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Direct Torque Control of Inverter Fed PMSM Drive using SVM

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ABSTRACT

PMSM is widely used in servo-drive applications because of its advantages such as high efficiency, high power density and torque/inertia ratio and maintenance free. However, there still exist challenges to design position-sensor less vector control of PMSM operating in a wide speed range, which covers both constant-torque and constant-power region. The DTC technique has been recognized as viable and robust solution to achieve these requirements. Direct Torque Control of permanent magnet synchronous motor (PMSM) is one of the widely used methods for the speed control of the motor. The feasibility and effectiveness of Space Vector pulse width modulation technique implemented for PMSM are addressed in this paper and verified by computer simulation. The whole drive system is simulated in MATLAB/SIMULINK based on the mathematical model of the system devices including PMSM and inverter. The aim of the drive system is to have speed control over wide speed range. Simulation results show that the speed controller has a good dynamic response.

Keywords: Permanent Magnet Synchronous Motor, Direct Torque Control, Space Vector Pulse-width Modulation.

1. INTRODUCTION

Modern electrical drive systems consist of power electronics components, transformers, analog/digital controllers and sensors or observers. The improvements in the semiconductor power electronic components have enabled advanced control techniques with high switching frequency and high efficiency. Complex control algorithms have been widely used and got simplified in drivers due to the developments in software technology [3]. DC, asynchronous and synchronous motors are frequently used motor types with these driver systems. New kinds of motors are developed like linear motors, step motors, switched reluctance motors, and permanent magnet synchronous motors. Permanent magnet synchronous motors are used where in general high demands are made with regard to speed stability and the synchronous operation of several interconnected motors [1]. They are suitable for applications where load-independent speeds or synchronous operation are required under strict observance of defined speed relations within a large frequency range [2].

As the technology gets improved, studies on PMSM such as direct torque control method have been improved as well. DTC has many advantages such as faster torque control, high torque at low speeds, and high speed sensitivity. The main idea in DTC is to use the motor flux and torque as basic control variables, identical to the DC drives [5].

This paper presents a nonlinear model of PMSMs which incorporates both the structural and saturation saliencies to enable the numerical simulation of new rotor position detection. In this model, the self and mutual differential inductances of the phase windings are expressed as functions of the rotor position and stator current. Based on the model, the direct torque control (DTC) scheme is simulated within the MATLAB/ SIMULINK environment.

2. MATHEMATICAL MODELING

The voltage equations for the permanent magnet motor in rotor reference frame are

$$v_{qs} = r_a i_{qs} + l_{qs} p i_{qs} + l_{aq} p i_{qr} + \omega_r l_{ds} i_{ds} + \omega_r l_{ad} i_{dr} + \omega_r \psi \quad \text{--- (1)}$$

$$v_{ds} = r_a i_{ds} + l_{ds} p i_{ds} + l_{ad} p i_{dr} - \omega_r l_{qs} i_{qs} - \omega_r l_{aq} i_{qr} \quad \text{--- (2)}$$

$$v_{qr} = r_{qr} i_{qr} + l_{qr} p i_{qr} + l_{aq} p i_{qs} \quad \text{--- (3)}$$

$$v_{dr} = r_{dr} i_{dr} + l_{dr} p i_{dr} + l_{ad} p i_{ds} \quad \text{--- (4)}$$

Where, ψ- air gap flux linkage

The eqn. (1) can be rewritten as

$$v'_{qs} = (v_{qs} - \omega_r \psi) = r_a i_{qs} + l_{qs} p i_{qs} + l_{aq} p i_{qr} + \omega_r l_{ds} i_{ds} + \omega_r l_{ad} i_{dr} \quad \text{--- (5)}$$

The electrical torque developed is

$$T_e = \frac{3}{2}\frac{P}{2}\left[(l_{ad} - l_{aq})i_{qs}i_{ds} + l_{ad}i_{qs}i_{dr} - l_{aq}i_{qr}i_{ds} + \psi i_{qs}\right] \quad \text{--- (6)}$$

The torque balance equation is

$$\frac{2}{P}jp\omega_r = T_e - T_l - \frac{2}{P}\beta\omega_r \quad \text{--- (7)}$$

Where all voltages (v) and currents (i) refer to the rotor reference frame. The subscripts qs, ds, qr and dr correspond to q and d axis quantities for the stator(s) and rotor(r) in all combinations, r_a denotes the armature resistance, l_{qs} denotes quadrature axis inductance, l_{ds} denotes direct axis inductance etc. and T_e is the developed torque. The rotor speed is given by ω_r and the load torque by T_l. J is moment of inertia, P is the number of poles and β is the co-efficient of viscous friction. The derivative operator is represented by the symbol *p*.

Representing the voltage eqns. (1)-(5) into a state space representation as given below:

$$\begin{bmatrix} v'_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_a & \omega_r l_{ds} & 0 & \omega_r l_{ad} \\ -\omega_r l_{qs} & r_a & -\omega_r l_{aq} & 0 \\ 0 & 0 & r_{qr} & 0 \\ 0 & 0 & 0 & r_{dr} \end{bmatrix} . \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} l_{qs} & 0 & l_{aq} & 0 \\ 0 & l_{ds} & 0 & l_{ad} \\ l_{aq} & 0 & l_{qr} & 0 \\ 0 & l_{ad} & 0 & l_{dr} \end{bmatrix} . \begin{bmatrix} pi_{qs} \\ pi_{ds} \\ pi_{qr} \\ pi_{dr} \end{bmatrix} \quad \text{--- (8)}$$

3. DIRECT TORQUE CONTROL (DTC) OF PMSM

There are two control methods used for the PMSM; field oriented control and direct torque control. The AC drives using field oriented control (FOC) in which field control leads to flux control. Here, rotor flux space vector is calculated and controlled by using the angular velocity which is derived from the speed feedback and the stator current vector. The greatest drawback of the flux vector control is the need for a tachogenerator or an encoder for high accuracy. This indeed/need definitely increases the cost of the system.

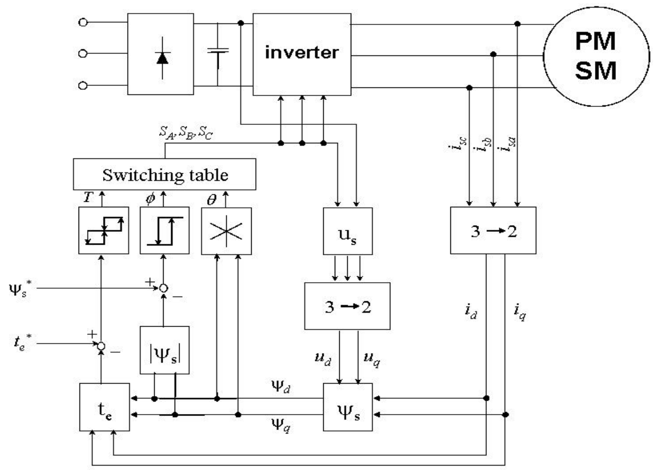

Figure 1 Block diagram of DTC based PMSM

The basic principle of DTC is to directly select the stator voltage vectors according to the errors between the reference and actual values of the torque and stator flux. Torque and flux are resolved and directly controlled using nonlinear transformations on hysteresis controllers, without performing coordinate transformations. A double layer hysteresis band controller is utilized for stator flux control and a three-layer hysteresis band controller is used for torque control. DTC is an alternative to field oriented control method in high performance applications due to the advantages of reduced computations The torque and flux estimators in DTC requires and relies on the parameters identification and accuracy of the estimations, so the estimation of the electromagnetic torque is essential for the entire system performance.

In classical PWM and flux vector controlled drives, voltage and frequency are used as basic control variables and that are modulated and then applied to the motor. This modulator layer needs an additional signal processing time and restricts the torque and speed response. The key notion behind DTC is to directly steer the stator flux vector by applying the appropriate voltage vector to the stator windings. This is done by using a pre-designed switching table to directly update the inverter's discrete switch positions whenever the variables to be controlled, the electromagnetic torque and the stator flux, exceed the hysteresis bounds around their references. The switching table is derived on the basis of the desired performance specifications on the controlled variables also include the balancing of the inverter's neutral point potential around zero.

The Principle of conventional DTC

The key idea of the conventional DTC is the rate of change of torque that is proportional to the instantaneous slip between the stator flux and rotor flux under constant stator flux linkage. It has been widely recognized for its fast and robust torque and flux control. As the rotor time constant of a standard squirrel-cage induction machine is very large, the rotor flux linkage changes slowly compared to the stator flux linkage. However, during a short transient, the rotor flux is almost unchanged.

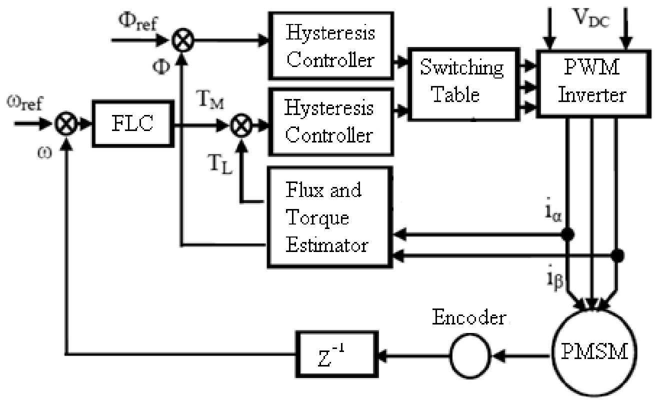

Figure 2 Block diagram of conventional DTC based PMSM

4. PULSE WIDTH MODULATION (PWM)

Fig.4 shows circuit model of a single-phase inverter with a centre-tapped grounded DC bus, and Fig.4 illustrates principle of pulse width modulation.

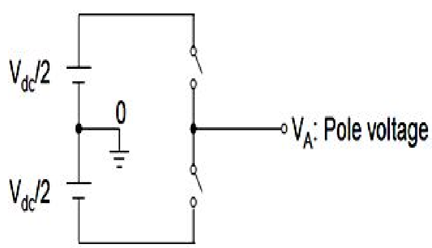

Figure 3 Circuit model of a single-phase inverter

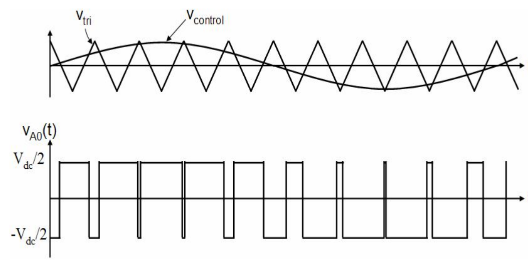

Figure 4 Pulse width modulation

As depicted in Fig. 3, the inverter output voltage is determined in the following

- When $V_{control} > V_{tri}$, $V_{A0} = V_{dc}/2$
- When $V_{control} < V_{tri}$, $V_{A0} = -V_{dc}/2$

Also, the inverter output voltage has the following features:

- PWM frequency is the same as the frequency of V_{tri}
- Amplitude is controlled by the peak value of $V_{control}$
- Fundamental frequency is controlled by the frequency of $V_{control}$

4.1 Principle of Space Vector Modulation

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig. 5. S_1 to S_6 are the six power switches that shape the output, which are controlled by the switching variables a, a′, b, b′ and c, c′. When an upper transistor is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0. Therefore, the on and off states of the upper transistors S_1, S_3 and S_5 can be used to determine the output voltage.

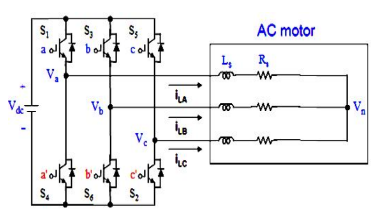

Figure 5 Three-phase voltage source PWM Inverter.

The relationship between the switching variable vector [a, b, c] ^{T} and the line-to-line voltage vector [V_{ab} V_{bc} V_{ca}] ^{T} is given as follows

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \text{--- (10)}$$

Also, the relationship between the switching variable vector [a, b, c] ^{T} and the phase voltage vector [V_a V_b V_c] ^{T} can be expressed below.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \text{--- (11)}$$

As illustrated in the Fig 6, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. According to equations stated above the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link V_{dc}, are given in Table.1 and Fig.8 shows the eight inverter voltage vectors (V_0 to V_7).

Table 1: Switching Vectors

Ψ	T	θ					
		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
1	1	V_2(110)	V_3(100)	V_4(101)	V_5(001)	V_6(011)	V_1(010)
	0	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)
	-1	V_6(011)	V_1(010)	V_2(110)	V_3(100)	V_4(101)	V_5(001)
0	1	V_3(100)	V_4(101)	V_5(001)	V_6(011)	V_1(010)	V_2(110)
	0	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)
	-1	V_5(001)	V_6(011)	V_1(010)	V_2(110)	V_3(100)	V_4(101)

Note: The respective voltage should be multiplied by V_{dc}

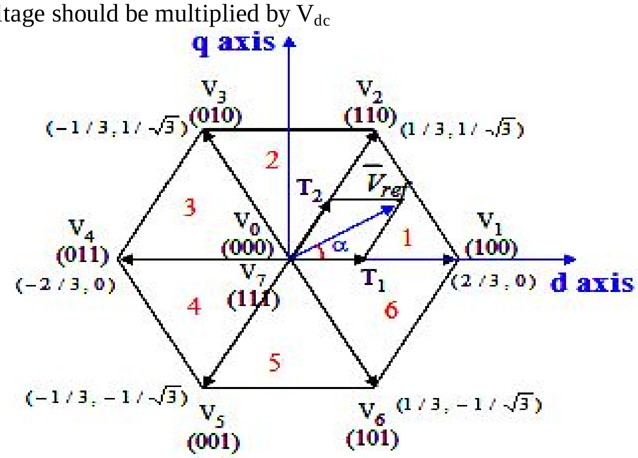

Figure 6 Basic switching vectors and sectors

$$\therefore T_0 = T_Z - (T_1 + T_2), \left(\begin{matrix} where, n = 1-6 (i.e., \sec tor 1 to 6) \\ 0 \le \alpha \le 60^0 \end{matrix} \right)$$

$$\therefore T_2 = \frac{\sqrt{3}.T_Z.\left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin\left(\alpha - \frac{n-1}{3}\pi \right) \right)$$

$$\therefore T_1 = \frac{\sqrt{3}.T_Z.\left|\overline{V}_{ref}\right|}{V_{dc}} \left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n+1}{3}\pi \right) \right)$$

Table 2: Switching Time Calculation at Each Sector

Sector	Upper Switches(S_1,S_3,S_5)	Lower Switches(S_4,S_6,S_2)
1	$S_1=T_1+T_2+T_0/2$ $S_3=T_2+T_0/2$ $S_5=T_0/2$	$S_4= T_0/2$ $S_6=T_1+ T_0/2$ $S_2=T_1+T_2+T_0/2$
2	$S_1=T_1 +T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5= T_0/2$	$S_4= T_2+T_0/2$ $S_6= T_0/2$ $S_2=T_1+T_2+T_0/2$
3	$S_1= T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5= T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+ T_0/2$
4	$S_1= T_0/2$ $S_3=T_1+ T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_2+T_0/2$ $S_2= T_0/2$
5	$S_1= T_2+T_0/2$ $S_3= T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2= T_0/2$
6	$S_1=T_1+T_2+T_0/2$ $S_3= T_0/2$ $S_5=T_1+ T_0/2$	$S_4= T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2= T_2+T_0/2$

5. SIMULATION RESULTS AND DISCUSSIONS

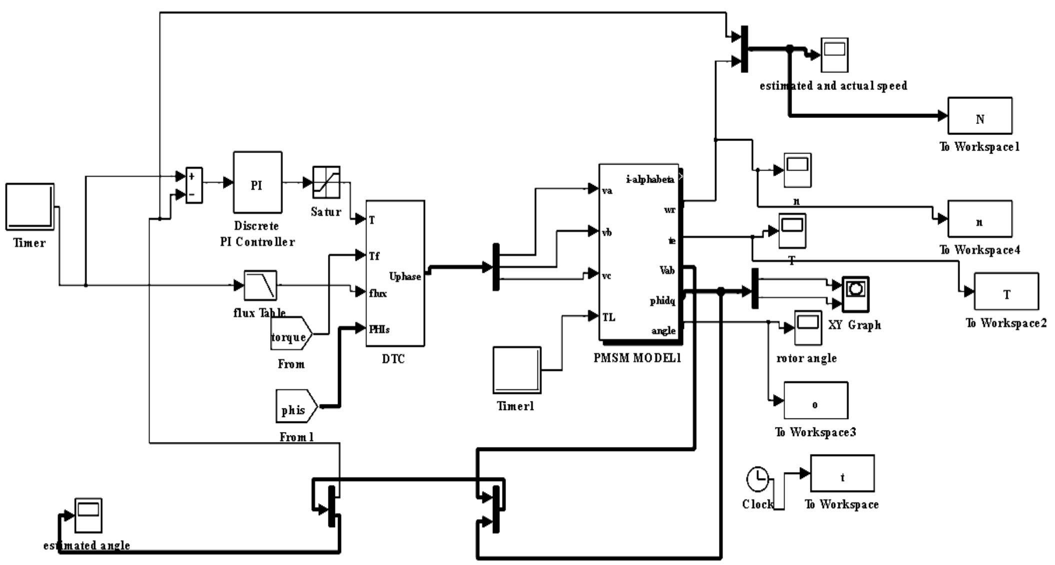

Figure 6 Simulation model of direct torque controlled PMSM

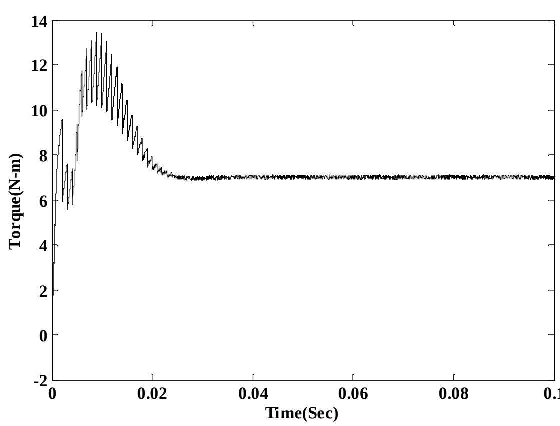

Figure 7 Torque Versus Time

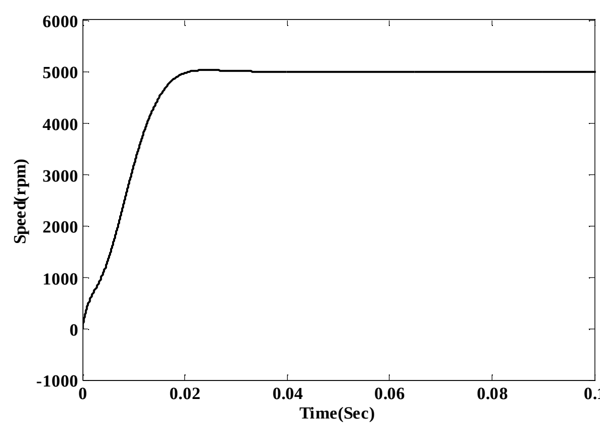

Figure 8 Speed versus Time

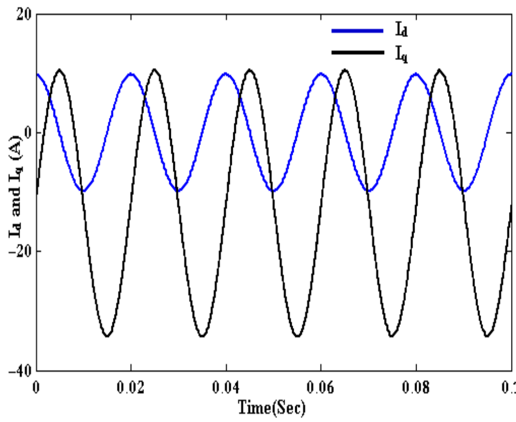

Figure 9 Direct And Quadrature Axis Currents

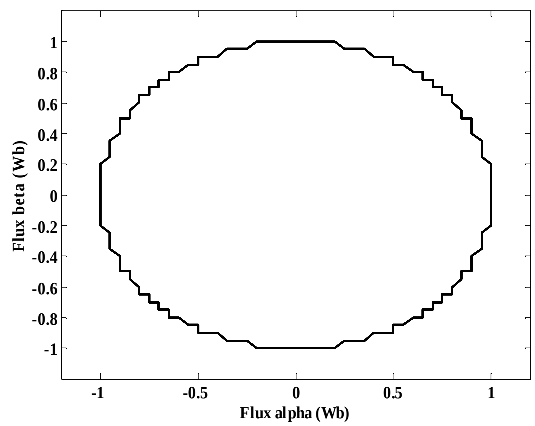

Figure 10 fluxlinkage

The simulation results shows that by using proposed scheme the steady state performance of system is good when compared with the basic conventional control scheme. Simulation results show that the steady state and dynamic performance of motor is improved with SVM-DTC technique when compared with conventional control technique. Fast speed tracking, less torque dynamics are the advantages of the proposed method.

6. CONCLUSION

This paper proposes a method for PMSM drive based on DTC using SVM. A comparison between the conventional and proposed method is performed. The key point of the proposed control is to compensate the drawbacks of the conventional control method. Several numerical simulations using MATLAB-Simulink have been carried out in steady-state and transient-state. The results shows that, the proposed control technique gives better performance as the motor torque and the speed are better than that of the conventional type the feedback based modulation technique was replaced by carrier based space vector modulation at the expense of simplicity lost and partially worse dynamics.

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