SMC based DTC-SVM control of five-phase permanent magnet synchronous motor drive

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ABSTRACT

This article presents an improved Direct Torque Control (DTC) technique with space vector modulation (SVM) for a five-phase permanent magnet synchronous motor (PMSM) using a sliding mode speed control (SMC). The proposed control scheme of the five-phase PMSM combines the advantages of SMC control and the SVM algorithm. The SMC method insensitive to uncertainties, in particular external disturbances and parameter variations. In this paper, the SMC controller is used to control the rotor speed of the five-phase PMSM based on DTC-SVM. The rotor speed response, torque and stator flux are determined and compared with traditional control method. The simulations results confirm the validity and effectiveness of the proposed control technique in terms of performance and robustness against machine parameter variations (inertia variation). The efficiency of the proposed method applied on the five-phase PMSM is verified by the MATLAB/Simulink.

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1. INTRODUCTION

The Multiphase machines (MPMs) have more advantages compared to the 3 phase machines like stable speed response, low torque pulsations and high output power rating [1, 2]. MPMs have gained attention in numerous fields of applications such as automobiles, ship propulsion and the wind energy conversion system [3, 4]. Direct torque control is the most important method used nowadays. The DTC strategy was first proposed for the induction motor (IM) in 1985 by Takahashi et al. [5]. The basic idea of this technique is a direct command of the stator flux and torque of IM without any pulse width modulation (PWM) strategy and proportional-integral (PI) controllers. However, this method is a simple structure compared to the field-oriented control (FOC) strategy and Scalar Control (V/f) [6, 7]. In this method, the switching table is used to control the inverter. On the other hand, the DTC method has many advantages, the fast dynamic response, lower parameter dependency, and reliability. But, the principal drawbacks, is the stator flux and torque ripples [8, 9]. More recently, from the traditional DTC methods a new control technique called DTC with SVM has been developed. In [10], the DTC method was proposed based on SVM to command IM drive by using two PI controllers. In [11], the authors propose a variable speed control of PMSM using SVM-based DTC by employing using Ultra Sparse Matrix Converter (USMC). In this work the structures of DTC with switching table (DTC-ST) and the DTC with SVM of the five-phase PMSM have been presented. Traditional speed control structures which include PI regulator for application to an MPMs have some disadvantages such as parameter tuning complications, mediocre dynamic performances and reduced robustness [12, 13]. In [14], the authors propose a four-level DTC strategy with the ANN controller by using neural PI controller of speed. In [15], a modified DTC-SVM with the enhancements of fuzzy logic control and closed loop stator flux estimation is presented. In this paper, we apply the sliding mode speed control (SMC) on the five-phase PMSM controlled by the DTC method using the SVM technique. This proposed control scheme is a simple method and minimizes the stator flux and torque ripple compared to conventional DTC. On the other hand, this proposed method is easy to implement and robust.

2. MODEL OF FIVE-PHASE PMSM

The five-phase PMSM stator voltage equation can be expressed in a rotating *d-q-x-y* frame as follows [16, 17]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{d}{dt}\Phi_{ds} - w_r \Phi_{qs} \\ v_{qs} = R_s i_{qs} + \dfrac{d}{dt}\Phi_{qs} + w_r \Phi_{ds} \\ v_{xs} = R_s i_{xs} + \dfrac{d}{dt}\Phi_{xs} \\ v_{ys} = R_s i_{ys} + \dfrac{d}{dt}\Phi_{ys} \\ v_{0s} = R_s i_{0s} + \dfrac{d}{dt}\Phi_{s0} \end{cases} \tag{1}$$

Where v_{ds}, v_{qs}, v_{xs} and v_{ys} are the stator voltages in the *d-q-x-y* axis, i_{ds}, i_{qs}, i_{xs} and i_{ys} are the stator currents in *d-q-x-y*, R_s is the stator resistance.

$$\begin{cases} \Phi_{ds} = L_d i_{ds} + \phi_f \\ \Phi_{qs} = L_q i_{qs} \\ \Phi_{xs} = L_{ls} i_{xs} \\ \Phi_{ys} = L_{ls} i_{ys} \\ \Phi_{s0} = L_{ls} i_{0s} \end{cases} \tag{2}$$

Where L_d, L_q and L_{ls} are inductances in the rotating frame.

The electromagnetic torque can be obtained as follows:

$$T_e = \frac{5}{2} P((L_d - L_q) i_{ds} i_{qs} + \phi_f i_{qs}) \tag{3}$$

Mechanical motion equations are given by:

$$J_m \frac{dw_r}{dt} = p\ T_e - p\ T_r - f_m w_r \tag{4}$$

With J_m is the inertia coefficient, f_m is the viscous damping, P is the number of poles pairs, and T_r is the external load torque.

3. DIRECT TORQUE CONTROL WITH SWITCHING TABLE

In the conventional DTC, the stator flux amplitude ϕ_s^* and the electromagnetic torque T_e^* are the reference signals which are compared with the estimated ϕ_s and T_e values respectively in the stationary frame. The flux, torque errors and stator flux position are the inputs of switching Takahashi Table to deliver an appropriate voltage vector to the inverter.

The stator flux linkages components in the stationary reference frame can be estimated by [16]:

$$\begin{cases} \Phi_\alpha = \int (v_\alpha - R_s i_\alpha) dt \\ \Phi_\beta = \int (v_\beta - R_s i_\beta) dt \end{cases} \quad (5)$$

The stator flux amplitude and phase are expressed using Concordia quantities, as follows:

$$\begin{cases} \Phi_s = \sqrt{\Phi_\alpha{}^2 + \Phi_\beta{}^2} \\ \theta_s = \tan^{-1} \dfrac{\Phi_\beta}{\Phi_\alpha} \end{cases} \quad (6)$$

The electromagnetic torque can be expressed in terms of stator current and flux as:

$$T_e = \frac{5}{2} p(\Phi_\alpha i_\beta - \Phi_\beta i_\alpha) \quad (7)$$

In DTC-ST control structure three control loops are applied: the control loop for motor angular speed with PI controller, the control loop for magnitude of the stator flux vector with hysteresis controller and the control loop for electromagnetic torque with hysteresis controller. The appropriate stator voltage vectors are chosen from the switching table which is presented in Table 1. In this control system only the long voltage vectors have been used.

Table 1. Optimum active voltage vector look-up table

		N=1	N=2	N=3	N=4	N=5	N=6	N=7	N=8	N=9	N=10
$d\phi$=1	dT=1	V_{24}	V_{28}	V_{12}	V_{14}	V_6	V_7	V_3	V_{19}	V_{17}	V_{25}
	dT=0	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}
	dT=-1	V_{17}	V_{25}	V_{24}	V_{28}	V_{12}	V_{14}	V_6	V_7	V_3	V_{19}
$d\phi$=0	dT=1	V_{14}	V_6	V_7	V_3	V_{19}	V_{17}	V_{25}	V_{24}	V_{28}	V_{12}
	dT=0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0
	dT=-1	V_7	V_3	V_{19}	V_{17}	V_{25}	V_{24}	V_{28}	V_{12}	V_{14}	V_6

The advantages of DTC method are as follows: structure independent on rotor parameters, no coordinate transformation, no current control loops. The disadvantages of classical DTC are: high switching losses provide by variable switching frequency, difficult implementation due to high sampling frequency (25μs).

4. DIRECT TORQUE CONTROL WITH SPACE VECTOR MODULATION

The traditional DTC algorithm is based on the instantaneous values and directly calculated the digital control signals for the inverter. DTC-SVM methods are based on averaged values, whereas the switching signals for the inverter are calculated by space vector modulator. This is the main difference between classical DTC and DTC-SVM control methods.

For the five-phase Voltage Source Inverter the total number of the state combinations of inverter switches is equal to 2^5=32. In the set of all generated voltage vectors, thirty active vectors and two zero vectors can be identified [18]. The active switching vectors are divided in to three groups; small, medium and large switching vectors. Stator voltage space vectors generated by the five-phase VSI in the coordinate system α-β are presented in Figure 1 (a) and in the coordinate system x-y are presented in Figure 1 (b).

It can be observed from Figure 1 that medium length space vectors of the α-β plane are mapped into medium length vectors in the x-y plane and large vectors of the α-β plane are mapped into small vectors in the x-y plane, and vice-versa [18].

In the applied SVM method the reference voltage vector lying in the considered sector is synthesized by using the appropriate switching times of two long and two medium voltage vectors, chosen from the same sector and of two zero voltage vectors. The case when the reference voltage vector V_s^* is situated in sector 1 has been presented in Figure 2. In this case the reference voltage vector is synthesized with using: two long voltage vectors: V_{25}, V_{24} two medium voltage vectors: V_{16}, V_{29} and two zero voltage vectors: V_0, V_{31}.

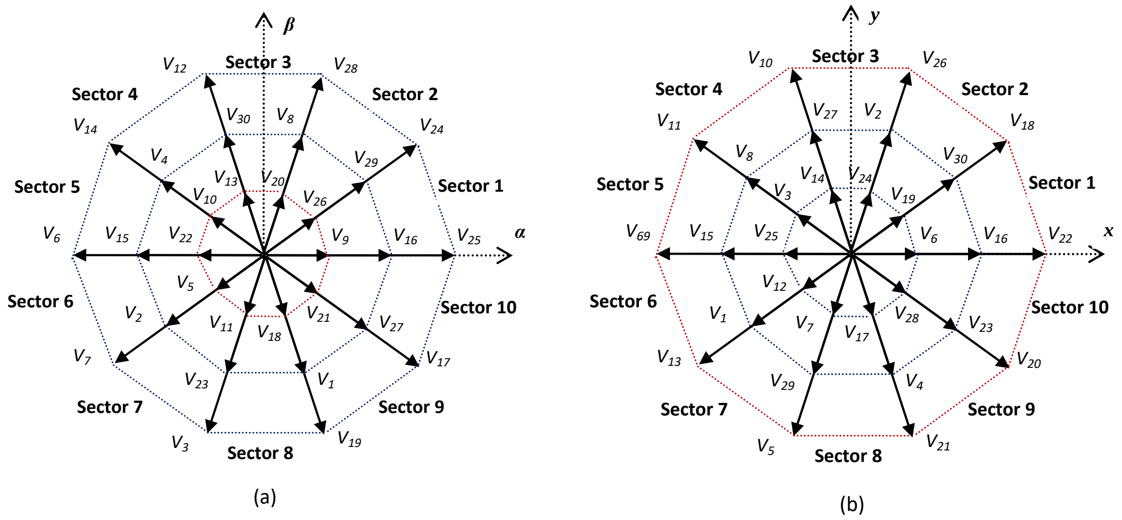

Figure 1. Voltage space vectors generated by the 5-phase VSI in coordinate systems: (a) *α-β* subspace, (b) *x-y*

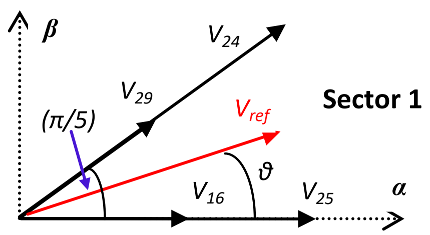

Figure 2. The principle of space vector modulation of 5-phase VSI

Switching times of individual voltage vectors are calculated as follows [18]:

$$\begin{cases} T_{am} = \dfrac{\left|0.2764V_{ref}\right|\sin\left(k\pi/5-\theta\right)}{\left|V_m\right|\sin\left(\pi/5\right)}T_s \\ T_{al} = \dfrac{\left|0.7236V_{ref}\right|\sin\left(k\pi/5-\theta\right)}{\left|V_l\right|\sin\left(\pi/5\right)}T_s \\ T_{bm} = \dfrac{\left|0.2764V_{ref}\right|\sin\left(\theta-(k-1)\pi/5\right)}{\left|V_m\right|\sin\left(\pi/5\right)}T_s \\ T_{bl} = \dfrac{\left|0.2764V_{ref}\right|\sin\left(\theta-(k-1)\pi/5\right)}{\left|V_l\right|\sin\left(\pi/5\right)}T_s \end{cases} \tag{8}$$

The dwell time equations used to describe the SVM algorithm in a sector *k* can be written as:

$$T_0 = T_s - \left(T_{am} + T_{al} + T_{bm} + T_{bl}\right) \tag{9}$$

where: T_{al}, T_{bl} switching times of long voltage vectors; T_{am}, T_{bm} switching times of medium voltage vectors; T_0 switching time of zero voltage vectors; V_{ref} magnitude of the reference voltage vector; T_s switching period; θ the angle of position of reference voltage vector; *k* number of sector.

Figure 3 shows the block diagram of the DTC-SVM in a five-phase PMSM.

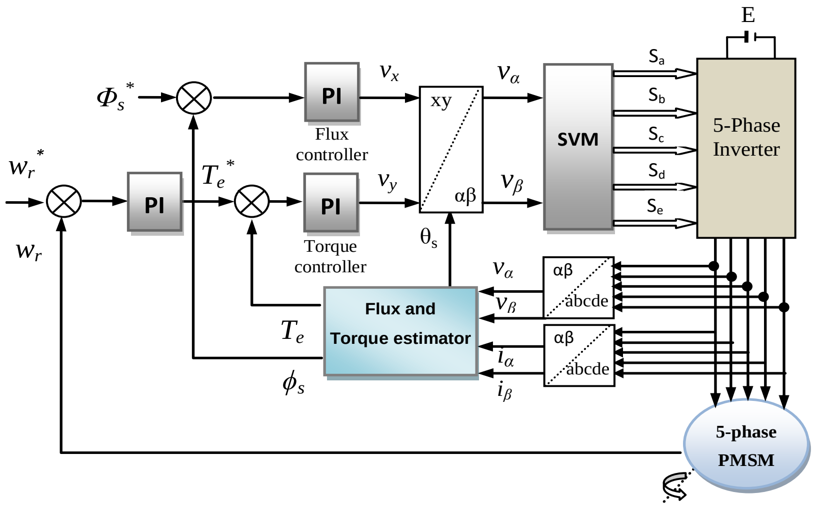

Figure 3. DTC-SVM control system of five-phase PMSM

In this scheme there are two proportional integral (PI) type controllers instead of hysteresis band regulate the torque and the magnitude of flux. The SVM unit produces the inverter control receives the reference voltages in a stator flux reference frame. The SVM principle is based on the switching between two adjacent active vectors and a zero vector during one switching period.

5. THE SLIDING MODE SPEED CONTROL

The approach of the SMC is based on the discontinuous function of state variables in the system that is used to create a “sliding surface”. When this surface is reached, the discontinuous function guarded the trajectory on the surface of such so that the desired system dynamics is obtained [19, 20]. One considers the system described by the following state space equation:

$$[\dot{X}] = A[X] + B[U] \tag{10}$$

With $[X] \in R^n$, is the state vector; $[U] \in R^m$ is the control input vector; $[A]$ and $[B]$ are system parameter matrices. The first phase of the control design consists of choosing the number of the switching surfaces *S(x).* Generally this number is equal the dimension of the control vector $[U]$. In order to ensure to convergence of the state variable *x* to its reference value *x**, [21] proposes a general function of the switching surface:

$$S(x) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(x) \tag{11}$$

Here, *e(x) = x*-x is* the tracking error vector, λ is a positive coefficient and *n* is the relative degree.

The second phase consists to find the control law which meets the sufficiency conditions for the existence and reachability of a sliding mode such as

$$S(x)\dot{S}(x) < 0 \tag{12}$$

So that the state trajectory be attracted to the switching surface *S(x) = 0*. A commonly used from of U_n is a constant relay control.

$$U_n = K_x \operatorname{sgn}(S(x)) \tag{13}$$

sgn(S(x)) is a sign function, which is defined as

$$\operatorname{sgn}(S(x)) = \begin{cases} -1 & if\ S(x) < 0 \\ 1 & if\ S(x) > 0 \end{cases} \tag{14}$$

k_x is a constant.

This introduces some undesirable chattering. Hence, one will substitute it by the function smooth [22-24].

$$U_n = K_x \frac{S(x)}{|S(x)| + \xi_x} \tag{15}$$

ξ_x is small positive scalar.

The sliding surfaces are chosen according to (4) as follows:

$$S(w_r) = w_r^* - w_r \tag{16}$$

Based on the proposed switching surface, the speed control laws are:

$$i_q^* = \frac{J_m \dot{w}_r^* + pT_r + f_m w_r}{\frac{5}{2} p\left((L_d - L_q) i_{ds} + \phi_f\right)} + \frac{S(w_r)}{|S(w_r)| + \xi_{wr}} \tag{17}$$

The bloc diagram of the sliding mode speed control of the five-phase PMSM is given by Figure 4.

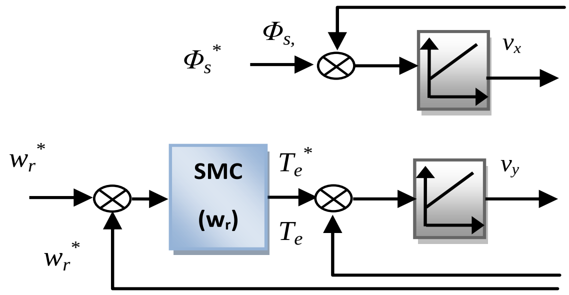

Figure 4. Block diagram of the sliding mode speed control

6. SIMULATION RESULTS AND DISCUSSION

In order to verify the effectiveness of the proposed scheme, simulations were carried out using Matlab/Simulink. The parameters of five-phase PMSM are as follows: R_s = 0.7 Ω, P=2, ϕ_f =0.5 web, f_m = 0.005 Nm/rad.s^{-1}, J_m = 0.0025 Kg/m^2, L_d = 0.0018 H and L_q = 0.0042 H [25].

In the objective to evaluate the performances of the control strategy, two categories of tests have been realized: sensitivity to the load torque variation and robustness (inertia variation).

Figure 5 show the responses of the five-phase PMSM under a sudden change in load torque from 0 Nm to 10 Nm at t = 0.2s, after that the load torque is returned to 0Nm at t=0.6s. In this test, the reference speed is step changed from 100 rad/s to -100 rad/s at t=0.8s. The speed response is shown in Figure 5 (a). The torque response for a step change of the load torque is shown in Figure 5 (b). The $\Phi_{\alpha\beta}$ curves in the DTC-ST and the DTC-SVM with SMC based speed controller are shown in Figure 5 (c). This figure express that the effect produced by the load torque variation is very clear on the speed curve of the system with PI controller, while the effects are almost negligible for the system with the SMC. It can be noticed that these last have a nearly perfect speed disturbance rejection (less than 2%). While Figure 5 (b) it's clear that DTC-SVM is able to reduced ripples level in torque compared with conventional DTC. In Figure 5 (c) the Lucas of stator flux is improved with very low ripple as compared with DTC-ST.

In order to test the robustness of the used controllers, the machine inertia has been doubled. The results presented in Figure 6 show that inertia variation presents a clear effect on the speed responses of all used PI controllers and that the effect appears more significant for DTC-ST than that with the DTC-SVM with SMC based speed controller for the five-phase PMSM. Thus it can be concluded that these last are robust against this parameter variation.

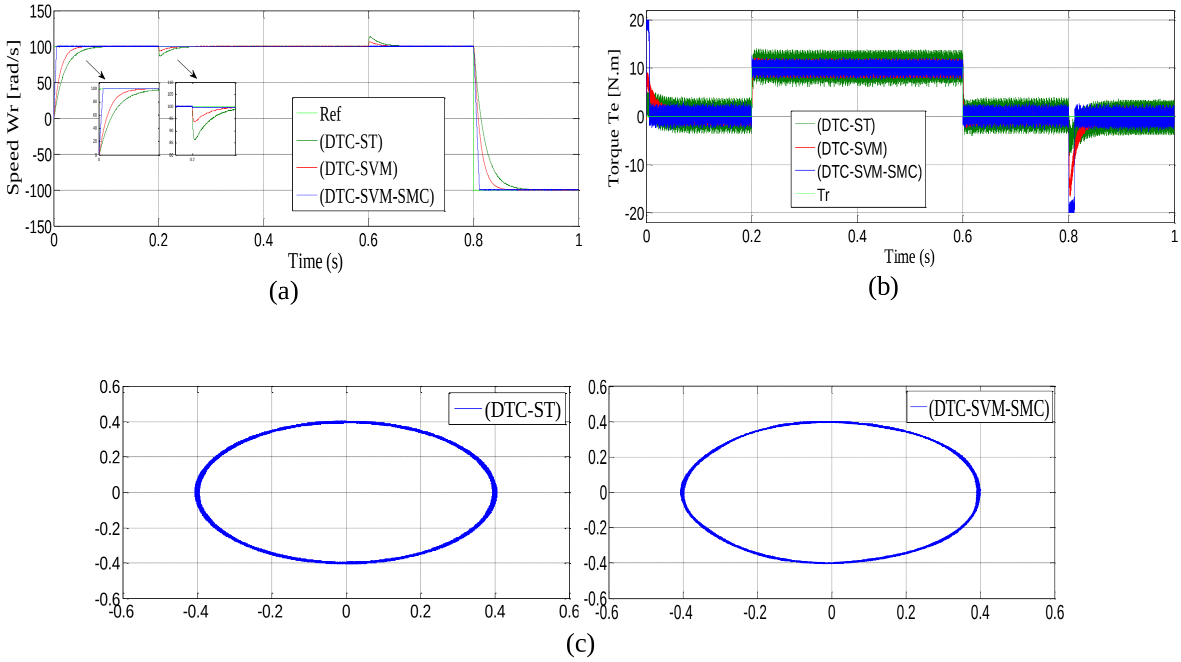

Figure 5. Dynamic responses of five-phase PMSM controlled by DTC-ST, DTC-SVM and DTC-SVM-SMC: (a) Rotor speed response, (b) Torque response, (c) Stator flux trajectory in α-β axis

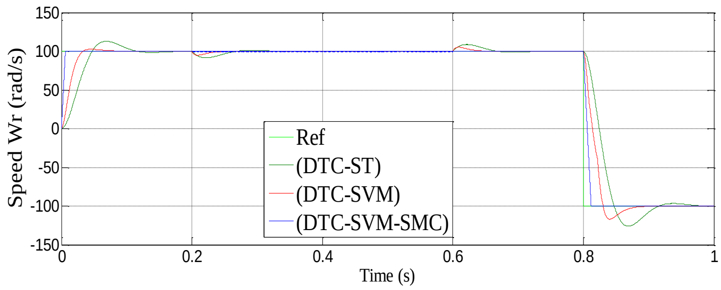

Figure 6. Robustness test (J_m =2*J_m)

7. CONCLUSION

In this work, we presented the DTC technique based on the SVM algorithm for a five-phase PMSM using a sliding mode speed control. With results obtained from the simulation, it was clear that for the similar operation conditions, the proposed method presents high-quality performance compared to the traditional DTC method. The SMC can be considered as more robust under loads variations, minimizing the rise time and a very high robustness against machine parameter variations compared with the same results obtained for the traditional DTC system and DTC-SVM with PI based speed controller. For future works, it will be interesting to apply our proposed method in the default operating mode and set up a prototype in the lab to perform the experimental validation.

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