A NOVEL SENSORLESS CONTROL TECHNIQUE FOR PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM) USING DIGITAL SIGNAL PROCESSOR (DSP)

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Abstract- A novel sensorless control scheme for Permanent Magnet Synchronous Motor (PMSM) is presented. The rotor position estimation is obtained by the position perturbation algorithm, and high performance of the PMSM is achieved by using the vector control technique. DSP56005 is used to realize the position estimation and vecor control algorithms. Experimental results are presented to substantiate the proposed scheme.

Key Words: Vector Control, Sensorless Control, Position Perturbation, Permanent Magnet Synchronous Motor (PMSM), Digital Signal Processor (DSP)

I. Introduction

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. High performance can be obtained by means of vector control. However, vector control requires information of rotor position, and usually a position encoder is used to achieve such a control scheme, which unfortunately increases the cost and causes inconvenience, and in some occasions is even not permitted. People are increasingly interested in the sensorless controls for PMSM and various rotor position estimation schemes have been reported[2]-[5]. However applications of the reported schemes are still limited since these algorithms are either structure demanding or parameter sensitive.

In this paper a position estimation scheme is proposed. Based on the small position perturbation algorithm, the rotor position is obtained by modifying the initial prediction of the rotor position. The estimated rotor position is used in the vector control algorithm. A Motorola DSP56005 based controller is designed and implemented which can operate in both development and standalone modes. Experimental results indicate that high performance is achieved with the rotor position estimation and vector control algorithm in the DSP.

II. Vector Control of PMSM

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 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.

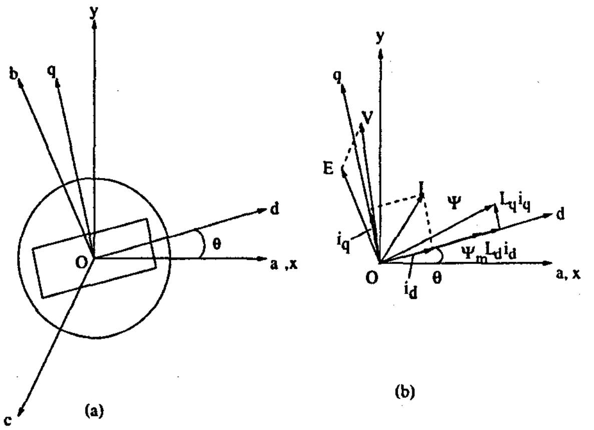

Figure 1: (a)Different frames of the PMSM. (b)Flux, Current and Voltage Vectors

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

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

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.

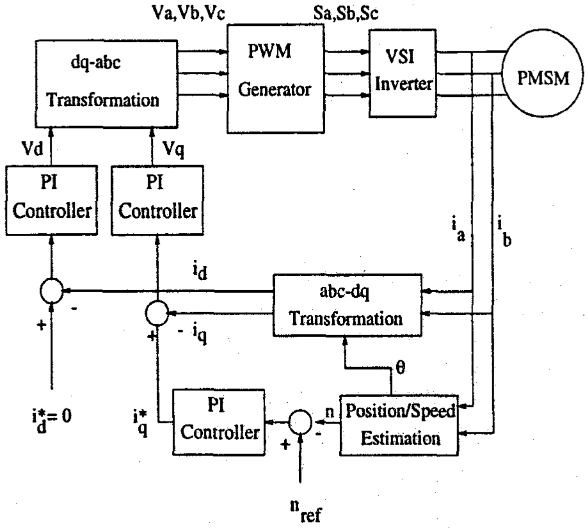

Figure 2: Vector Control of the PMSM

It is critical that in this scheme the rotor position must be always known so that proper current vector can be applied.

III. Rotor Position Estimation

A. Position Perturbation Algorithm

Assume that there is a small perturbation, $\Delta\theta$, from the actual rotor position θ, as shown in Fig. 3. The d-q axis denotes the reference frame corresponding to the actual rotor position, and d^e-q^e the perturbated rotor position.

The flux calculated in the d^e-q^e frame is denoted by ψ^e. The projection of ψ^e onto the q^e axis is:

$$\psi^e_{q^e} = L_q i_{q^e} \tag{9}$$

The projection of the actual flux vector ψ onto the q^e axis is ψ_{q^e},

$$\begin{aligned} \psi_{q^e} &= -\psi\sin(\Delta\theta - \delta) \\ &= -\psi\sin\Delta\theta\cos\delta + \psi\cos\Delta\theta\sin\delta \end{aligned} \tag{10}$$

where δ is the electrical angle between the flux linkage ψ and the d axis.

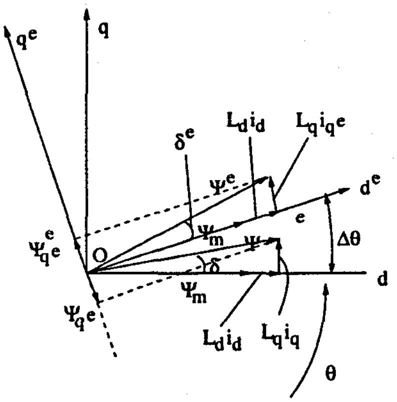

Figure 3: Flux under position perturbation

Because the reluctance of the permanent magnet is high, hence

$$L_d i_d << \psi_m \tag{11}$$
$$L_q i_q << \psi_m \tag{12}$$

Therefore, δ is small, and so is $\Delta\theta$. Hence, we can take the following approximations

$$\begin{aligned} \psi \cos\delta &= \psi_m, \\ \psi \sin\delta &= L_q i_q, \\ \sin\Delta\theta &= \Delta\theta, \\ cos\Delta\theta &= 1 \end{aligned} \tag{13}$$

Then (10) can be approximated by

$$\psi_{q^e} = -\psi_m \Delta\theta + L_q i_q \tag{14}$$

Due to the position perturbation $\Delta\theta$, the error flux in the q^e axis denoted by $\Delta\psi_{q^e}$ is

$$\begin{aligned} \Delta\psi_{q^e} &= \psi^e_{q^e} - \psi_{q^e} \\ &= L_q i_{q^e} - (-\psi_m \Delta\theta + L_q i_q) \\ &= \psi_m \Delta\theta + L_q (i_{q^e} - i_q) \end{aligned} \tag{15}$$

As δ and $\Delta\theta$ are small, by the approximations in (13), (15) can be further written as

$$\Delta\psi_{q^e} = \psi_m \Delta\theta \tag{16}$$

or, the position error can be expressed in terms of flux error by

$$\Delta\theta = \frac{\Delta\psi_{q^e}}{\psi_m} \tag{17}$$

Thus if $\Delta\psi_{q^e}$ is known, $\Delta\theta$ can be computed and the rotor position can be corrected.

B. *Procedures of Rotor Position Estimation*

The rotor position is estimated based on an initial prediction and the position perturbation algorithm described above. The general torque equation of the motor can be expressed by a second order equation as:

$$T_e = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + T_L \tag{18}$$

where T_e is the electromagnetic torque, J the inertia of the rotor, B the friction constant, and T_L the load torque. By solving the discrete difference equation for (18), the predicted position θ_e can be obtained based on the previous rotor positions by[2]:

$$\theta_e(k) = 3\theta(k-1) - 3\theta(k-2) + \theta(k-3) \tag{19}$$

This predicted position can be used to start a position perturbation process. The estimated flux based on the predicted position for a permanent magnet motor can be represented in the stationary x-y reference frame as:

$$\psi^e_x(k) = \psi_m \cos\theta_e(k) + L_x i_x(k) \tag{20}$$
$$\psi^e_y(k) = \psi_m \sin\theta_e(k) + L_y i_y(k) \tag{21}$$

The flux of the motor can also be obtained through integration by measuring the phase voltage and current:

$$\psi = \int (V - Ri)dt \tag{22}$$

where ψ is the flux linkage vector, V the terminal voltage vector, i the current voltage vector, and R the winding resistance. The discrete form of this integration in the stationary x-y reference frame is

$$\psi_x(k) = [V_x(k) - Ri_x(k)]\Delta T + \psi_x(k-1) \tag{23}$$

$$\psi_y(k) = [V_y(k) - Ri_y(k)]\Delta T + \psi_y(k-1) \tag{24}$$

where ΔT is the sampling period, ψ_x, ψ_y, V_x, V_y and i_x, i_y are flux linkages, terminal voltages and phase currents in x-y frame respectively.

The flux error due to the position error in the x-y reference frame is:

$$\Delta\psi_x(k) = \psi^e_x(k) - \psi_x(k) \tag{25}$$
$$\Delta\psi_y(k) = \psi^e_y(k) - \psi_y(k) \tag{26}$$

By the $xy - dq$ transformation the flux error in the d^e-q^e reference frame can be obtained by

$$\Delta\psi_{q^e}(k) = -\Delta\psi_x(k)\sin\theta_e(k) + \Delta\psi_y(k)\cos\theta^e(k) \tag{27}$$

$$\Delta\psi_{d^e}(k) = \Delta\psi_x(k)\cos\theta_e(k) + \Delta\psi_y(k)\sin\theta^e(k) \tag{28}$$

With regard to the position perturbation algorithm only the flux error on the q^e axis is of interest.

Using (17) the position perturbation can be obtained by (29):

$$\Delta\theta(k) = \frac{\Delta\psi_{q^e}(k)}{\psi_m} \tag{29}$$

Equation (29) gives the position error between the actual position and the initially predicted position. By correcting the predicted position with this error, we can obtain an improved position estimation. The corrected postion is

$$\theta(k) = \theta_e(k) - \Delta\theta(k) \tag{30}$$

The block diagram of this algorithm is shown in Fig. 4.

IV. Implementation of Sensorless Control Scheme

The position estimation and vector control algorithm has been implemented using Motorola DSP56005. DSP56005 is ideal in digital control with sophisticated algorithms for its powerful calculation capability and high speed. With DSP56005, one instruction cycle with a 50 MHz clock only takes 40 ns, and it also has powerful interfacing capabilities and convenient PWM outputs. The block diagram for the experimental setup is shown in Fig. 5.

The DSP system as shown in Fig. 5 is able to operate in two modes: development mode or standalone mode. In development mode, the DSP system is connected to the host computer through the Motorola ADS system. In this mode programs are downloaded from the host computer and the execution process is also controlled by the host computer. This mode is suitable for the target system during the development stage since software and hardware debugging is convenient through the host computer. Once the software development is finalized and the DSP target system is completed, the DSP system can operate in the standalone mode. DSP56005 has a bootstrap program that can automatically download programs from external EPROM to its internal program RAM and then start execution. Both operation modes are implemented in the lab.

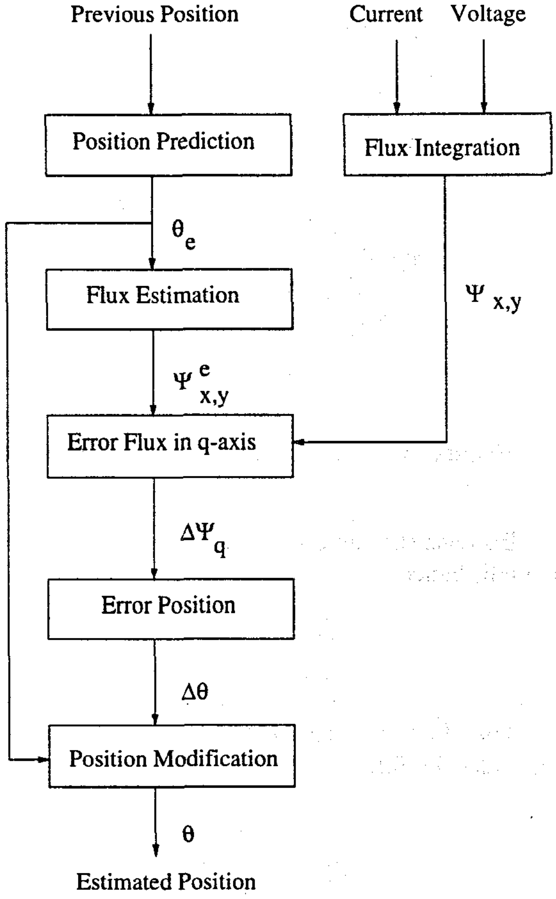

Figure 4: Block diagram of the position-perturbation estimation algorithm

V. Experimental Results

DSP 56005 application system has been set up and the position sensorless vector control scheme described above has been implemented. Experimental results have been obtained with a 4-pole PMSM.

Fig. 6 shows the estimated rotor position compared to that measured one through a rotor position encoder. The motor is under a light load in this test. It can be seen that the estimated rotor position is in good accordance to the actual rotor position.

Using the estimated rotor position and speed the closed loop vector control is achieved. The speed tracking performance is shown in Fig. 7. It can be seen that the estimated position is successfully used for the closed loop control and the speed can follow the command very well.

VI. Conclusions

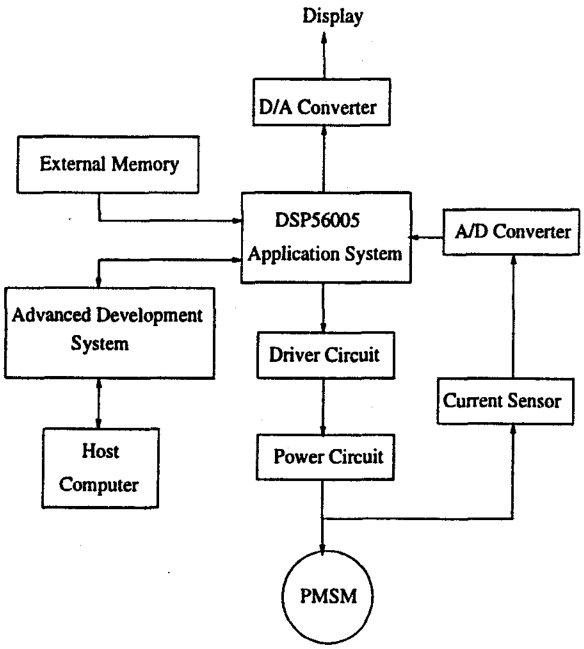

Figure 5: Block diagram of the DSP56005 system

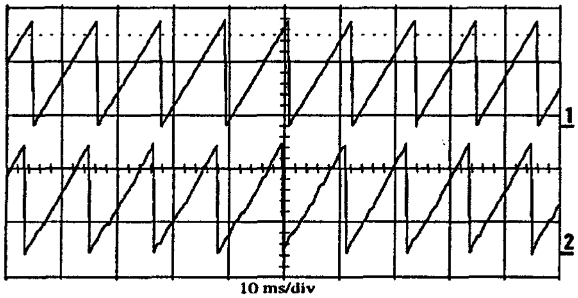

Figure 6: (1) Position measured through encoder. (2) Estimated position.

A position perturbation based position and speed estimation algorithm is proposed and experimental results are obtained. The accordance of the estimated rotor position to the actual position indicates that this algorithm is effective and can be used to replace the position encoder. Vector control of the PMSM is realized by using the estimated position and speed. Advanced speed tracking performance and high dynamic response is achieved.

The proposed position estimation and vector control algorithms are implemented in the DSP56005 based digital control system. Two different operation modes (development mode and standalone mode) have been realized. By using DSP, sophisticated control algorithms can be implemented through software approach, and the control capability of the system is greatly enhanced.

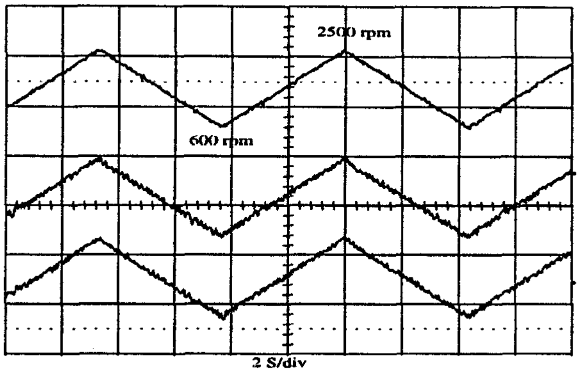

Figure 7: Speed tracking using the estimated position and speed. Upper: command speed. Middle: actual speed. Lower: estimated speed.

It needs to be noted that there is still a common limitation for the flux observation based position estimation: the low speed problem. Improvements for the algorithm and DSP implementation are in progress and more comprehensive results are expected.

VII. References

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VIII. Author Biographies

Minghua Fu received his B.S. and M.S. degree from Tsinghua University, China, in 1985 and 1987 respectively. He has been with the Department of Electrical Engineering at The Ohio State University since 1995 pursuing his Ph.D. degree. His research interests are in the design and analysis of electrical machines, on-line measurement of electrical machines, digital signal processor and microcontroller applications, motion control, and biomedical applications.

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