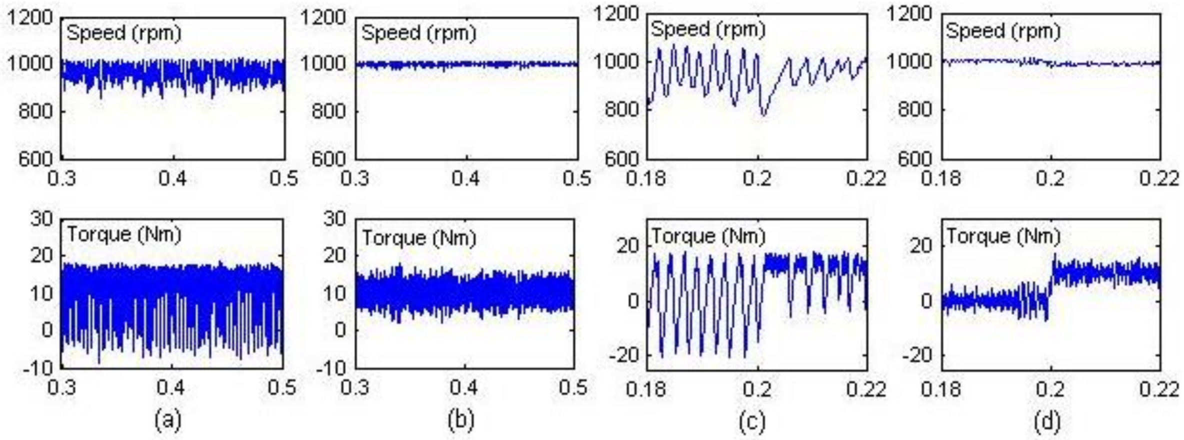


Fig. 5-Performance of BDTC and DSVM DTC with the same inverter switching frequency
(a) BDTC, 1000 *rpm*, $\Delta t=60\ \mu s$; (b) DSVM DTC, 1000 *rpm*, $\Delta t=75\ \mu s$; (c) BDTC, Load step to 5 Nm at t=0.5 s, $\Delta t=60\ \mu s$; (d) DSVM DTC, Load step to 5 Nm at t=0.5 s, $\Delta t=75\ \mu s$

5 CONCLUSIONS

The DSVM method is designed aiming to modify the basic DTC control scheme for improving the performance of PMSM drive system in terms of torque and flux ripples without adding any other complicate control algorithms. For this purpose the DSVM technique uses prefixed time intervals within a sampling cycle period to synthesise a higher number of voltage vectors with respect to basic DTC scheme. A set of switching table is carried out to minimise the torque error. An optimal vector selector is developed to reduce the switching loss and make the system more stable.

Simulation results of different DTC schemes are compared to show that the new DSVM method can improve the performance of both steady state and dynamic response of the DTC system with respect to the basic one even with the same switching frequency. The torque ripple can be reduced.

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