

Torque and Stator Flux Ripples Minimization for Direct Torque Control of PMSM by using Space Vector Modulation

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ABSTRACT:

This paper presents a Direct Torque Control (DTC) strategy for the Permanent Magnets Synchronous Machine (PMSM). The principle relies on a Space Vector Modulation (SVM) technique that uses hysteresis comparators for the determination of the voltage module and angle, the proposed control method is simple to implement. It allows reducing the fluctuations level of the torque and the flux in low speed conditions. Contrary to the classical DTC technique, the proposed approach is able to handle and to control the switching frequency even for driving the motor with a low speed as a reference. Simulations results were obtained and allowed demonstrating better performance of this command especially in the behavior of the couple and the flux.

KEYWORDS: Permanent Magnet Synchronous Machine, DTC, SVM, Voltage Inverter, PWM.

1. INTRODUCTION

The strategy of Direct Torque Control (DTC) was proposed by Depenbrock and Takahashi for the driving of induction motors [1], [2]. Afterward, numerous research works were developed in this field [3], [4], [5] to improve the performances of this technique and to compete with Field Orientated Control (FOC) methods [6]. The current trend consists of replacing induction motors by Permanent Magnets Synchronous Machines (PMSM) which are of low costs and with a higher torque [7]. The DTC control is based on an appropriate choice of voltage vector generated by the inverter. It has several advantages compared to other conventional techniques [8, 9], which are a fast dynamic torque, robustness with respect to parameter variations, a simple control with low-cost computing efforts because the Park transformation is not necessary, and the possibility to control the torque independently from the flux. However, the switching frequency is variable and difficult to be controlled due to the use of hysteresis controllers. As a consequence, high undulations appear on the torque and the flux [10], [11], [15] and this has generated some new research interests in the field of electrical drives. In particular, several techniques have been developed in order to reduce the oscillations released by an inverter. They led to an important evolution of the control design with inverters. In this spirit, the digital Pulse Wide Modulation (PWM) has been enhanced so that the control of the static converter is directly synthesized in a digital way.

This work proposes to control the switching frequency with a Space Vector Modulation (SVM)

technique. This method is based on the representation of the voltage vector in a rotating complex frame. It has been able to improve the efficiency of flux and torque to a great quantity and due to reasons, gaining fixed switching frequency and decreasing torque and flux ripples [16]. It is referred to as a modulation and it consists of calculating the switching instants assigned to every switch of the converter [12], [13], [14]. These times of conduction are determined by introducing the notion of "average vectors of the voltage" over a period of time. Furthermore, this SVM-DTC strategy is based on the calculation of the voltage module which is related to the position (of the voltage vector) and to the errors of torque and stator flux. The module of the voltage vector is kept proportional to the error of the torque and constant outside the hysteresis band. At the same time, the angle of the voltage vector is calculated according to the errors of the flux and torque. The difference between the conventional DTC and SVM-DTC are concerns only the generation of the stator voltage vector.

This arrangement provides flexibility of operation in sub-synchronous and super-synchronous speeds in both generating and motoring modes ($\pm 30\%$ around the synchronous speed). The power inverter needs to handle a fraction (about 25 to 30%) of the total power to achieve full control of the generator.

2. MODELLING OF PMSM

Under the simplified hypotheses based on a not saturated regime, without losses and with a sinusoidal repartition of the electromagnetic forces, the model of

PMSM in the plan of Park is defined by the following equations:

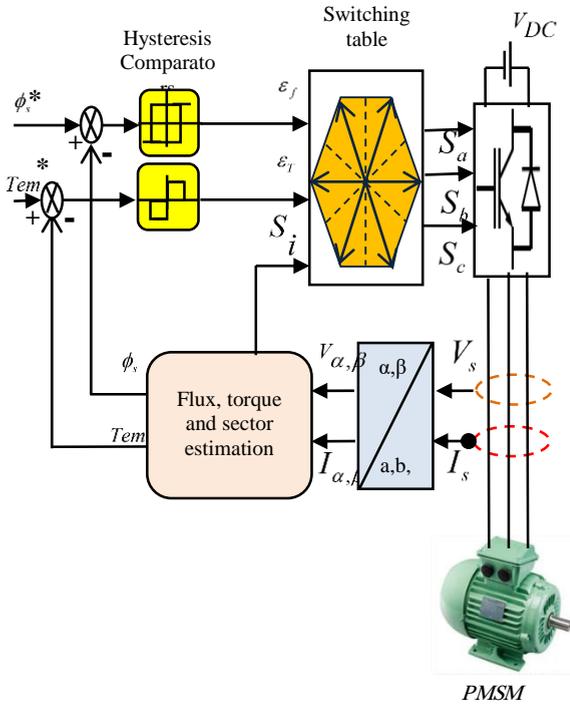


Fig. 1. The general structure of classic DTC.

2.1 Electric Equations

$$V_d = R_s I_d + \frac{d\phi_d}{dt} - \omega \phi_q$$

$$V_q = R_s I_q + \frac{d\phi_q}{dt} + \omega \phi_d$$

(1)

where
 R_s : represents stator resistance.
 I_d, I_q : represent stator current; d and q axis-components.
 V_d, V_q : represent stator voltage; d and q axis-components.
 ϕ_d, ϕ_q : represent stator flux.
 ω : represents angular speed.

2.2 Flux Equations

$$\phi_d = L_d i_d + \phi_f$$

$$\phi_q = L_q i_q$$

(2)

where L_d, L_q are direct-axis, quadrature-axis inductance and ϕ_f is permanent magnet flux

2.3 The Torque Equations

The electromagnetic torque equation is expressed as

$$T_{em} = p(L_d - L_q)I_d I_q + p\phi_f I_q$$

(3)

Where, p the number of pole pairs.

2.4 Mechanic Equation

The mechanical equation is given by:

$$\frac{d}{dt} \Omega = \frac{T_{em} - T_r - f_r \Omega}{J}$$

(4)

where $\Omega, T_r, f,$ and J represent the speed, load torque, and friction coefficient, and moment of inertia respectively.

3. PRINCIPLE OF DTC

The direct torque control of a PMSM is based on an appropriate selection of a stator voltage between the reference and actual values of the torque and stator flux [14]. In the classic version of the DTC, the generation of the PWM signals that are used to control the voltage inverter comes from a switching table. Moreover, hysteresis comparators are used for establishing the voltage vector needed to drive the flux and torque to the desired values, the general structure of classical DTC is illustrated by Fig. 1. The voltage V_s is issued by a voltage inverter whose state of switches is supposed to be perfect. This voltage is represented by three Boolean sizes of command:

$$V_s = \sqrt{\frac{2}{3}} U_0 \left[S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3} \right]$$

(5)

Where: S_a, S_b and S_c are the switching states with values 0 or 1.

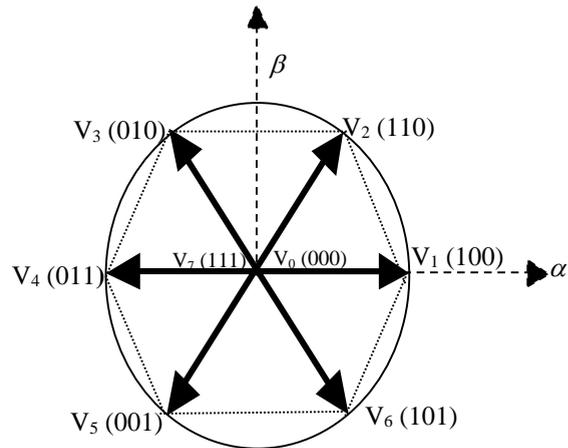


Fig. 2. Representation of the inverter voltage vector

Fig. 2 represents eight voltage vectors that can be generated by the inverter in the complex frame (α, β) .

3.1 Flux Control

The voltage module is presented by:

$$\overline{V}_S = R_S \overline{I}_S + \frac{d\overline{\varphi}_S}{dt} \quad (6)$$

From the expression of the voltage module, the stator flux can be defined by:

$$\varphi_S(t) = \int_0^t (\overline{V}_S - R_S \overline{I}_S) dt \quad (7)$$

If we suppose that the voltage drop due to the stator, resistance is neglected then the stator flux can be directly related to the stator voltage V_s according to:

$$\varphi_S(t) \approx \varphi_{s0} + \int_0^t V_S dt \quad (8)$$

Where φ_{s0} is the initial value of the flux.

During a sampling time T_e , the voltage vector applied to the machine remains constant, thus:

$$\varphi_S(k+1) \approx \varphi_S(k) + V_S T_e \quad (9)$$

Thus

$$\Delta\varphi_S = \varphi_S(k+1) - \varphi_S(k) \approx V_S T_e \quad (10)$$

This relation shows that if the sampling period is constant, the voltage vector applied to the machine is directly proportional to the stator flux. In the case of the PMSM, the stator flux changes even if we apply a zero voltage when magnets turn with the rotor. Consequently, the non-null voltage vectors are not used in the control of the flux.

3.2 Torque Control

The electromagnetic torque can be estimated from the values of the flux ($\varphi_{s\alpha}, \varphi_{s\beta}$) and the current values ($i_{s\alpha}, i_{s\beta}$):

$$T_{em} = p(\varphi_{s\alpha} i_{s\beta} - \varphi_{s\beta} i_{s\alpha}) \quad (11)$$

Where, p denotes pole pair number.

On the other hand, for the PMSM, the electromagnetic torque is proportional to the vectors of the stator flux and the rotor flux according to the following expression:

$$T_{em} = \frac{P}{L_d} \varphi_s \cdot \varphi_r \cdot \sin \gamma \quad (12)$$

Where γ is the angle between φ_s and φ_r .

From this expression, if we maintain the flux constant we can directly control the torque by changing the angle.

3.3. Voltage Vector Selection

The voltage space vector angle is represented in a frame in Fig. 3 and separated in 6 zones with an index 'i' with $i=1, 2 \dots 6$. When the vector flux is in a zone 'i', then the control of the flux and the torque is assured by selecting one of the four non-zero voltage vectors (V_1 to V_6) or one of the two zero vectors V_0 or V_7 [1], [2], [3]. The role of the selected voltage vector is described on Fig. 3. The control switching table is given by Table 1.

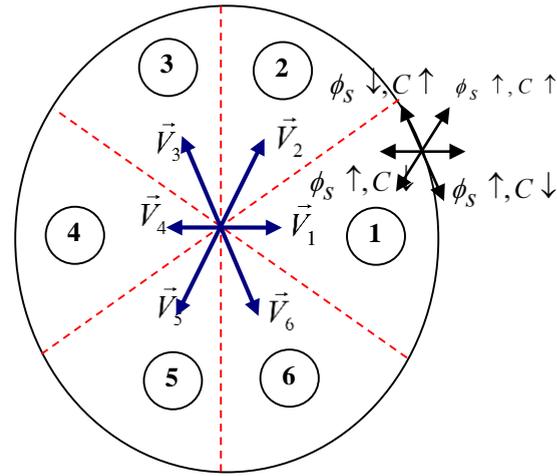


Fig. 3. The voltage space vector angle for flux and torque command.

Table 1. The control switching table of the classic DTC.

Torque	Flux	N=1	N=2	N=3	N=4	N=5	N=6
$\varepsilon_{T_{em}} = 1$	$\varepsilon_f = 1$	V_2	V_3	V_4	V_5	V_6	V_1
	$\varepsilon_f = 0$	V_3	V_4	V_5	V_6	V_1	V_2
$\varepsilon_{T_{em}} = 0$	$\varepsilon_f = 1$	V_6	V_1	V_2	V_3	V_4	V_5
	$\varepsilon_f = 0$	V_5	V_6	V_1	V_2	V_3	V_4

4. PRINCIPLE OF THE SVM-DTC

The approach of the SVM-DTC command with hysteresis comparators is based on the technique of the SVM approach. The SVM technique is used as an input of a reference voltage, i.e., a value for the module and for the angle. This strategy is centered on the determination of the module of the vector V_S according to the error of the electromagnetic couple [13], [15]. Indeed, the module of voltage vector is chosen as a maximum value if the torque is over a certain limit of the error of the torque. In addition, the module of V_S linearly decreases towards zero if the torque value is under the limit. The angle of the vector V_S is determined according to the error of the stator flux and to the electromagnetic torque. Finally, the SVM is used to determine the module and the angle of vector of

voltage to apply to the machine. This is detailed hereafter.

3.4. Determination of the Voltage Vector Module

\bar{V}_s
The module of the SVM's reference voltage vector is determined according to the error of the torque. The procedure to calculate the module of the vector is described in Fig. 4 with ΔT_{em} the limit of the error of the torque.

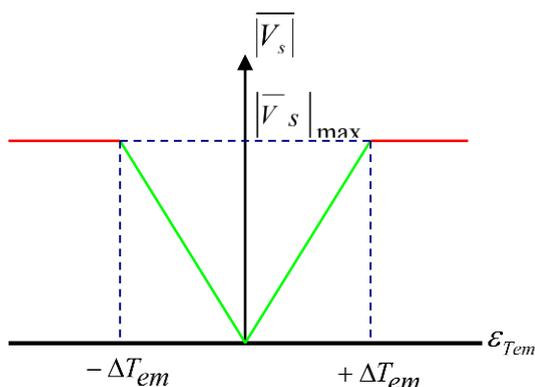


Fig.4. Determination of the voltage vector module \bar{V}_s .

We propose to use the following strategy in order to calculate the voltage vector module. Actually, it depends on one of the following cases:

- For a maximal error of the torque, the chosen voltage vector module will be maximal and constant.
- For a lower error of the torque, the module of the voltage vector will decrease gradually according to a slope as it is represented by Fig. 4. Obviously, in this case, the module of the voltage vector is proportional to the error of the torque.
- Finally, if the torque error is null, the module of the vector chosen will be either null.

We also propose to use the following value of the module of voltage vector which is the maximum voltage value that can be generated by the inverter [13]:

$$V_s = \sqrt{\frac{3}{2}} \frac{V_{DC}}{2} \quad (13)$$

4.1. Determination of the Voltage's Angle

The reference angle for the SVM is related to the flux error and at the same time to the error of the torque. Table 2 explains how to choose the angle of the voltage vector according to the outputs of hysteresis comparators of the torque and the flux in the $\alpha\beta$ -frame. Here, δ is the angle of voltage vector \bar{V}_s in the $\alpha\beta$ -frame and θ_s is the position of the stator flux.

Table 2. Selection of the angle δ of voltage vector \bar{V}_s .

Flux	0			1		
Torqu						
e	-1	0	1	-1	0	1
δ	$\theta_s - \delta_d$	$\theta_s + \pi$	$\theta_s + \delta_d$	$\theta_s - \delta_a$	θ_s	$\theta_s + \delta_a$

4.3. Generation of the States of the Inverter's Switches

The switching states S_a , S_b and S_c for the three branches a, b and c of the inverter are obtained from the voltage vector, its module $|\bar{V}_s| = f(\varepsilon_{Tem})$ and its angle θ_s by using an algorithm defined by the following steps [2]:

- a) Calculation the biphasic components of the desired voltage vector by using the following equations:

$$\begin{cases} V_{s\alpha} = V_s \cos(\theta_s) \\ V_{s\beta} = V_s \sin(\theta_s) \end{cases} \quad (14)$$

- b) Calculation of the position, i.e., the i -th zone of the voltage vector that must be generated.

- c) Determination of the switching states T_K and T_{K+1} for the voltage vector V_K and V_{K+1} and their operating cycle ; calculating the operating cycle of the non-zero switching vector T_0 is achieved by using the following expression [14]:

$$\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} = \frac{T_e \sqrt{2}}{2V_{DC}} \begin{bmatrix} \sin(\frac{k}{3}\pi) & -\cos(\frac{k}{3}\pi) \\ -\sin(\frac{k-1}{3}\pi) & \cos(\frac{k-1}{3}\pi) \end{bmatrix} \begin{bmatrix} V_{ref\alpha} \\ V_{ref\beta} \end{bmatrix} \quad (15)$$

Where, $T_0 + T_K + T_{K+1} = T_e / 2$, T_k is the time of the voltage vector \bar{V}_k , T_{k+1} is the time of the voltage vector \bar{V}_{k+1} , T_0 is the time of the voltage vectors \bar{V}_0 , and \bar{V}_7 . T_e is the sampling period of the digital process.

- d) Calculation of the relative position of the clock (PRH) in the sampling time by using the following equation with $rem(x)$ the remainder after division:

$$PRH = rem(t/T_e) / T_e \quad (16)$$

The value of the PRH allows obtaining the components of S_a , S_b and S_c according to the following routine:

- If $PRH < t_0/4$ then the switching vector is $V_0(0\ 0\ 0)$.
- If not, if $PRH < t_0/4 + t_1/2$ then the switching vector is V_k
- If not, if $PRH < t_0/4 + (t_1 + t_2)/2$ then the switching vector is V_{k+1} .
- If not, if $PRH < 3t_0/4 + (t_1 + t_2)/2$ then the switching vector is $V_7(1\ 1\ 1)$.
- If not, if $PRH < 3t_0/4 + t_1/2 + t_2$ then the switching vector is V_{k+1} .
- If not, if $PRH < 3t_0/4 + t_1 + t_2$ then the switching vector is V_k .
- If not, switching vector is $V_0(0\ 0\ 0)$.

Here V_k , and V_{k+1} , are the voltages that define a sector.

4.4. General Structure of the SVM-DTC

The general structure of the SVM-DTC is represented by Fig. 5. Here, the switching table is replaced by a SVM modulator. The outputs of the two comparators of torque, and the stator flux amplitude, and the angle of stator flux vector are used for determining the amplitude and the angle of the reference voltage that are fed into the SVM block to generate the switching states.

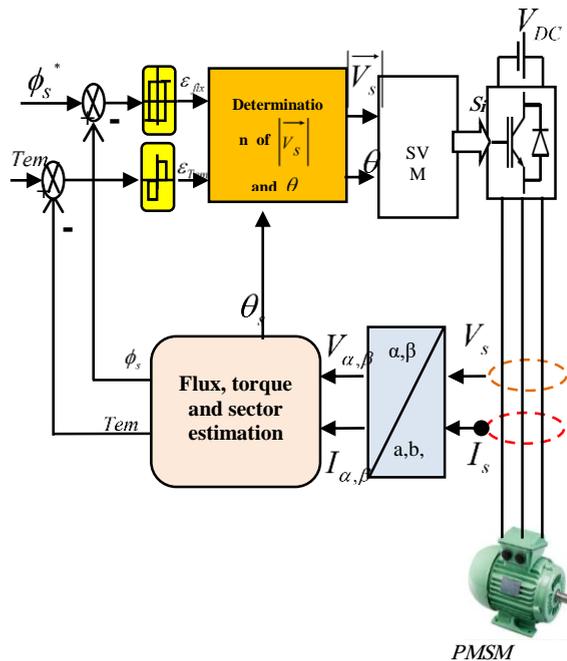


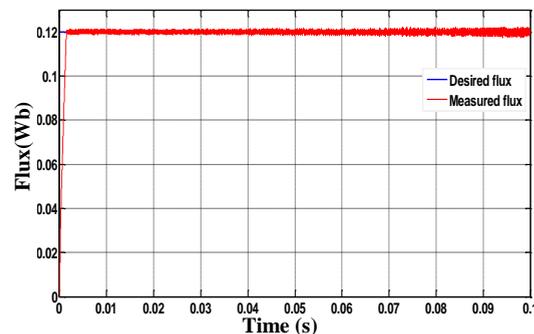
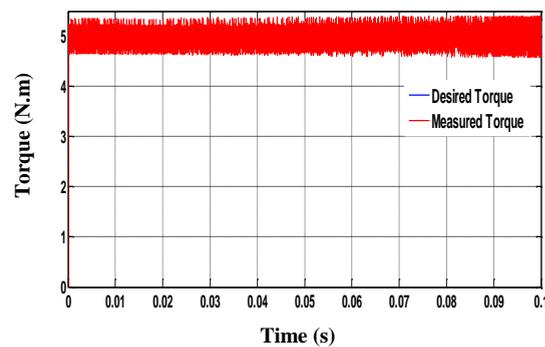
Fig. 5. The general structure of the SVM- DTC.

5. RESULTS AND SIMULATION

The DTC command was applied to the PMSM and has been evaluated by simulation tests. The numerical values of the parameters are given in Table 3. Simulation tests have been executed by using the Matlab/Simulink software. Both methods the classic DTC and the SVM-DTC have been used in order to provide some comparisons. Comparative simulations results are illustrated in Fig. 6. a and Fig. 6.b. It can be seen that the ripples of the torque and the stator flux are always inside the bands of the hysteresis comparator and the responses of these control variables are faster and with few ripples compared to the classic DTC. On the other hand, the SVM-DTC command presents a constant switching frequency. In addition, the SVM-DTC's response time is shorter; its torque and flux ripples are lower and the stator current has very low ripples compared to those obtained with the classic DTC.

Table. 3. The PMSM motor parameters.

Parameters	Value	Unit
Nominal power (P)	1.1	KW
Stator voltage (V)	220	V
Stator frequency (f)	50	Hz
Number of pairs poles (p)	4	
Permanents magnet flux linkage (ϕ_f)	0.12	Wb
Stator resistance (R_s)	0.6	Ω
Direct-axis inductance (L_d)	1.4	mH
Quadrature-axis inductance (L_q)	2.8	mH
Friction coefficient (F)	0.0014	N.m.s/rad
Moment of Inertia (J)	0.0011	Kg.m ²



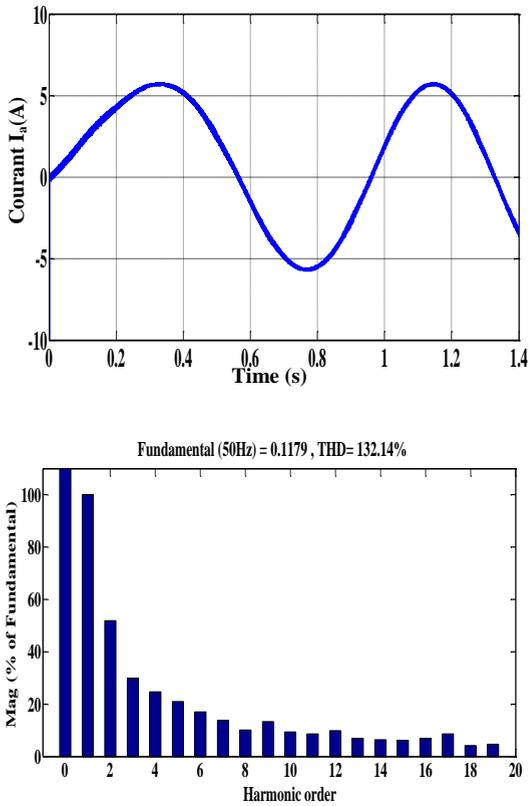


Fig. 6.a. Simulation results with the DTC Classic of PMSM.

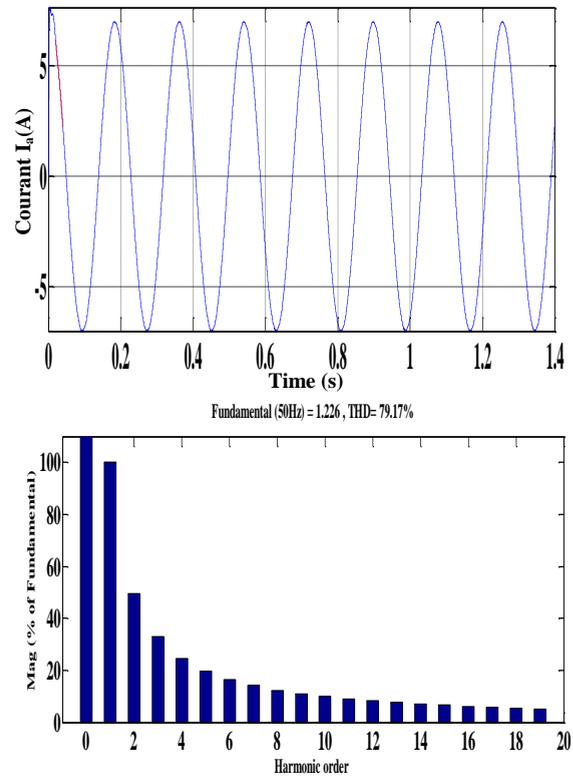
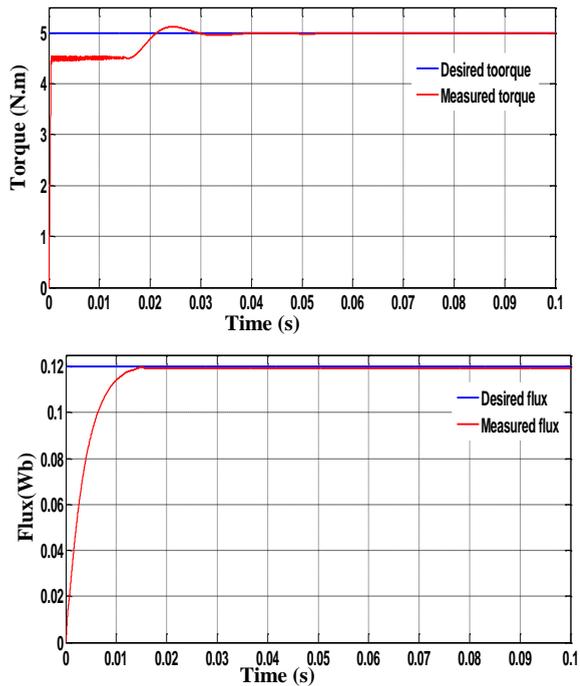


Fig. 6.b Simulation Results with the DTC-SVM of PMSM.



6. CONCLUSION

A new strategy of the direct torque control based on a space vector modulation (SVM) with a hysteresis comparator has been presented in this paper. This technique is characterized by a constant switching frequency. The original contribution of this work comes from the module value of the voltage vector which is calculated from the error of the torque and from the angle of the vector which is calculated according to the output of the hysteresis comparators of the torque and the flux. Finally, the strategy of the new SVM-DTC allows reducing the ripples of switching of the inverter, reducing the oscillations of the torque and the stator flux, and improving the overall performances of the classic DTC.

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