

# A Novel MATLAB/Simulink Model of PMSM Drive using Direct Torque Control with SVM

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## ABSTRACT

A modified Direct Torque Control (DTC) by using Space Vector Modulation (DTC-SVM) for permanent magnet synchronous machine (PMSM) drive is proposed in this paper. DTC-SVM technique improves the basic DTC performances, which features low torque and flux ripple and also fixed switching frequency. The computer simulation results, in Matlab/Simulink, demonstrate the effectiveness of the proposed control scheme which improves the performance of the PMSM.

## Keywords

PMSM, DTC, DTC-SVM, Torque ripple, Flux ripple, Fixed switching frequency.

## 1. INTRODUCTION

Direct Torque Control (DTC) method has been first proposed and applied for induction machines in the mid- 1980's as reported in [1]. This concept can also be applied to synchronous drives [2]. Indeed, in the late 1990s, DTC techniques for the interior permanent magnet synchronous machine appeared, as reported in [1]. Permanent magnet (PM) synchronous motors are widely used in high-performance drives such as industrial robots and machine tools to their advantages as: high efficiency, high power density, high torque/inertia ratio, and free maintenance. In recent years, the magnetic and thermal capabilities of the PM have been considerably increased by employing the high coercive PM material [2]. For some applications, the DTC becomes unusable, despite it significantly improves the dynamic performance of the drive compared to the vector control due to torque and flux ripples. Indeed, hysteresis controllers used in the conventional structure of the DTC generates a variable switching frequency, causing electromagnetic torque oscillations [4], this frequency is also varying with speed, load torque and hysteresis bands selected [1]. In addition, a high sampling frequency needed for digital implementation of hysteresis comparators and a current and torque distortion caused by sectors changes [2]. Several contributions have been proposed to overcome these problems, by using a multilevel inverter: more voltage space vectors available to control the flux and torque. However, more power switches are needed to achieve a lower ripple and almost fixed switching frequency, which increases the system cost and complexity [2]-[5].

In [1] and [2], two structures of modified DTC have been proposed to improve classical DTC performances by replacing the hysteresis controllers and the commutation table by a PI

regulator, predictive controller and Space Vector Modulation (SVM). In this paper, a modified DTC algorithm with fixed switching frequency for PMSM is proposed to reduce the flux and torque ripples. It is an extension of the modified DTC scheme for the PMSM proposed by the authors in [1] and [2]. The performance of the basic DTC and the proposed DTC scheme is analyzed by modeling and simulation using MATLAB.

## 2. DTC AND DTC-SVM STRUCTURES

Figures 1 and 2 represents two system configuration of DTC controlled PMSM drive respectively; both of them use the same flux vector and torque estimators. However, torque and flux hysteresis controllers and the switching table are replaced by a PI torque controller and a predictive calculator of vector voltage reference to be applied to stator coils of the PMSM.

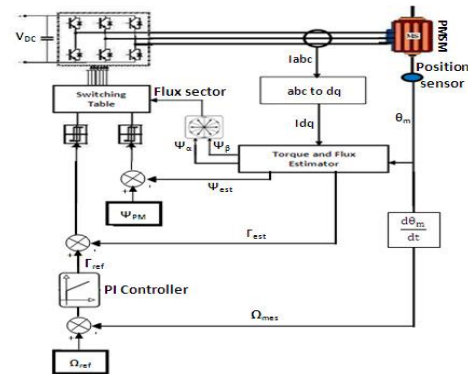


Fig.1. Basic DTC scheme for PMSM drive with speed loop

In the proposed scheme of DTC-SVM with speed loop control, shown in Figure.2, after correction of the mechanical speed through a PI controller, the torque PI controller delivers  $V_{sq}$  voltage to the predictive controller and also receives, more the reference amplitude of stator flux  $\Theta_{sr}$ , information from the torque and flux estimator namely, the amplitude and position  $\Theta_s$  of the actual stator flux and measured current vector.

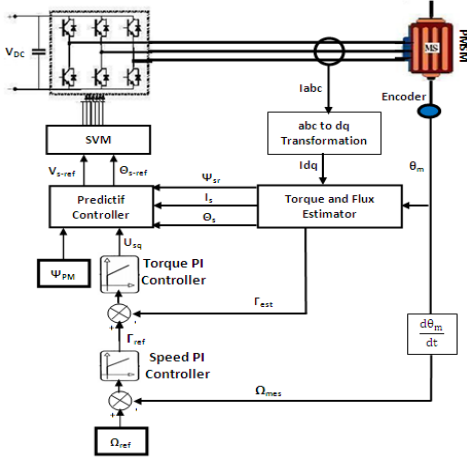


Fig.2. DTC-SVM for PMSM drive

After calculation, the predictive controller determines the polar coordinates of stator voltage command vector  $\vec{V}_{sref} = [V_{sref}, \theta_{sref}]$  for space vector modulator, which finally generates the pulses  $S_1, S_3$  and  $S_5$  to control the inverter.

### 3. MODEL OF PMSM ANALYSIS

The vector diagram of PMSM is shown in figure 3. The voltage and flux equations for a PMSM in the rotor oriented coordinates d-q can be expressed as:

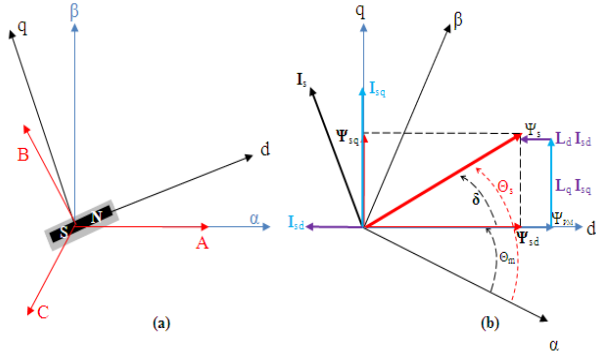


Fig.3. (a) Different coordinate of PMSM, (b) Flux, current and voltage vectors. (A-B-C) 3-phase coordinates. ( $\alpha, \beta$ ) stator oriented and ( $d, q$ ) rotor oriented coordinates.

$$U_{sd} = R_s \cdot I_{sd} + \frac{d\Psi_{sd}}{dt} - P \cdot \omega_m \cdot \Psi_{sq} \quad (1)$$

$$U_{sq} = R_s \cdot I_{sq} + \frac{d\Psi_{sq}}{dt} - P \cdot \omega_m \cdot \Psi_{sd} \quad (2)$$

$$\Psi_{sd} = L_d \cdot I_{sd} + \Psi_{PM} \quad (3)$$

$$\Psi_{sq} = L_q \cdot I_{sq} \quad (4)$$

Where  $I_{sd}$  and  $I_{sq}$  are the d - q axis stator currents,  $R_s$  is the stator resistance,  $\Psi_{PM}$  is the flux linkage of the rotor magnets linking the stator,  $L_d$  and  $L_q$  are the d - q axis stator inductances,  $p$  is the

number of pole pairs and  $\omega_m$  is the mechanical speed,  $\Psi_{sd}$  and  $\Psi_{sq}$  are d-q components of the stator flux linkage.

And the electromagnetic torque equation in the rotor oriented coordinates d-q can be expressed as:

$$\Gamma_{em} = \frac{3}{2}P(\Psi_{sd}I_{sq} - \Psi_{sq}I_{sd}) \quad (5)$$

Finally, the motion equation is expressed as:

$$J \frac{d\omega_m}{dt} = \Gamma_{em} - \Gamma_r - f_r \omega_m \quad (6)$$

Where  $J$  moment of inertia,  $\Gamma_r$  motor load and  $f_r$  damping constant. From the vector diagram of figure.3b, equations (3) and (4) we demonstrate that expression of electromagnetic torque is given by:

$$\Gamma_{em} = \frac{3}{2}P \frac{\Psi_{sr}}{L_d L_q} \left[ \Psi_{PM} L_q \sin \delta + \frac{1}{2} \Psi_{sr} (L_d - L_q) \sin \delta \right] \quad (7)$$

Above equation consist of two terms, the first is the excitation torque, which is produced by permanent magnet flux and the second term is the reluctance torque. In the case where  $L_d = L_q$ , the expression of electromagnetic torque becomes:

$$\Gamma_{em} = \frac{3}{2}P \frac{\Psi_{sr}}{L} [\Psi_{PM} \sin \delta \sin \delta] \quad (8)$$

From equation (8) we can see that for constant stator flux amplitude and flux produced by PM, the electromagnetic torque can be changed by control of the torque angle. This is the angle between the stator and rotor flux linkage, when the stator resistance is neglected. The torque angle  $\delta$ , in turn, can be changed by changing position of stator flux vector in respect to PM vector using the actual voltage vector supplied by PWM inverter [2].

In the PMSM drive, we distinguish between two cases:

- Steady state: the angle  $\delta$  is constant and its value is the load torque of the machine, while the stator flux and rotor rotate at the same speed is the synchronous speed.
- The transient state, the angle  $\Theta_s$  is variable then the stator and rotor flux rotate at different speeds (Figure.4).

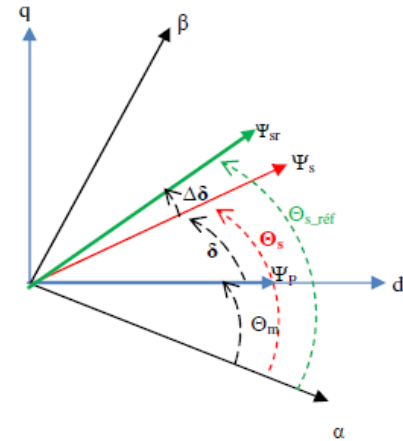


Fig.4. Vector diagram of illustrating torque and flux control conditions

The change of the angle  $\Theta_s$  is done by varying the position of the stator flux vector relative to the rotor flux vector with the vector  $\Psi_s$ -réf provided by the predictive controller to the power of the SVM.

The figure.4 above shows the evolution of the stator flux vector at the beginning and the end of a period vector modulation. At the beginning, stator flux vector is at the position  $\Theta_s$  with an amplitude  $\Psi_s$ , it's at this moment that the predictive controller calculated the variation  $\Delta\delta$  of the stator flux angle, it's also at this same moment that the space vector modulator receives the new position and amplitude of the voltage vector that must be achieved at the end of the modulation period, and of course it this vector will allow the stator flux to transit to the location as defined by the predictive controller to adjust the torque fluctuations, and this by calculating the time of application of the adjacent vectors  $V_1$ ,  $V_2$  and  $V_0$  as well as their sequence that depends on the symmetry of the modulation vector.

#### 4. COMPARISON BETWEEN THE CNVENTIONAL DTC AND DTC-SVM

The objective of the DTC is to maintain the stator flux and torque within the hysteresis bands of Regulators close to their reference values by selecting the output voltage of the inverter. And when the couple or the modulus of stator flux reaches the upper or lower limit of the hysteresis comparator, a single vector suitable voltage is applied during each sampling step to bring the quantity involved within its hysteresis band.

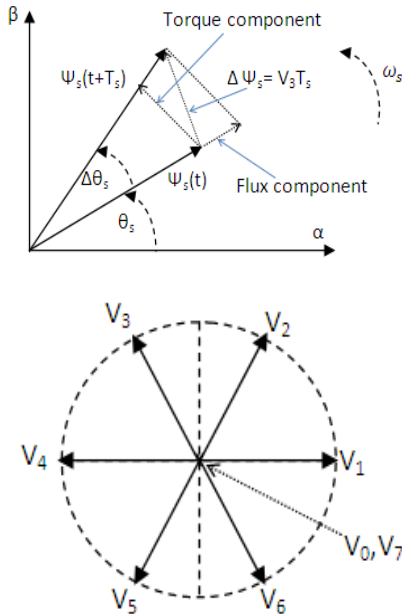


Fig.5. Stator flux vector evolution in the first sector

The stator voltage equation of PMSM is given by the vector relation:

$$V_s = R_s \cdot I_s + \frac{d\Psi_s}{dt} \quad (9)$$

The equation (9) can be represented as discrete as follows:

$$\Psi_s(k+1) - \Psi_s(k) = T_s \cdot V_s(k+1) + R_s \cdot T_s \cdot I_s(k) \quad (10)$$

If the voltage drop across the stator resistance is negligible compared with the stator voltage, while there is an interval  $[t, t+T_s]$ , the end of the vector  $\Psi_s$  moves on a straight line whose direction is given by the vector  $V_s$  selected during  $T_s$ .

Indeed, this vector with two components, one for controlling the flow and the other to control the torque.

#### 5. FLUX ESTIMATOR

The block diagram of flux estimator based on the equations (3) and (4) is shown in figure 6.

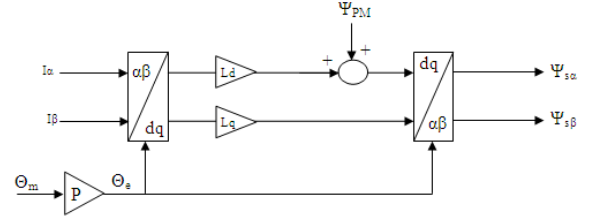


Fig.6. Current model for flux vector estimator

The estimation of flow requires the measurement of stator currents and rotor position.

#### 6. DIRECT TORQUE CONTROL WITH SVM: DTC-SVM

The block scheme of the investigated direct torque control with space vector modulation (DTC-SVM) for voltage source inverter (VSI) fed PMSM is presented in Figure.2. The internal structure of the predictive torque and flux controller is shown in Figure.7.

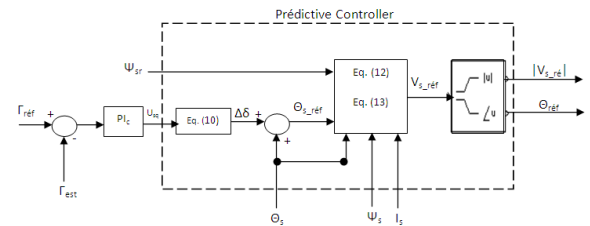


Fig.7. Internal structure of predictive controller used in DTC-SVM

From equation we can write:

$$I_{Sq} = \frac{1}{R_s} \left[ U_{Sq} - \frac{d\Psi_{Sq}}{dt} - P \cdot \omega_m \cdot \Psi_{sd} \right] \quad (10)$$

So the average change  $\Delta\delta$  of the angle  $\delta$  is calculated from equation (10) and figure.3.b, which gives:

$$\Delta\delta = T_e \frac{d}{dt} \left[ \text{Arcsin} \left( \frac{\Psi_{s,r}}{L_q I_{Sq}} \right) \right] \quad (11)$$

$T_e$  is the sampling time.

From equation (11), the relation between error of torque and increment of load angle  $\Delta\delta$  is non linear. Therefore PI controller, which generates the load angle increment required to minimize

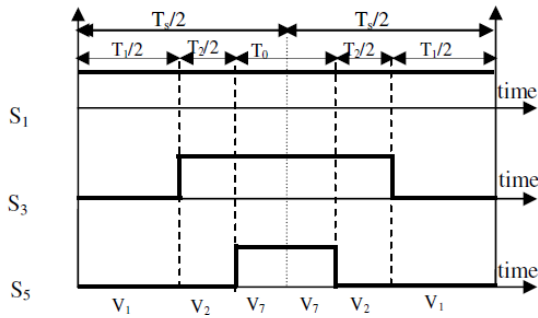
the instantaneous error between reference and actual estimated torque, has been applied [1]. The step change  $\Delta\delta$  that corresponds to the torque error is added to the current position  $\Theta_s$  of the stator flux vector to determine the new position of this vector. The module and argument of the reference vector of the stator voltage is calculated by the following equations, based on stator resistance  $R_s$ ,  $\Delta\delta$  signal, and actual flux angle:

$$V_{sref} = \sqrt{V_{s\alpha\_ref}^2 + V_{s\beta\_ref}^2}, \theta_{sref} = \arctan\left(\frac{V_{s\beta\_ref}}{V_{s\alpha\_ref}}\right) \quad (12)$$

$$V_{s\alpha\_ref} = \frac{\Psi_{s\_r} \cos(\theta_s + \Delta\delta) - \Psi_s \cos \theta_s}{T_s} + R_s \cdot I_{s\alpha} \quad (13)$$

$$V_{s\beta\_ref} = \frac{\Psi_{s\_r} \sin(\theta_s + \Delta\delta) - \Psi_s \sin \theta_s}{T_s} + R_s \cdot I_{s\beta} \quad (14)$$

The Figure.8 below shows the sequence of application of the two adjacent vectors and zero vector in the first sector of vector  $V_{s\_ref}$ . Indeed, after the vector modulation algorithm computation times  $T_1$ ,  $T_2$  and  $T_0$  successively apply the voltage vectors  $V_1$ ,  $V_2$  and  $V_0$ , we choose the symmetry in the schematic figure.8 of dividing each modulation period  $T_p$  into two sequences and transistor control of the upper arms of the VSI, in the second half of the period are an image of themselves in relation to the vertical axis passing through the point  $T_s / 2$ .



**Fig.8. Time sequences and applications of adjacent vectors in the first sector**

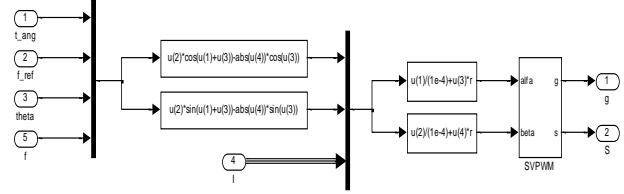
So to have a fast transit of stator flux vector, very low flux ripple and fast torque response, the space vector modulator generates a voltage vector  $V_{s\_ref}$  governed by the following law:

$$V_{s\_ref} = \frac{1}{T_s} \left[ \left( \frac{T_1}{2} V_1 + \frac{T_2}{2} V_2 + \frac{T_0}{2} V_0 \right) + \left( \frac{T_0}{2} V_0 + \frac{T_2}{2} V_2 + \frac{T_1}{2} V_1 \right) \right] \quad (15)$$

So at each modulation period and in this case, the sequence of adjacent vectors in the first sector is applied ( $V_1$ - $V_2$ - $V_0$ - $V_2$ - $V_1$ ) respectively during the time  $\left(\frac{T_1}{2}, \frac{T_2}{2}, \frac{T_0}{2}, \frac{T_0}{2}, \frac{T_2}{2}, \frac{T_1}{2}\right)$  to rebuild the better the rotating vector.

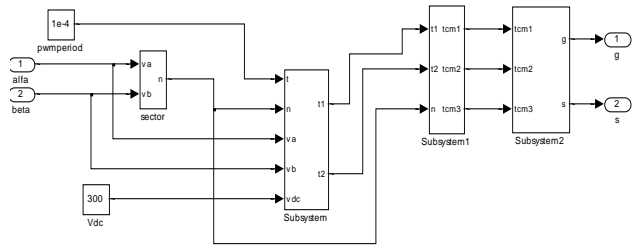
## 7. MATLAB/SIMULINK MODEL

The MATLAB Simulink model of Park's transformation which is used for 3-phase to two axis conversion is shown in Figure 9. By using this we can analyze the PMSM in D.C. analysis.

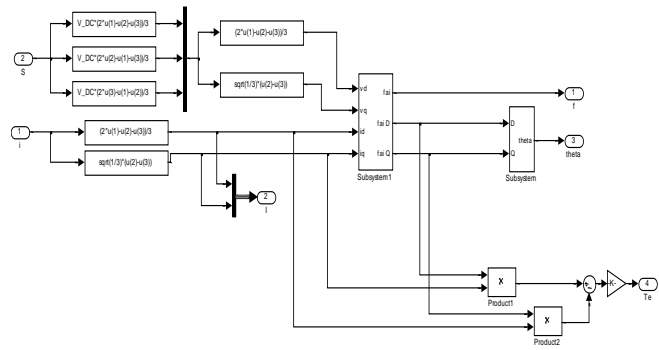


**Fig. 9 Simulink model of Park's transformation.**

The Simulink model for proposed SVM topology and also flux estimator for PMSM are shown in Figure 10. and Figure 11 respectively.



**Fig10. Simulink model of SVM topology.**



**Fig11. Simulink model of Flux Estimator**

The complete Matlab/Simulink model of proposed DTC-SVM topology for PMSM is shown in Figure 12.



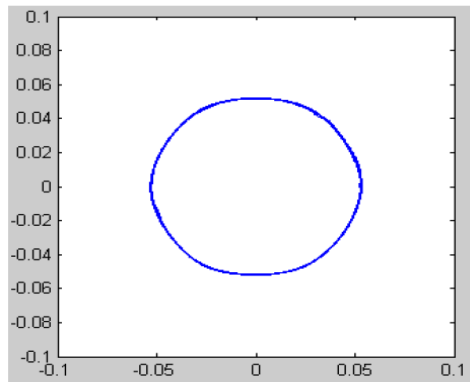


Fig17. Stator flux in ( $\alpha$ ,  $\beta$ ) axis

Table 1: PMSM model Parameters:

Rated Power	3.6 Kw
Rated phase to phase voltage	300 V
Rated phase current	12 A
Rated Speed	1500 rpm
Rated Torque ( $T_e$ )	8 N-m
Number of pole pairs (p)	4
Stator resistance ( $R_s$ )	0.95 ohm
D-axis inductance( $L_d$ )	0.0525 H
Q-axis inductance( $L_d$ )	0.0525 H
Permanent magnetic flux ( $\lambda_{PM}$ )	0.1827 Wb
Inertia moment (J)	0.000629
Viscous friction coefficient ( $B_m$ )	0.0003025

## 9. CONCLUSION

In this paper it was presented a method of utilization of Space Vector Modulation for the Direct Torque control of a PMSM. To determine the reference voltage, a simple algorithm was proposed, based on the torque error and the flux phase angle. The results show that a smooth steady state operation was obtained when using the proposed method. Moreover, a constant inverter switching frequency is ensured by using SVM topology. A modified direct torque control (DTC-SVM) with speed loop has been proposed and validated in Matlab/Simulink. The torque and flux ripples are agree with the simulation results, additionally the implementation shows that the speed and torque dynamic state is the same as the simulation results. Basic and modified DTC assure very good decoupling in torque and stator flux control.

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