A DSP Based Servo System Using Permanent Magnet Synchronous Motors (PMSM)

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Abstract- A digital servo system using a Digital Signal Processor (DSP) is presented in this paper. A Permanent Magnet Synchronous Motor (PMSM) with rotor position encoder and Hall sensor is used. The field oriented vector control technique is employed to achieve robust performance and fast torque response. The system uses position and speed regulations as the system outer loop, and the current regulation with vector control as the inner loop. A DSP system using TI's TMS320C240 is developed, and the proposed digital control strategy is implemented in the DSP.

Key Words: Vector Control, Motion Control, Servo System, Digital Control, Permanent Magnet Synchronous Motor (PMSM), Digital Signal Processor (DSP)

I. Introduction

Precise motion control plays an important role in various areas such as automation industry, semiconductor industry, etc. Permanent magnet synchronous motors (PMSM) are ideal for advanced motion control systems for their potentials of high efficiency, high torque to current ratio, and low inertia. Advances in Digital Signal Processors (DSP) have greatly enhanced the potential of PMSM in servo applications. Digital control can be implemented in the DSP, which makes it superior to analog based stepper control, since the controller is much more compact, reliable, and flexible. High performance of PMSM can be obtained by means of field oriented vector control, which is only realizable in a digital based system.

In this paper a DSP based servo system is presented. A digital servo controller using TI's TMS320C240 is developed. Position and speed regulations are developed to ensure accurate position control and fast tracking, and current regulation with field oriented vector control is implemented to secure fast dynamic response. The system has been proved to be robust and effective with very reasonable cost.

II. Analysis of PMSM Vector Control

The model of a PMSM is shown in Fig. 1. Different reference frames can be used to analyze the motor, that is, 3-phase frame (a-b-c), stationary frame (x-y), or rotational frame (d-q) [1]. From the control point of view, the d-q reference frame is convenient and most widely used. Note that the d-axis of the reference frame is locked to that of the permanent magnet.

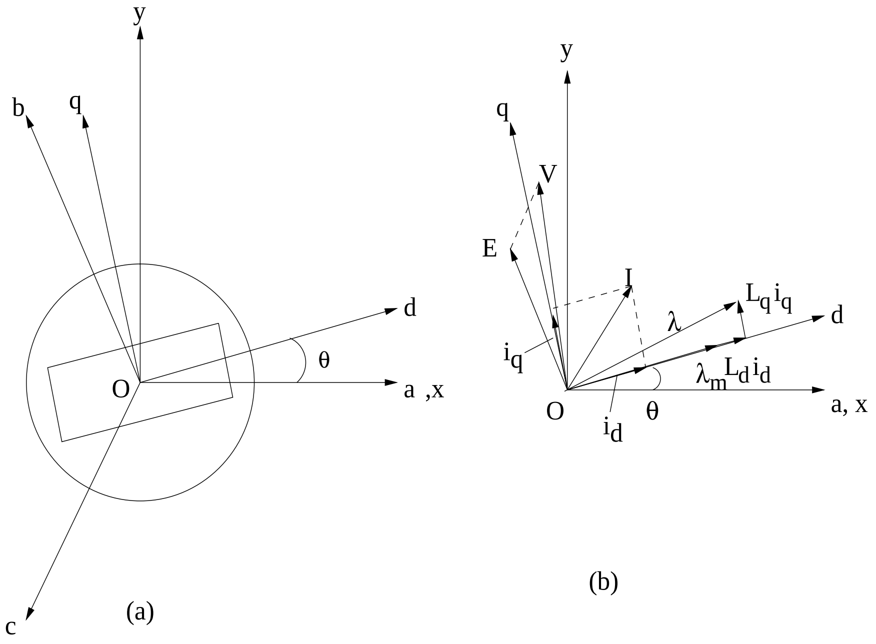

Figure 1: (a)Different frames of the PMSM. (b)Flux, Current and Voltage Vectors

The voltage and flux equations for a PMSM in the rotational d-q reference frame can be expressed as:

$$V_d = R_s i_d + \frac{d\psi_d}{dt} - \omega\psi_q \tag{1}$$

$$V_q = R_s i_q + \frac{d\psi_q}{dt} + \omega\psi_d \tag{2}$$

$$\psi_d = L_d i_d + \psi_m \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

where V_d, V_q and i_d, i_q are voltages and currents in the d-q axis, R_s is the stator winding resistance, L_d, L_q are inductances in d-q axis, ψ_d, ψ_q are flux linkages in d-q axis, ψ_m is the main flux linkage of the permanent magnet, and ω is the angular frequency of the rotor. The transformation between different reference frames can be achieved by[1]

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = T_{abc-dq} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_x \\ i_y \\ 0 \end{bmatrix} = T_{abc-xy} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T_{xy-dq} \begin{bmatrix} i_x \\ i_y \end{bmatrix} \tag{7}$$

where

$$T_{abc-dq} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

$$T_{abc-xy} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

$$T_{xy-dq} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

and

$$\begin{aligned} T_{dq-abc} &= T^{-1}_{abc-dq}, \\ T_{xy-abc} &= T^{-1}_{abc-xy}, \\ T_{dq-xy} &= T^{-1}_{xy-dq}. \end{aligned}$$

The torque T_e can be written as

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_d i_q - \psi_q i_d) = \frac{3}{2}\frac{P}{2}[\psi_m i_q - (L_q - L_d) i_d i_q] \tag{8}$$

where P is the motor pole numbers.

It is apparent that if we can control i_d to be zero then the torque is directly proportional to i_q. Hence, vector control is achieved by controlling i_d to be zero and i_q to produce the required torque. Thus, the PMSM has the fastest dynamic response and also operates in the most efficient state. The vector control scheme is shown in Fig. 2.

The mechanical equation of the PMSM can be written as

$$T_e = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + T_L \tag{9}$$

where T_e is the motor torque, J the inertia, θ the rotor position, B the friction constant, and T_L the load torque.

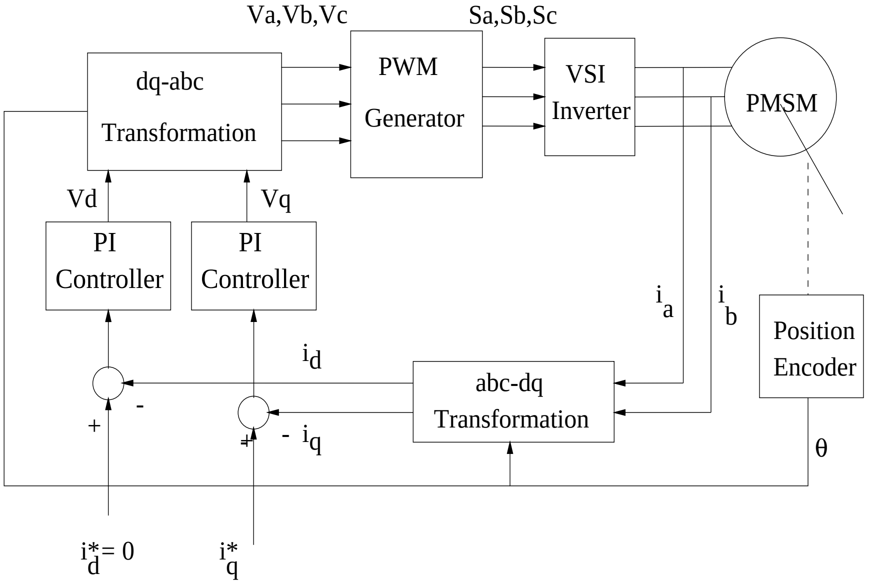

Figure 2: Vector Control of the PMSM

III. Servo Control Scheme

A. System Structure

The servo control scheme of the PMSM is illustrated in Fig. 3. As shown in Fig. 3, the controller has an inner loop of current regulation using vector control, and an outer loop of hybrid speed and position regulation. This dual-loop structure ensures the fast torque response by using the vector control, high position accuracy with the position controller, and fast tracking performance with the hybrid (speed and position) control. The structure is also important to secure the stability of the system.

B. Initial Position Identification

Incremental encoders can only give displacements from the initial position and cannot provide absolute position. Hence to achieve vector control usually initial position alignment to a known position is required. However in some circumstances such alignment is not desired and needs avoided.

By means of Hall sensors the rotor initial position can be identified, and further corrected when the rotor starts rotating. Assuming the Hall sensors are located at each phase, as shown in Fig. 4. The output signals of the Hall sensors are illustrated in Fig. 5. It can be seen that the resolution of the Hall sensor signals are 60^o (electrical degree). Table 1 shows the possible combinations corresponding to different positions.

From Fig. 5 and Table 1, given a specific Hall sensor output combination, the rotor must reside in certain region with a range of 60^o. The initial position is determined as follows. When a group of output signals are obtained, for example, (101), we can find which region the rotor is in (region 1 in this example). We can set the initial position at the center of the region (30^o in this example). It can be seen that the maximum error of the initial position is 30^o, which occurs

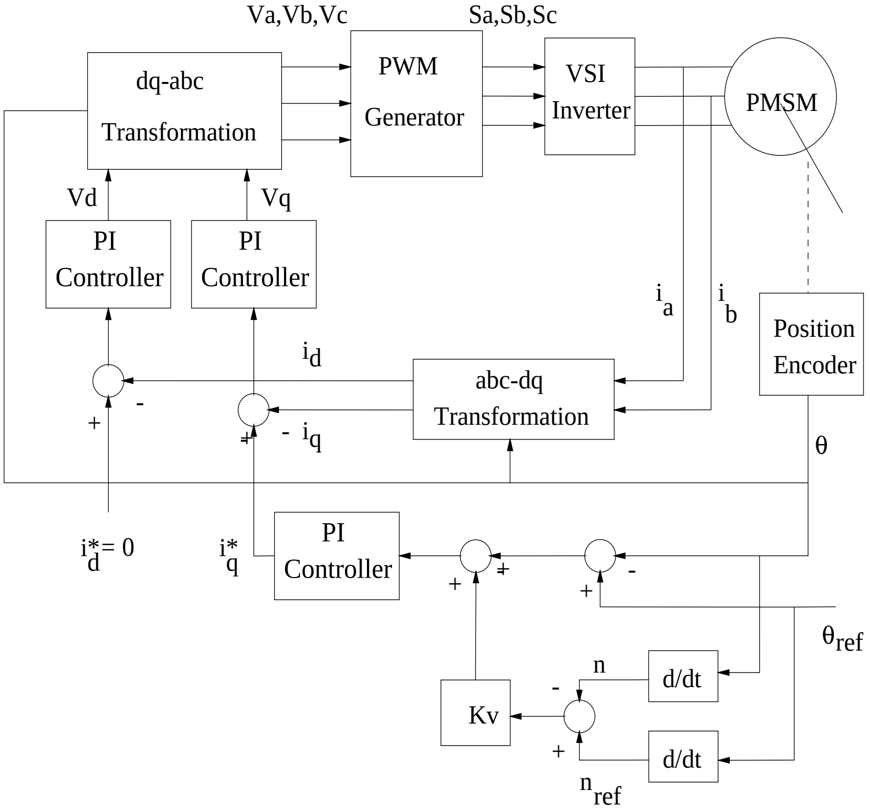

Figure 3: Servo Control Scheme of the PMSM

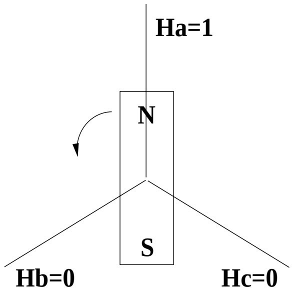

Figure 4: Hall Sensor Locations

when the rotor is at the edge of two regions. However, even with 30^o error, the motor will still be able to produce sufficient torque to start the motor.

Once the motor starts rotating, the position can be readily corrected when the rotor moves out of the initial region and enters the next region. This position is accurate. In the previous example, when the motor starts rotating in the positive direction from region 1, the rotor position can be corrected when the position $\theta = 60^o$.

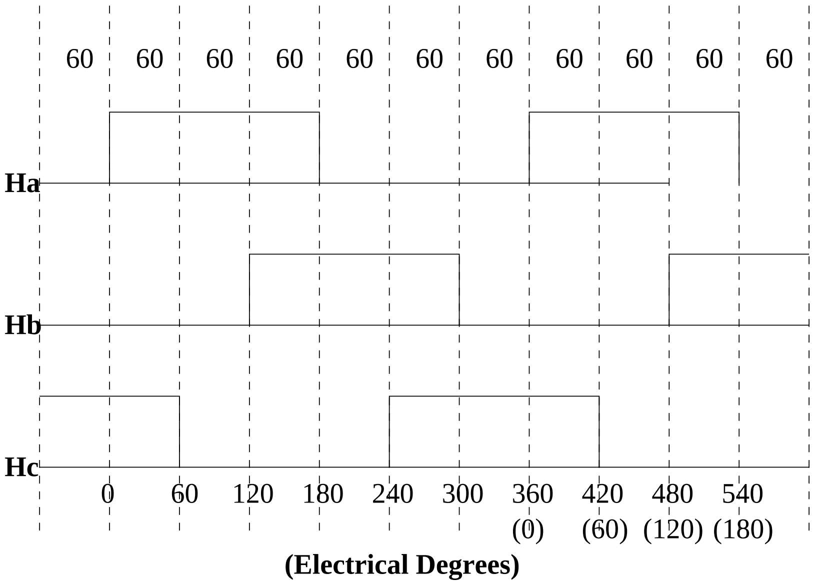

Figure 5: Hall Sensor Output Signals

Region	H_a	H_b	H_c	Position
1	1	0	1	0-60
2	1	0	0	60-120
3	1	1	0	120-180
4	0	1	0	180-240
5	0	1	1	240-300
6	0	0	1	300-360

Table 1: Combinations of Hall Sensor Output Signals

C. Anti-Hunt Processing

When the motor reaches to the required position and needs to produce torque at standstill, special attention needs paid since the rotor will very likely oscillate (hunting). A variable gain anti-hunt algorithm is developed.

As shown in Fig. 6, the PI gains of the speed and position regulators are kept normal when the position error is large. When the position error is small enough (in region 1 or 3), the gains should be gradually reduced. Once the rotor enters the anti-hunt window (region 2), the gains are reset to zero. This approach has effectively avoided the rotor oscillation at the standstill position.

IV. Hardware Setup

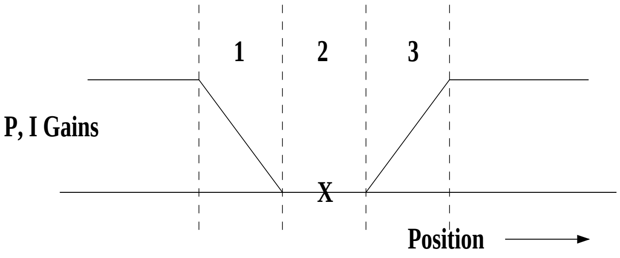

Figure 6: Variable Gains for Anti-Hunt

The DSP based servo system is shown in Fig. 7. The system is composed of the DSP controller, power circuit, PMSM with encoder/Hall sensor, and development tools (emulator and host PC).

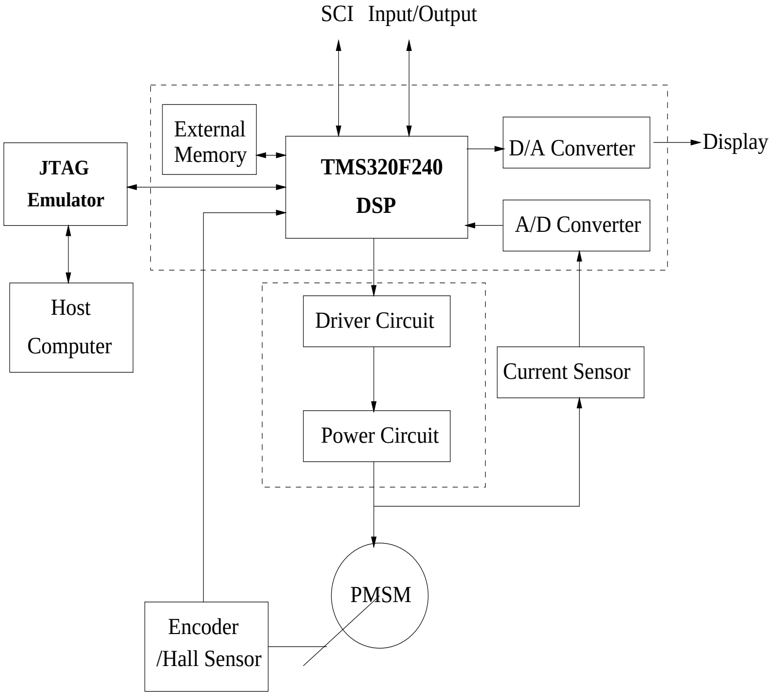

Figure 7: Servo System Structure

Fig. 8 shows the picture of the DSP servo controller. Main components in the controller include DSP (TMS320F240), FPGA, memories, DAC, etc. The controller directly outputs PWM signals for the power circuit, and accepts analog signals (motor currents, analog commands, etc.) and position information (encoder and Hall sensor signals). The controller also has RS232 interface for on-line tuning. A new version of the controller, which is under development using TMS320F243, will also include Control Area Network (CAN) bus interface.

V. Conclusions

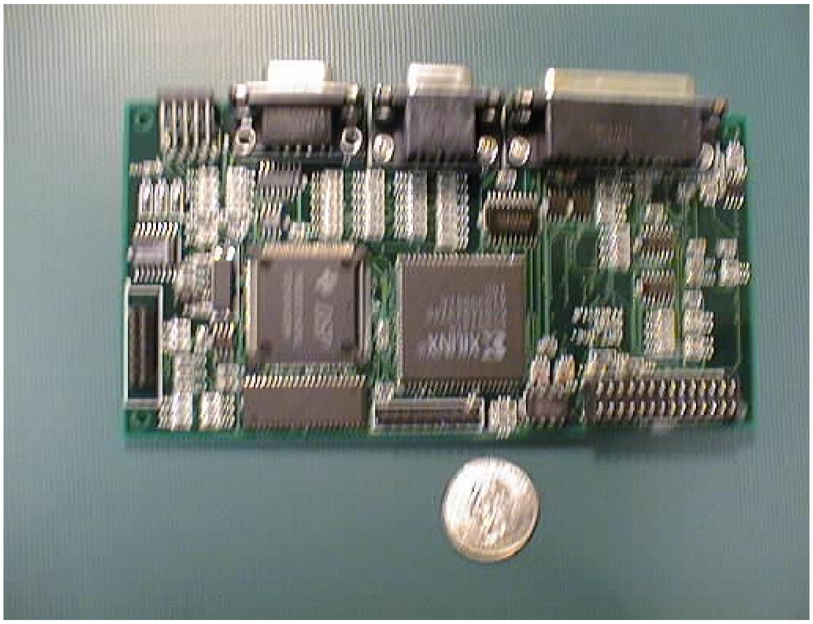

Figure 8: The DSP Servo Controller

A TMS320F240 based DSP servo controller has been developed. The system has reached compact size and high reliability. Highly complicated digital control algorithms, including vector control, current regulation, and speed/position regulations have been implemented in the DSP. To avoid initial rotor alignment, initial position identification using the Hall sensor signals are implemented. Anti-hunt technique using anti-hunt window and variable controller gains are also developed. The system has been proven to be highly effecticve and efficient with relatively low cost.

VI. References

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