Direct Torque Control of Permanent Magnet Synchronous Motor (PMSM) Using Space Vector Modulation (DTC-SVM) – Simulation and Experimental Results

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Abstract - **This paper presents digital signal processor (DSP) based direct torque control scheme using space vector modulation (DTC-SVM) for permanent magnet synchronous motor (PMSM) drives. The analysis of PMSM shows that the increase of electromagnetic torque is proportional to the increase of the angle between the stator and rotor flux linkages and therefore fast torque response can be obtain by increasing the rotating speed of the stator flux linkage as fast as possible. The presented control strategy DTC-SVM is implemented in software of the DS1103 board. Simulations and experimental results well demonstrate the effectiveness of the proposed control scheme. Also comparison with conventional DTC scheme and results of speed control loop are given.**

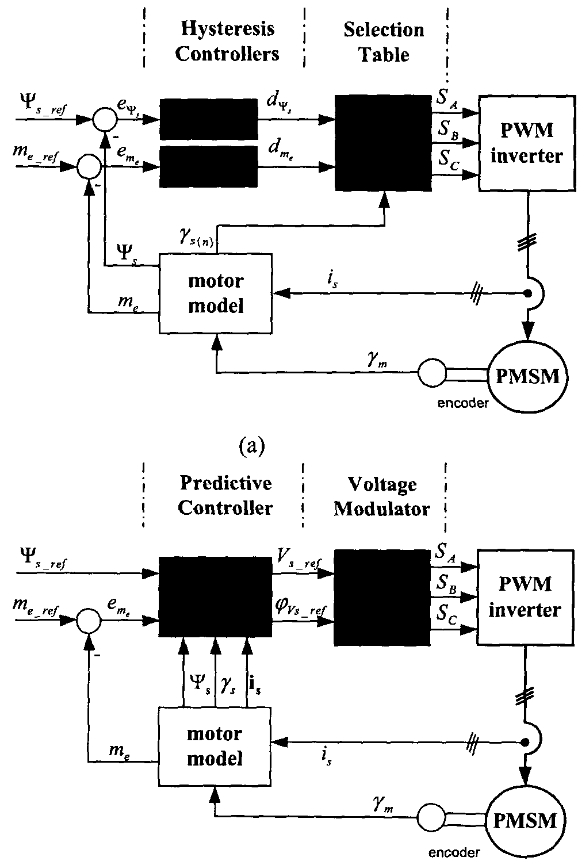
I. INTRODUCTION

Permanent magnet (PM) synchronous motors are widely used in high-performance drives such as industrial robots and machine tools thanks to their known advantages as: 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 materials.

Direct Torque Control (DTC) method has been first proposed for induction machines (Takahashi and Noguchi [1], Depenbrock [2]). This concept can also be applied to synchronous drives [3],[4]. The DTC technique is different from the conventional vector control method, where torque is controlled in the rotor reference frame via current control loops [5],[6]. Fig.1 shows two system configuration for DTC controlled PMSM drive. Both systems use stator flux vector and torque estimators. The advantages of the hysteresis based DTC (Fig.1a) over conventional rotor oriented control include the elimination of the dq-axes current controllers, coordinate transformation and voltage modulator. On the other hand, among the well-known disadvantages of the hysteresis based DTC scheme are [7],[8]:

- variable switching frequency,
- violence of polarity consistency rules,
- current and torque distortion caused by sector changes,
- high sampling frequency needed for digital implementation of hysteresis comparators.

All the above difficulties can be eliminated when, instead of the selection table (Fig. 1a), a voltage modulator is applied (Fig. 1b).



(b)

Fig. 1. Comparison between two schemes of DTC transistor PWM inverter fed PMSM drive. (a) Conventional scheme with hysteresis controllers and selection table. (b) Proposed scheme with predictive controller and voltage modulator.

In the proposed scheme, shown in Fig. 1b, the error signal e_{m_e} and reference amplitude of stator flux Ψ_{s_ref} are delivered to predictive controller, which also uses information on the amplitude and position γ_s of the actual stator flux vector and measured current vector. The predictive controller determinates the stator voltage command vector in polar coordinates $v_{ref} = [V_{ref}, \varphi_{Vref}]$ for space vector modulator (SVM), which finally generates the pulses S_A, S_B, S_C to control the inverter.

This paper is an extension of [11] and include results of speed control loop.

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II. MODEL OF PMSM

The voltage and flux equations for a PMSM in the rotor oriented coordinates d-q can be expressed as:

$$
\begin{aligned}
u_{sd} &= r_s i_{sd} + \frac{d\Psi_{sd}}{dt} - p\omega_m \Psi_{sq} \\
u_{sq} &= r_s i_{sq} + \frac{d\Psi_{sq}}{dt} + p\omega_m \Psi_{sd}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\Psi_{sd} &= L_d i_{sd} + \Psi_{PM} \\
\Psi_{sq} &= L_q i_{sq}
\end{aligned} \tag{2}
$$

and the electromagnetic torque equation

$$m_e = \frac{3}{2} p(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) = \frac{3}{2} p(\Psi_{PM} i_{sq} - (L_d - L_q) i_{sd} i_{sq}) \tag{3}$$

where p is the number of pole pairs, r_s is the stator winding resistance, ω_m is the angular frequency, u_{sd}, u_{sq} and i_{sd}, i_{sq} are d,q components of the stator winding voltage and current, Ψ_{sd}, Ψ_{sq} are d,q components of the stator flux linkage, L_d, L_q are d and q axis inductances, and Ψ_{PM} is the PM rotor flux linkage. Finally, the motion equation is expressed as:

$$\frac{d\omega_m}{dt} = \frac{1}{J}(m_e - m_L - d\omega_m) \tag{4}$$

where J moment of inertia, m_L motor load and d damping constant.

From the vector diagram of Fig.2 and eqs. (2) we can obtain following relation:

$$m_e = \frac{3}{2} p \frac{\Psi_{s\_ref}}{L_d L_q} [\Psi_{PM} L_q \sin\delta + \frac{1}{2} \Psi_{s\_ref} (L_d - L_q) \sin 2\delta] \tag{5}$$

From equation (5) we can see that for constant stator flux amplitude and flux produced by permanent magnet, 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 angel δ, in turn, can be changed by changing position of the stator flux vector in respect to PM vector using the actual voltage vector supplied by PWM inverter.

In the steady state, δ is constant and corresponds to a load torque, whereas stator and rotor flux rotate at synchronous speed. In transient operation, δ varies and the stator and rotor flux rotate at different speeds (Fig. 2).

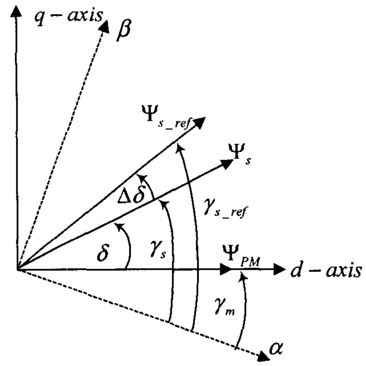


Fig. 2. Vector diagram of illustrating torque control conditions.

III. SPEED AND TORQUE CONTROL USING SPACE VECTOR MODULATION (DTC-SVM)

The block scheme of the investigated speed and torque control with space vector modulation (DTC-SVM) for a voltage source PWM inverter fed PMSM is presented in Fig. 3a [9],[10]. The internal structure of the predictive torque and flux controller is shown in Fig. 3b.

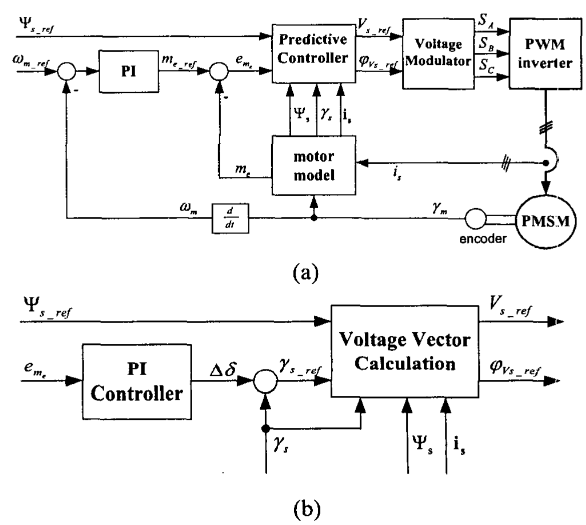


Fig. 3. Direct torque control of PWM inverter-fed PMSM using space vector modulation (DTC-SVM). (a) Block scheme, (b) Predictive controller.

Sampled torque error e_{m_e} and reference stator flux amplitude Ψ_{s_ref} are delivered to the predictive controller. The relation between error of torque and increment of load angel $\Delta\delta$ is nonlinear. Therefore PI controller, which generates the load angel increment required to minimize the instantaneous error between reference m_{e_ref} and actual m_e torque, has been applied. The reference values of the stator voltage vector $v_{ref} = [V_{ref}, \varphi_{Vref}]$ is calculated based on stator resistance r_s, $\Delta\delta$ signal, actual stator current vector $\mathbf{i}_s$, actual stator flux amplitude Ψ_s and position γ_s as:

$$V_{ref} = \sqrt{{v_{s\alpha\_ref}}^2 + {v_{s\beta\_ref}}^2}, \varphi_{Vref} = \arctan\frac{v_{s\beta\_ref}}{v_{s\alpha\_ref}} \tag{6}$$

where:

$$\begin{aligned} v_{s\alpha\_ref} &= \frac{\Psi_{s\_ref}\cos(\gamma_s + \Delta\delta) - \Psi_s \cos\gamma_s}{T_s} + r_s i_{s\alpha} \\ v_{s\beta\_ref} &= \frac{\Psi_{s\_ref}\sin(\gamma_s + \Delta\delta) - \Psi_s \sin\gamma_s}{T_s} + r_s i_{s\beta} \end{aligned} \tag{7}$$

and T_s is sampling time.

For constant flux operation region, the reference value of stator flux amplitude Ψ_{s_ref} is equal to the flux amplitude produced by permanent magnet Ψ_{PM}.

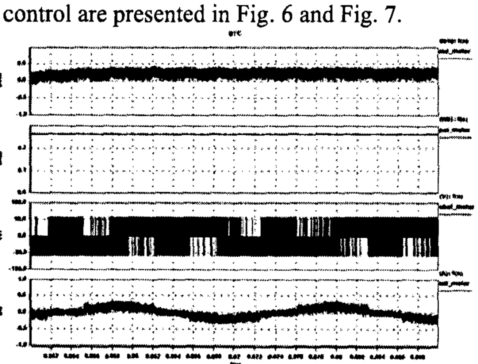
In the speed loop the PI controller has been used. Thus, the control scheme operates in cascade structure, which allows simple limit of the PMSM torque, and also – with constant flux magnitude – the stator current is limited.

IV. SIMULATION RESULTS

Simulation study of the hysteresis based DTC and DTC-SVM schemes was carried out for the motor and inverter parameters given in Appendix.

The steady state at no load and rated torque operation are presented in Fig. 4 and Fig. 5, respectively. Note, that in spite of lower switching frequency DTC-SVM guarantee lower current and torque ripple. This is mainly because in SVM operation, contrary to hysteresis operation, the inverter switching is unipolar (compare output voltage waveform in Fig. 4a and 5a with Figs. 4b and 5b). Additionally, application of the SVM also reduce semiconductor device voltage stress by avoiding ± 1 dc voltage transition and instantaneous current reversal in dc link.

The dynamic performances of the speed loop for DTC-SVM control are presented in Fig. 6 and Fig. 7.



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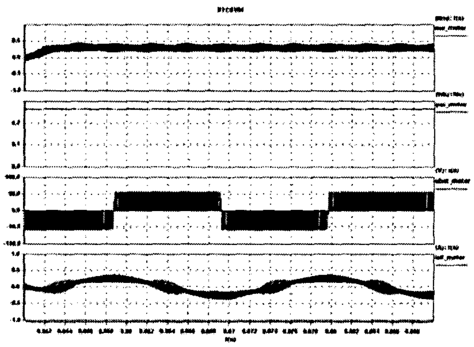
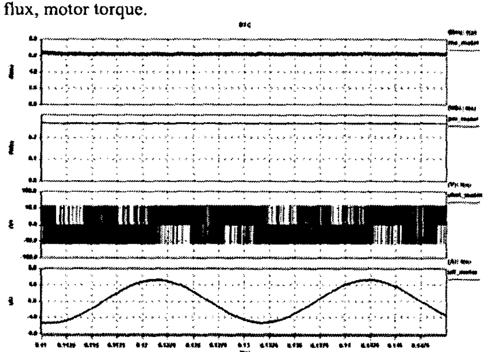


(b)

Fig. 4 No load steady state operation at 50Hz stator frequency. (a) DTC (b) DTC-SVM. From the top: line to line voltage, phase current, amplitude of stator flux, motor torque.



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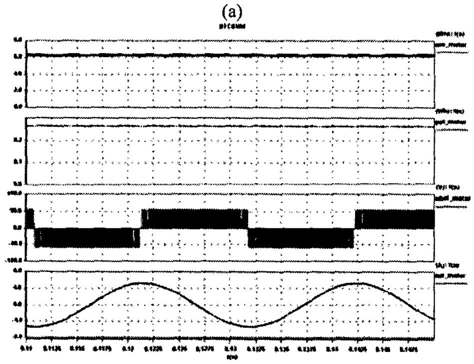
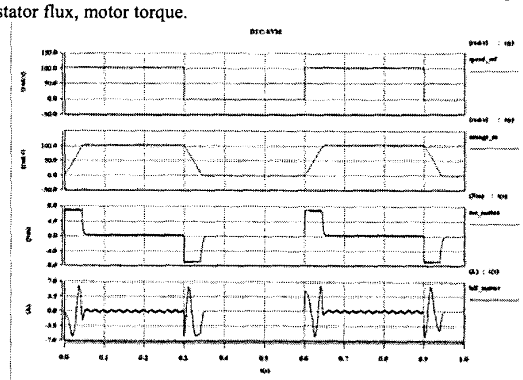


(b)

Fig. 5 Rated load steady state operation at 50Hz stator frequency. (a) DTC (b) DTC-SVM. From the top: line to line voltage, phase current, amplitude of stator flux, motor torque.



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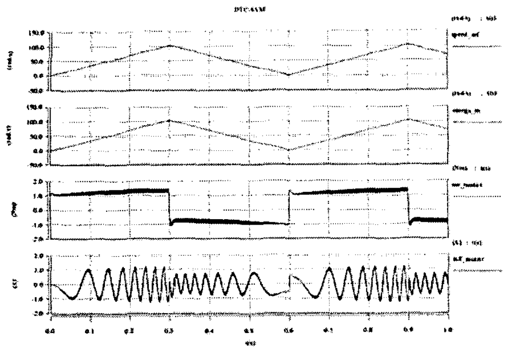
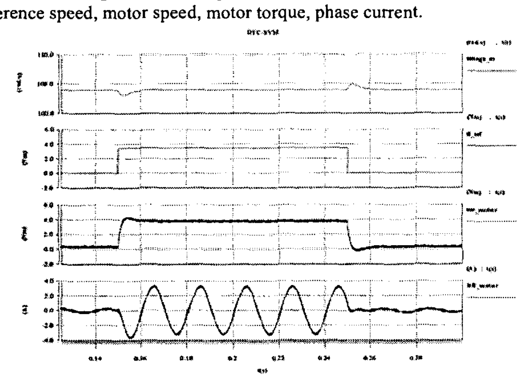


(b)

Fig. 6 Start and braking to zero speed for the : (a) reference step change (b) for the triangle reference speed (triangle period: 0.6s). From the top: reference speed, motor speed, motor torque, phase current.



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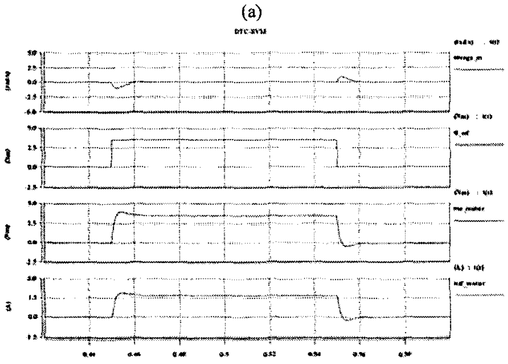


(b)

Fig. 7 Step change of the half nominal load torque. (a) at nominal speed (b) at zero speed. From the top: motor speed, reference load torque, motor torque, phase current.

V. EXPERIMENTAL RESULTS

To verify the proposed DTC-SVM concept, a simulation program and the laboratory setup with 3-kW permanent magnet synchronous motor drive with dSPACE DS1103 laboratory control board was constructed (Fig. 8). The system is based on Motorola PowerPC604 and TMS320F240 DSP. The first (main) processor implements the DTC-SVM control and flux and torque estimation algorithm, whereas the second provides the space vector modulation. The board is equipped with analog-to-digital converters, digital-to-analog converters, and the input for an encoder. A PC Pentium 750 is used for software development and results visualization. Optic fibers are used as interface between the PWM voltage-source inverter and the DSP board. The software is written in high-level language C.

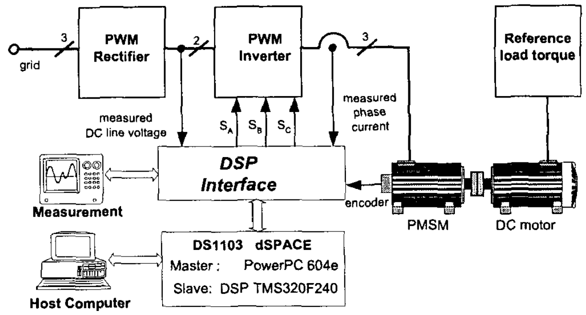
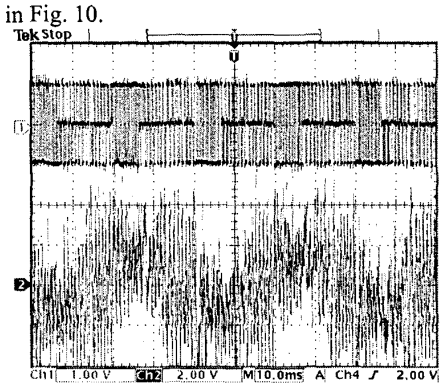


Fig. 8 Laboratory setup.

The experimental steady state operation at no load is presented in Fig. 9. The sampling time has been set to 100us for DTC-SVM and 25us for hysteresis DTC method. The excellent speed tracking performance of the scheme are shown in Fig. 10.



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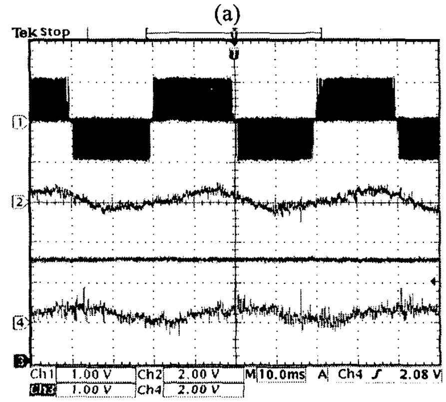

(b)

Fig. 9 No load experimental steady state oscillograms at stator frequency 25Hz. (a) DTC (b) DTC-SVM. From the top: line to line voltage, phase current, amplitude of stator flux, motor torque.

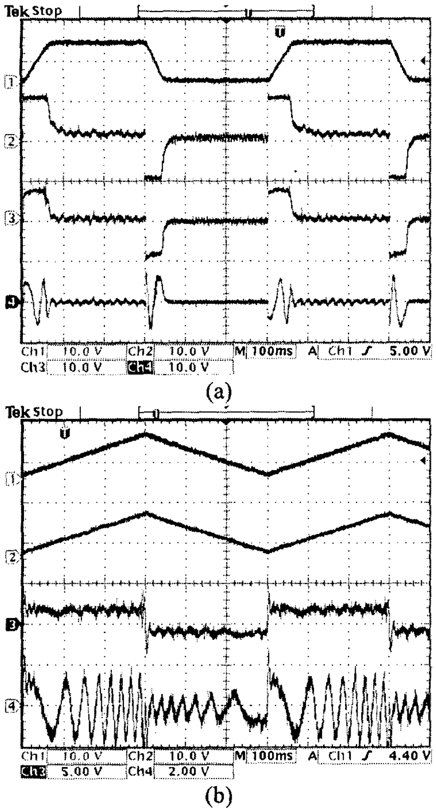

Fig. 10 Experimental start and braking to zero speed for the : (a) reference step change (b) for the triangle reference speed (triangle period: 0.6s). From the top: reference speed, motor speed, motor torque, phase current.

VI. CONCLUSION

The presented simulated and experimental results can be summarized as follows:

- The inductance of the PMSM is smaller than an equivalent induction motor, therefore, application of the hysteresis based DTC leads to high current and torque ripple. Using space vector modulation based DTC-SVM scheme of Fig. 3a much better results can be achieved.
- In spite of lower switching frequency, the DTC-SVM scheme has lower harmonic current, and consequently lower torque ripple (see Fig. 4,5) than conventional hysteresis based DTC .
- Both schemes perform very good decoupling in torque and stator flux control. Additionally, the application of SVM guarantee:
  - inverter switching frequency is constant,
  - dc link voltage switching ± 1 are eliminated,
  - distortion caused by sector changes are eliminated,
  - low sampling frequency is required,
  - dynamic performance of DTC-SVM are comparable with selection table based DTC.
- Finally, the DTC-SVM offers very good speed control performance (see Fig. 6, 7).

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VIII. APPENDIX

Motor and inverter parameters:

Sampling time DTC:	10us
Sampling time DTCSVM:	100us
Stator winding resistance Rs:	0.692Ω
Inductance d-axis Ld:	6mH
Inductance d-axis Lq:	6mH
Number of pole pairs p:	3
Permanent magnet flux linkage Ψ:	0.264Wb
Moment of inertia J:	0.003kgm^2
Phase voltage V:	70V(rms)
Phase current I:	6A(rms)
Nominal torque m_e:	7Nm
Base speed ω_b:	104rad/s
DC-link voltage:	180V

IX. ACKLOWLEDGMENT

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