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Simulation and Digital Control of Speed for Permanent Magnet Synchronous Motor with Space Vector Modulation

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Abstract

This paper presents the field oriented vector control scheme for permanent magnet synchronous motor (PMSM) drives, where space vector modulation is used. The field oriented vector control, that regulates the speed of the PMSM, is provided by a quadrature axis current command developed by the speed controller. The simulation includes all realistic components of the system. This enables the calculation of currents and voltages in different parts of the voltage source inverter (VSI) and motor under transient and steady state conditions. Implementation has been done in MATLAB/Simulink. A study of space vector modulation scheme associated with current controllers has been made. Experimental results of the PMSM control using TMS320F24X DSP board are presented. The speed of the PMSM is successfully controlled in the constant torque region. Experimental results show that the PMSM exhibits improved speed stability especially in very low speed range. The validity and usefulness of the proposed control scheme are verified through simulation and experimental results.

Keywords: Vector Control, Field Orientation, PMSM, Space Vector Modulation, DSP

1. Introduction

Permanent magnet (PM) synchronous motors are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives, electric vehicles and other applications in a variety of automated industrial plants. In such applications, the motion controller may need to respond relatively swiftly to command changes and to offer enough robustness against the uncertainties of the drive system, M.H. Rashid (2004), H.B. Ertan and M.Y. Üctung and R. Colyer (2000). Among ac and dc drives, PMSM has received widespread appeal in motion control applications. The complicated coupled nonlinear dynamic performance of PMSM can be significantly improved using vector control theory where torque and flux can be controlled separately, L. Harnefors and P. Taube and H.-P. Nee (1997), N. Matsui (1996).

The growth in the market of PM motor drives has demanded the need of simulation tools capable of handling motor drive simulations. Under perfect field orientation and with constant flux operation, a simple linear relation can characterize the torque production in the motor when the magnetic circuit is linear, B. Cui, J. Zhou, and Z. Ren (2001). However, the control performance of PMSM drive is still influenced by uncertainties, which usually are composed of unpredictable plant parameter variations, external load disturbances, and unmodeled and nonlinear dynamics of the plant.

Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems .

In this work, the simulation of a field oriented controlled PM motor drive system is developed using MATLAB/Simulink. The simulation circuit will include all realistic components of the drive system. This enables the calculation of currents and voltages in different parts of the inverter and motor under transient and steady state conditions. A closed loop control system with a PI controller in the speed loop has been designed to operate in constant torque region. A study of space vector modulation scheme associated with current controller has been made. Simulation results are given for the speed range in constant torque region of motor operation. Finally, the experimental verification obtained by using the DSP based vector control is presented.

2. PMSM Drive System

In the PMSM, excitation flux is set-up by magnets; subsequently no magnetizing current is needed from the supply. This easily enables the application of the flux orientation mechanism by forcing the *d* axis component of the stator current vector (i_d^*) to be zero. As a result, the electromagnetic torque will be directly proportional to the *q* axis component of the stator current vector (i_q^*), B. K. Bose (2002), A.-K. Daud (2006), hence better dynamic performance is obtained by controlling the electro-magnetic torque separately. Therefore, this torque can be written by

$$T_e = k_t . i_q \tag{1}$$

with

$$k_t = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f \tag{2}$$

where λ_f is flux linkage of rotor permanent magnet and *p* is number of poles [15]. This equation describes the constant torque control strategy for PMSM, where the maximum possible torque is desired at all times like the dc motor. This is performed by making the torque producing current i_q^* equal to the supply current.

A system configuration of a vector-controlled PMSM drive system is shown in Figure 1. In the vector control scheme, torque control can be carried out by suitable regulation of the stator current vector; this implies that accurate speed control depends on how well the current vector is regulated. In high-performance vector drives, a current-control loop, with a considerably high bandwidth, is necessary to ensure accurate current tracking, to shorten the transient period as much as possible and to force the voltage source inverter (VSI) to equivalently act as a current source amplifier within the current loop bandwidth. In this work, a space vector modulation controlled VSI is used, G. K. Dubey (2001).

Space Vector Modulation (SVM)

In a voltage fed three phase inverter as shown in Figure 2, the switching commands of each inverter leg are complementary. ***So*** for each leg a logic state ***Si*** (i=a,b,c) can be defined. ***Si*** is 1 if the upper switch is commanded to be closed and 0 if the lower one is commanded to be close (first).

Since there are **3** independent legs there will be eight different states so **8** different voltages.

Figure 1: PMSM vector-controlled drive with constant flux operation

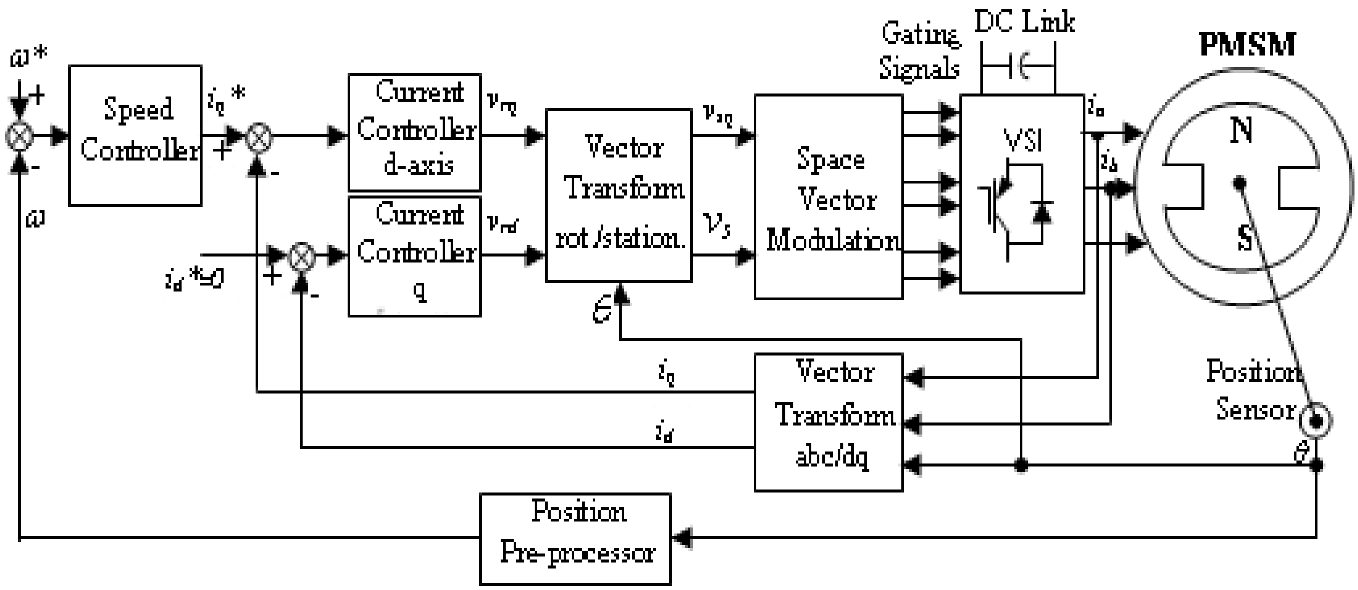
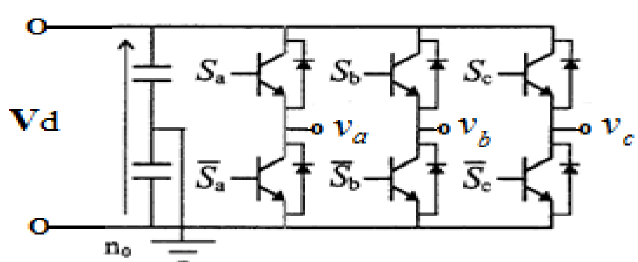


Figure 2: Three phase voltage fed inverter



Applying the vector transformation described as:

$$v_s = \sqrt{\frac{2}{3}}\left(a^0 v_a + a v_b + a^2 v_c\right) \tag{3}$$

to phase voltages v_a, v_b, and v_c, where :

$$a = e^{j\frac{2\pi}{3}} \tag{4}$$

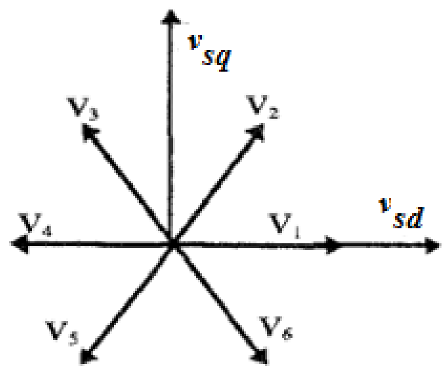
Voltage vector can be written as:

$$v_s = \sqrt{\frac{2}{3}} v_s = Vd\left(S_a + aS_b + a^2 S_c\right) \tag{5}$$

As it can be seen in Figure 3, there are six non-zero voltage vectors and two zero voltage vectors which correspond to:

(Sa,Sb.Sc) = (111) / (000) (6)

Figure 3: Non zero inverter output voltage vectors



V_0	(111)
V_1	(100)
V_2	(110)
V_3	(010)
V_4	(011)
V_5	(001)
V_6	(101)
V_7	(000)

For SVM we need the reference voltages to be in stationary frame. As the output parameters of the current controllers are in the rotating frame, therefore, a T^{-1} Transformation (as shown in Figure 1) is used, N. Mohan (2001).

For the same reason, the feedback currents must be in the rotating frame. Therefore, the real output currents (i_a, i_b, i_c) from VSI have to be transformed into the rotating frame through D/T Transformation.

Speed controller calculates the difference between the reference speed (ω*) and the actual speed (ω) producing an error, which is fed to the PI controller, P. Pillay and R. Krishnan (1985) . PI controllers are used widely for motion control systems. An incremental encoder is used as a position sensor.

The dynamic d-q modeling is used for the study of motor during transient and steady state. It is done by converting the dqo variables to three phase currents by using inverse Parks transformation, E. Arroyo (2006).

Software Implementation

Control loops in the actual system are implemented in software on a Texas processor (TMS320F24X) and executed with a cycle period of 200µs.

The flow chart of the program is shown in Fig. 4. It is relative at the scheme of Fig. 1. At the switching on, the program initialises the hardware registers, I/O ports are then pre-set to their initial states, the inverter, software variables and ADC converters, and then it calculates offset currents and initialises position sensor (optical encoder). The system now completes all initialisations and starts the main program, which requires a computational time of 200µs of cycle period.

The main program will first calculate actual speed of the motor (ω) and read reference speed (ω*) or current depending on the state of switch, if it is ON then it is speed control and i_q* is calculated, if it is OFF it is current control i_q* is imposed by reference (potentiometer of command board). The dc bus voltage and actual phase currents (i_a, i_b and i_c) are read from ADCs. Maximum generable voltage V_{MAX} is calculated. Then it will read position from the encoder. From current errors (differences i_q*- i_q and i_d*- i_d), the voltages v_{rd} and v_{rq} in the two-phase rotating reference frame are calculated by the PI current regulators, and finally voltages v_{sd} and v_{sq} in the two-phase stationary reference frame needed by SVM block, W. Leonnard (1986).

Figure 4: System Flow Diagram

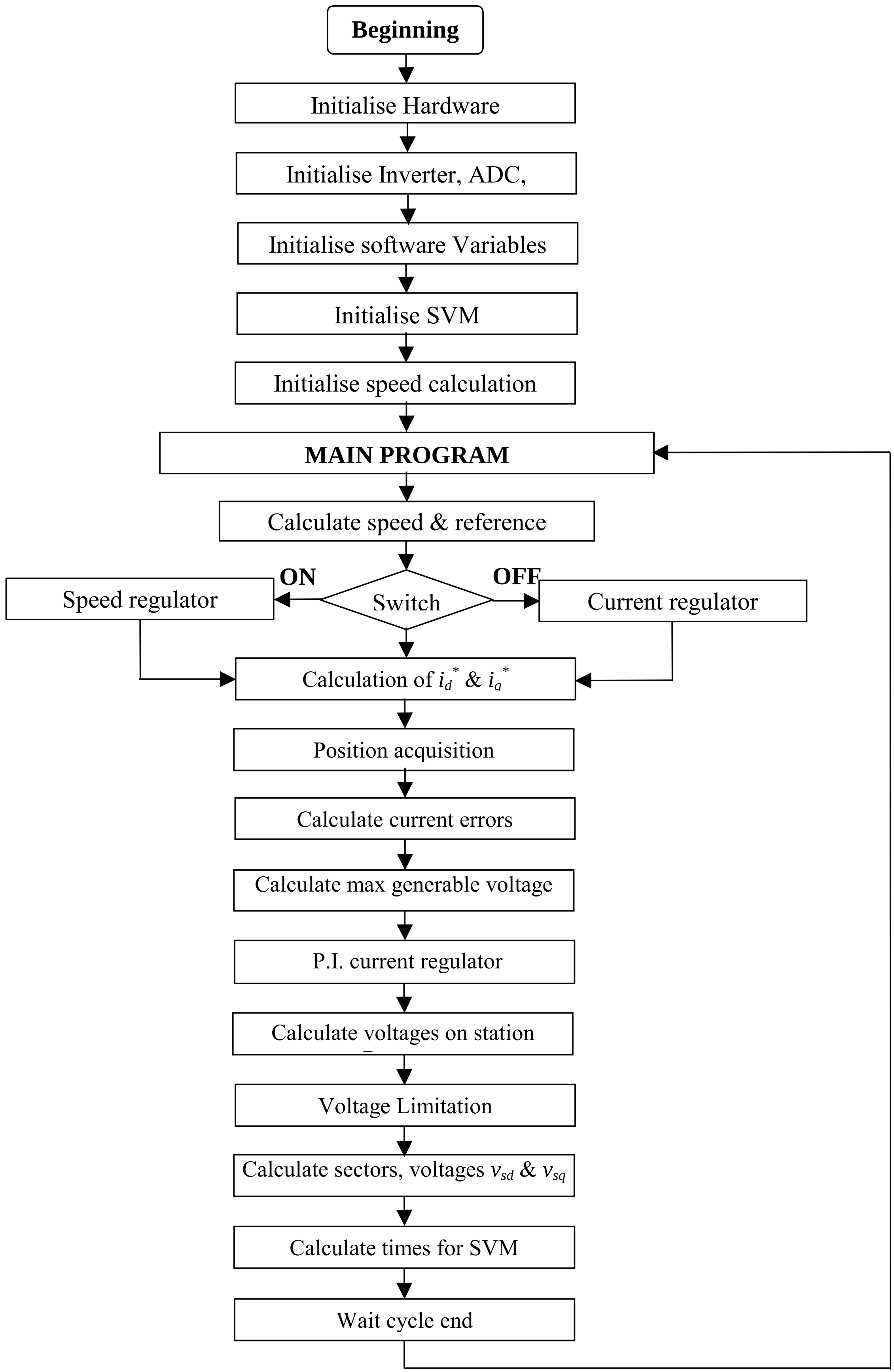
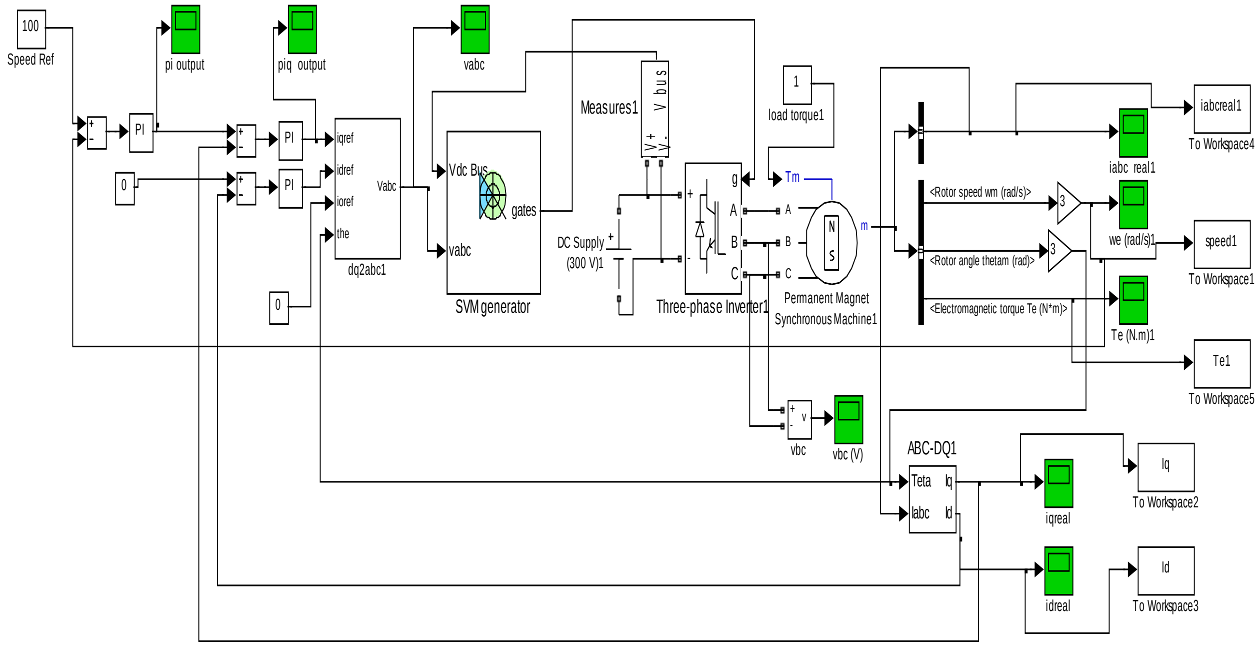


Figure 5: PM Synchronous Motor Drive System in Simulink



3. Simulation in SIMULINK

Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of tool boxes, C.-m. Ong (1998). The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device. System blocks are constructed of lower level blocks grouped into a single maskable block. Simulink simulates analogue systems and discrete digital systems G. K. Dubey (2001).

The PMSM drive simulation was built in several steps like dqo variables transformation to abc phase, calculation torque and speed, control circuit, inverter and PMSM. The dqo variables transformation to abc phase is built using the reverse Parks transformation. For simulation purpose the voltages are the inputs and the current are output. Using all the drive system blocks, the complete system block has been developed as shown in Figure 5.

The system built in Simulink for a PMSM drive system has been tested with the space vector modulation method at the constant torque region of operation.

The motor parameters used for simulation are given in Table 1.

Figure 6 shows the real three phase currents drawn by the motor as a result of the SVM control for a speed step of 600rpm and load of 3.66 Nm. It is clear that the current is non sinusoidal at the starting and becomes sinusoidal when the motor reaches the controller command speed at steady state.

Figure 7 shows a variation of the speed with time. The steady state speed is the same as that of the commanded reference speed.

Table 1: PMSM Parameters

Name	Symbol	Value
Rated power	$P_{n.}$	3.9 kW
Rated voltage	V_n	180 V
Rated torque	T_n	12.5 N·m
Pull out torque	T_{max}	45 N·m
Rated current	I_n	14.9 A
Rated speed	n_n	3000 RPM
Number of poles	P	6
Stator resistance	R_s	0.3 Ω
PM flux linkage	λ_f	0.185 Wb
q-axis Inductance	L_q	0.0085 H
d-axis Inductance	L_d	0.0085 H
Motor Inertia	J	0.0755 kgm^2

Figure 6: Actual phase currents with SVM at 600 rpm rad/s and 3.66 Nm

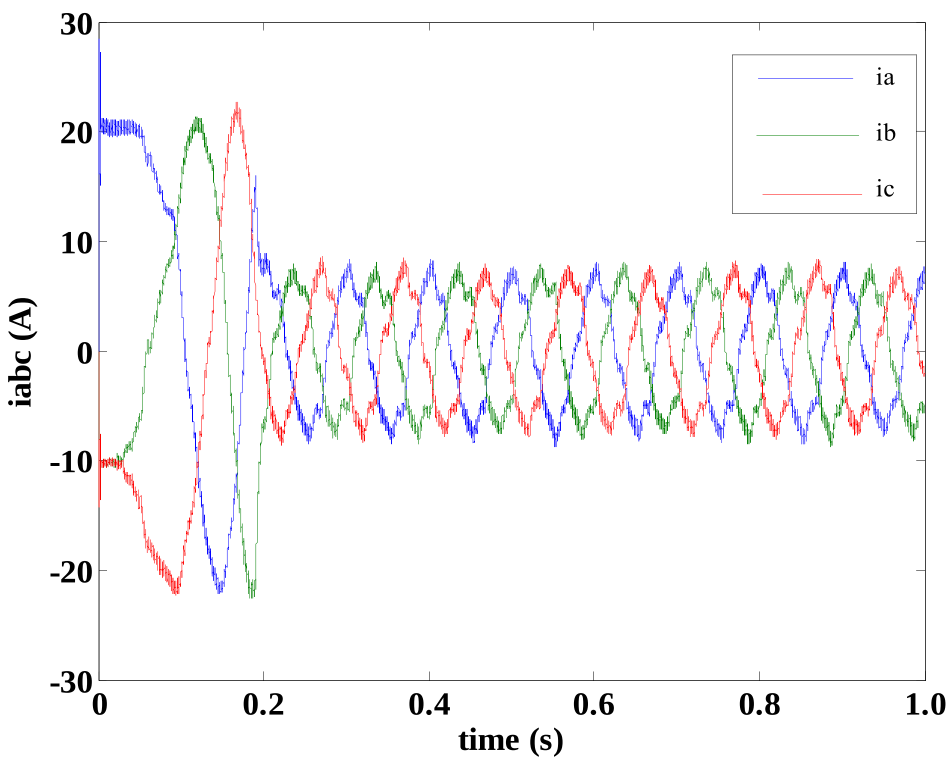


Figure 8 shows the developed torque of the motor. The starting torque is the rated torque. The steady state torque is about 1 Nm.

The q-component of the current (i_q) is displayed in Figure 9 for a speed step of 600 rpm and load of 3.66 Nm. This current is obtained using Park's reverse transformation.

Figure 7: Dynamic performance for a step variation of the reference speed from 0 RPM to 2200 RPM (ω =230 rad/s) with a torque of 1 Nm

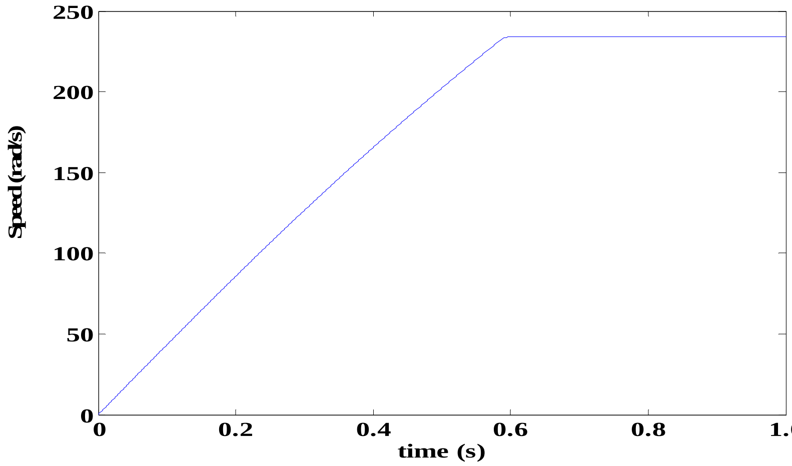


Figure 8: Developed Torque with SVM Control at 2200 rpm, 1Nm

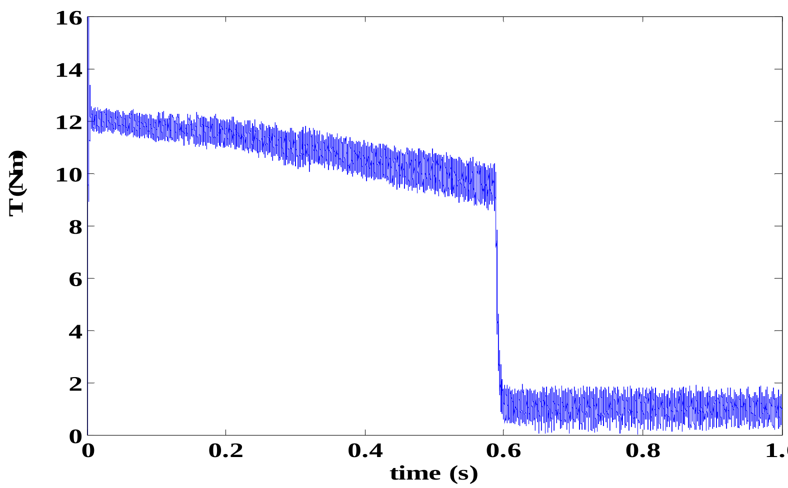
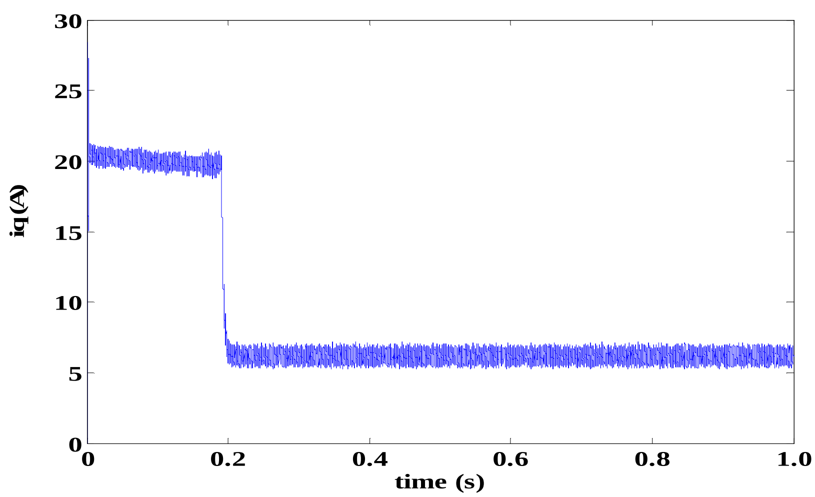


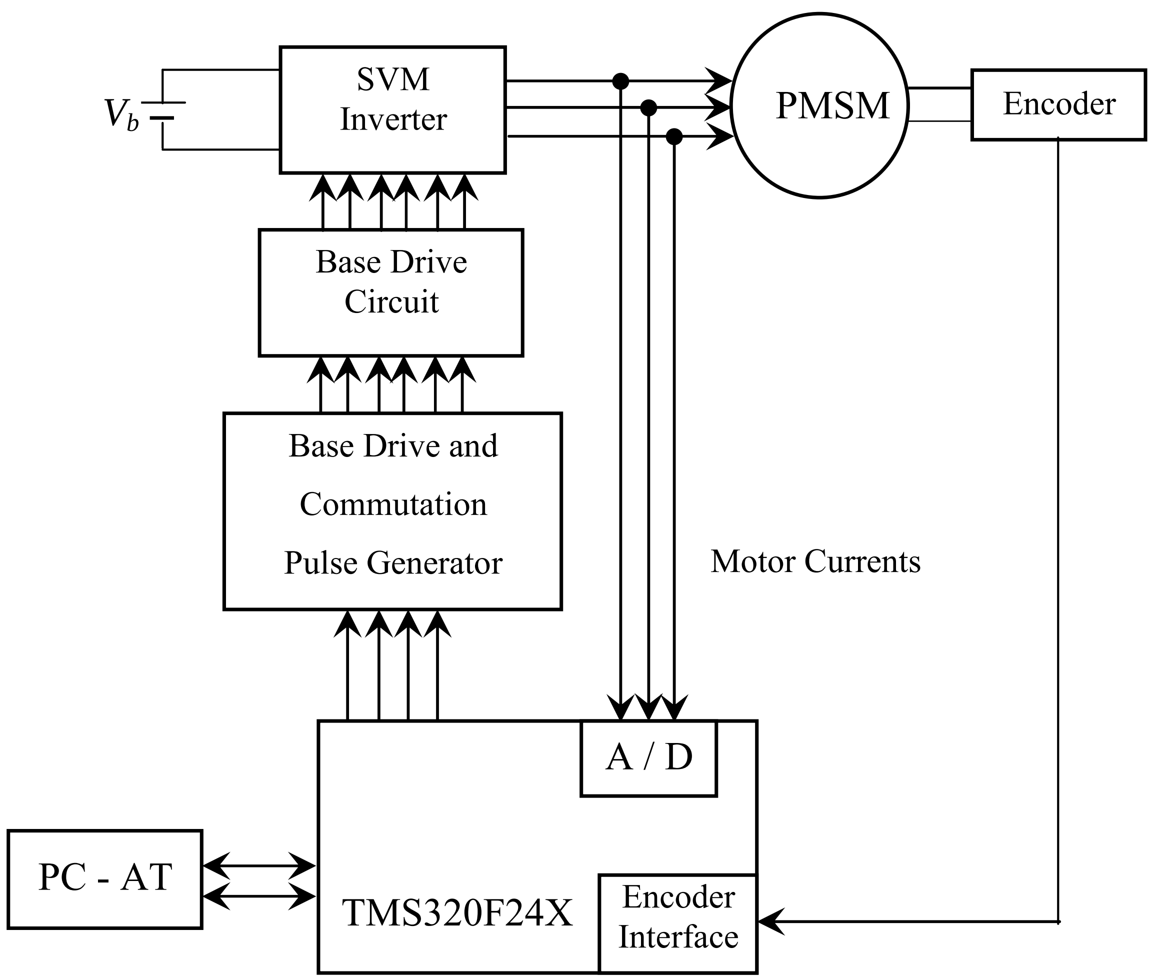
Figure 9: The actual current i_q with SVM Control at 600 rpm and 3.66Nm



4. Experimental Results

A DSP based PC board integrated system (TMS320F24X DSP board), is used for vector control of PMSM drive. The schematic diagram of the hardware implementation is shown in Figure 10. Feedback signals to the controller board are the actual motor currents and the rotor position angle. The currents are measured by the Hall-effect transducers. The currents are then buffered and fed to the **A/D** ports of the controller board. The motor shaft position is measured by an optical incremental encoder installed at the motor shaft. The commutating signals for the drive pulses have also been generated by the SVM. The control algorithm has been implemented via the controller board using assembly language programming.

Figure 10: The hardware schematic of Experimental system



A series of experiments has been carried out to evaluate the performances of the proposed vector controlled PMSM drive system using SVM. Sample results are presented in Figures 11, 12 and 13 in this digest. Figure 11 demonstrates the actual phase current i_a wave form at 600 rpm and torque of 3.66Nm.

The experimental evaluation of speed with load as parameter of DSP based PMSM drive is shown in Figure 12. It shows the step speed response of 2200rpm of the proposed system for a load of 1Nm. The actual current i_q is shown in Figure 13 for speed of 600 rpm, which is proportional to a load of 3.66Nm.

Figure 11: Actual phase current i_a wave form at 600 rpm and 3.66 Nm

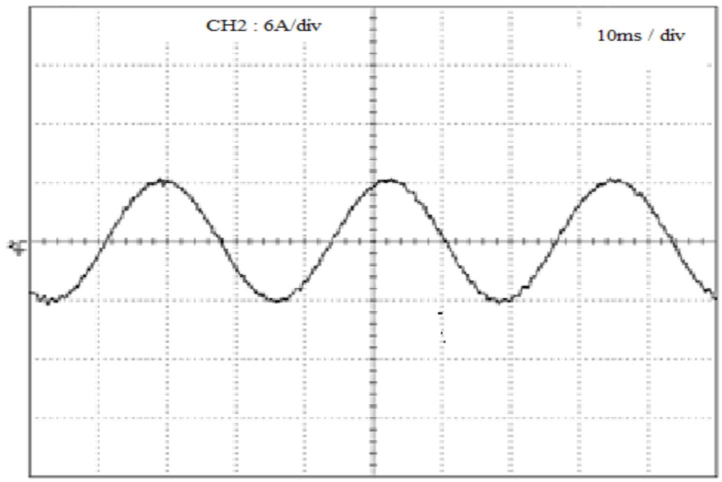


Figure 12: Experimental speed responses of PMSM drive with step change of 2200rpm and load of 1Nm

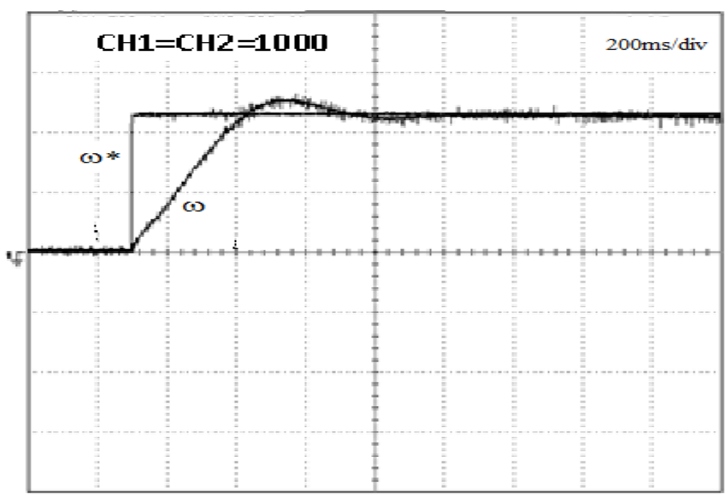
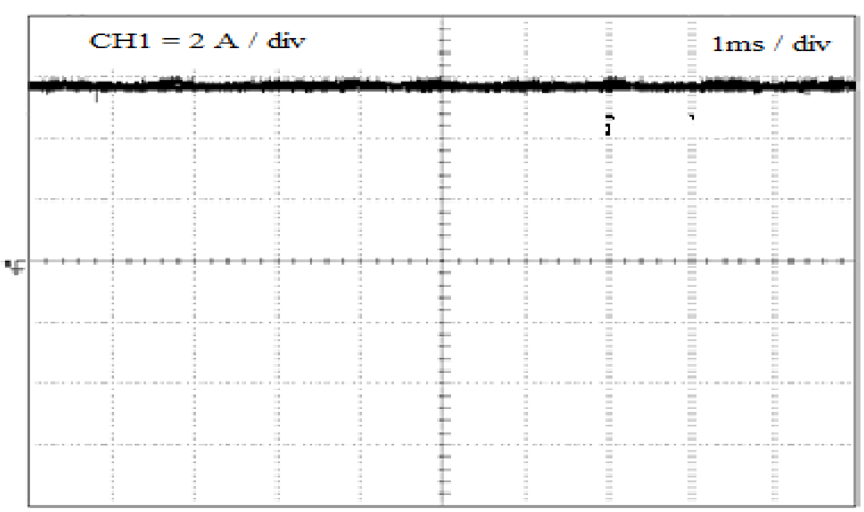


Figure 13: Actual current i_q in the rotating reference at 600 rpm and load of 3.66 Nm



5. Conclusion

The proposed field oriented vector controlled PMSM drive can handle the effects of step change in reference speed and parameter variations. The overall system performances are quite good in terms of dynamic, transient and steady-state responses.

Simulation and experimental results show that the proposed control scheme guarantees stable and robust response of the PMSM drive, under a wide range of operating conditions. Subsequently, it can be utilized in high performance motion control applications.

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