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PMSM AXIS DRIVE CONTROLLER FOR THE ROBOTIC APPLICATIONS

Calin RUSU, Szabo ENIKŐ

Technical University of Cluj, Faculty of Electrical Engineering,
Dept. of Electrical Drives and Robots
15 Constantin Daicoviciu, RO-400020 Cluj,
E -mail: calin.rusu@edr.utcluj.ro

Abstract **– Permanent Magnet Synchronous Motors (PMSM) have wide applications in industry, especially in AC servo drives such as industrial robots. Motion control of multi-axis robots demand to compensate various kinds of non-linear dynamical forces. These forces can be considered as a disturbance for the electrical servo drive. Digital Signal Processors (DSP) has greatly enhanced the potential of PMSM servo drive in such applications. Most of controller drives the PMSM by using the field-orientation control mode. This method laid the motor at maximum theoretical performance. In order to prove its effectiveness the controller is applied to drive the joints of an industrial robot.**

Keywords: *PM Synchronous Motor Axis Drive, Field Oriented Control, Robot Motion Control*

1. INTRODUCTION

Most of industrial robots are widely uses to perform tasks such as welding, machine tending, material handling, grinding, packaging and assemblage. For the previous applications the robot drives cycle consist of acceleration, a part with constant speed, a retardation and standstill. The drive cycle usually has a low intermittence, so as the motor has to supply high torque during the cycle, but only during a small fraction of the total cycle time. The peak torque during the drive cycle can therefore be substantially higher than the rated torque of the motor. The electrical drive system becomes an important part of the robot.

A servo system is commonly used in an application that requires high instantaneous torque response, lower torque ripple and a wide adjustable speed range. The Permanent Magnet Synchronous Motor (PMSM) is considered to be a better fit for a servo application because the PMSM offers some advantages as low rotor inertia, high efficiency, efficient heat dissipation structure, and reduced motor size. The elimination of brushes reduces noise and suppresses the need for brush maintenance is another big advantage.

The motors inertia is another important parameter for the robot servo drives. During the acceleration time the motor not only has to supply torque to accelerate the load, but also has to supply the torque to accelerate itself.

On the other side, to control a multi-axis industrial robot request to compensate a various kinds of non-linear dynamical forces. These forces can be treated as an unknown disturbance and viewed as an external load torque disturbance for the drive system.

The control of the PMSM servo drive is not an easy task but, the advances in Digital Signal Processors (DSP) have greatly enhanced the potential of PMSM in servo applications. High performances can be obtained by means of field oriented vector control, which is only realizable in a digital based system.

A digital motion controller implementation based on a DSK243 microcontroller is considered since the controller is much more compact, reliable and flexible. Highly complicated digital algorithms, including vector control, current regulation, and speed/position regulations have been developed.

In order to investigate the dynamic behavior of the proposed PMSM servo drive, the dynamic model of an IRB L6/2 ABB industrial robot was considered. Hardware in loop simulation was made and it proves the efficiency for the proposed controller in multi-axis applications, at a relatively low cost.

2. PMSM MOTOR MODEL

For the PM synchronous machine the stator phase voltages and currents are ideally sinusoidal. The flux in the machine is mainly set up by the permanent magnets in the rotor, which ideally produce a sinusoidal distributed flux in the air gap. There are some different ways of mounting the magnets on the rotor. Among these we mentioned three of them; with *surface mounted magnets*, *inset magnets* and *buried magnets* [3].

Depending on these configurations, different properties of the machine are obtained. For the PMSM with surface mounted magnets, the rotor iron is approximately round and the stator inductance is low, as well as independent of the rotor position. The control of the machine becomes simple and the reluctance effect can be neglected. Field weakening is difficult due to the low stator inductance, and thus the operation above base speed becomes difficult. For the PMSM with inset magnets, the stator inductance becomes position dependent. During field weakening, a certain amount of reluctance torque is obtained, making the operation above base speed more feasible. This configuration is properly for traction applications, where the operation above base speed is frequent. In case of PMSM with buried magnets the flux density in the air gap can be higher than in the magnets. Low energy magnets (Ferrites) can thus be used and high torque density is obtained.

Different reference frames can be used to analyze the motor, that is, 3-phase frame (*a-b-c*), stationary frame (*α-β*), or rotational frame (*d-q*) [5]. In order to have constant reference values for the currents, the control is performed in a reference frame rotating synchronously with the rotor, see Fig. 1.

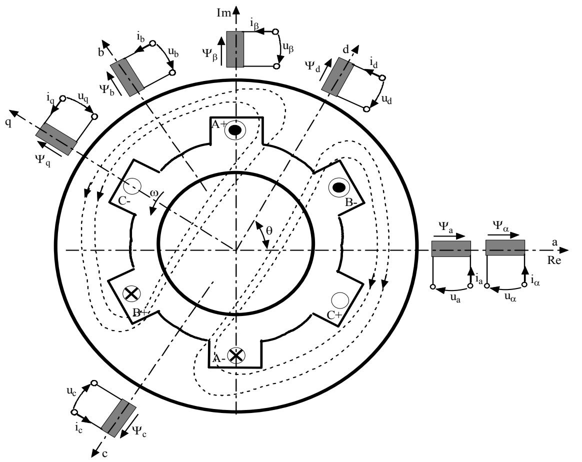

Figure 1. Rotor oriented coordinate system – *dq*

The rotor oriented coordinate system – *d-q*, is rotating synchronously with the rotor, while the coordinate system *α-β* is stationary. With quadrature current control, the current vector is always aligned with the *q*-axis. Only the fundamental of the flux and current distribution in the machine is considered. The state equations of PMSM model in the rotational *d-q* reference frame are described by the following equations:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_{sd}} & \omega\frac{L_{sq}}{L_{sd}} \\ -\omega\frac{L_{sd}}{L_{sq}} & -\frac{R_s}{L_{sq}} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{sd}} & 0 & 0 \\ 0 & \frac{1}{L_{sq}} & -\frac{\omega}{L_{sq}} \end{bmatrix} \cdot \begin{bmatrix} u_{sd} \\ u_{sq} \\ \psi_m \end{bmatrix} \tag{1}$$

L_{sd} and L_{sq} are the stator inductances in the *d* and *q*-directions, respectively.

The torque T_e can be written as

$$T_e = \frac{3}{2}\frac{P}{2}\cdot\left(\psi_{sd} i_{sq}(t) - (L_{sq} - L_{sd})\cdot i_{sd}(t)\cdot i_{sq}(t)\right) \tag{2}$$

where *P* is the motor pole numbers.

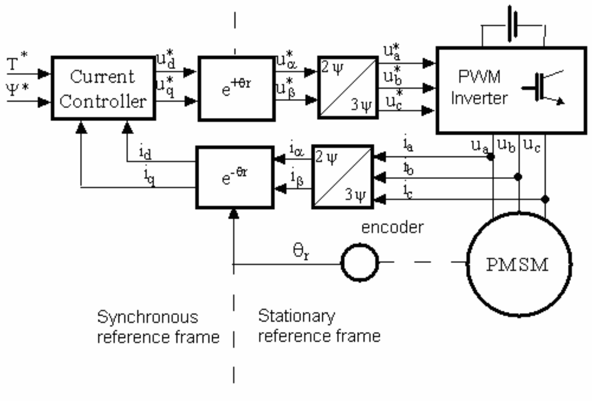

Figure 2. A current controller in a synchronous frame

A block diagram of a synchronous reference frame controller is shown in Figure 2. A coordinate transformation has to be made to obtain the current values in the synchronous reference frame and the voltage references in the stationary reference frame.

3. ANALYSIS OF PMSM VECTOR CONTROL

To control a PM synchronous machine different algorithms can be used, in either a stationary or a synchronous reference frame. A usually method is vector control in synchronous coordinates, which today is widely used in industrial robots.

In this application, the so called quadrature current control is used. This means that $i_{sd} = 0$. Generally, for machines with surface mounted magnets, the rotor has no saliency, so $L_{sd} = L_{sq} = L_s$. Then quadrature current control gives the maximum torque per unit stator current. The torque equation now become simple, as the torque only is depending on i_{sq} and ψ_m.

$$T_e = \frac{3}{2}\frac{P}{2}\cdot\psi_m i_{sq}(t) = K_T \cdot i_{rms} \tag{3}$$

K_T is the torque constant and i_{rms} is the root mean square value of the stator line current. The value of the torque constant is only relevant when quadrature current control is applied, i.e. i_{sd}=0. Since K_T is proportional to the magnet flux-linkage - ψ_m, a change in the magnets remanence directly affects K_T . The required stator voltage modulus $\left|u_s\right|$ is calculated as

$$\left|u_s\right| = \sqrt{u_{sd}^2 + u_{sq}^2} \cdot \tag{4}$$

At no load, which means that i_{sq}=0, the stator voltage is

$$\left|u_s\right| = \omega_s \cdot \psi_m \tag{5}$$

It is apparent that if we can control i_{sd} to be zero then the torque is directly proportional to i_{sq}. Hence, vector control is achieved by controlling i_{sd} to be zero and i_{sq} 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. 3. The mechanical equation of the PMSM can be written as

$$T_e = J\frac{d^2\theta}{dt} + B\frac{d\theta}{dt} + T_L \tag{6}$$

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

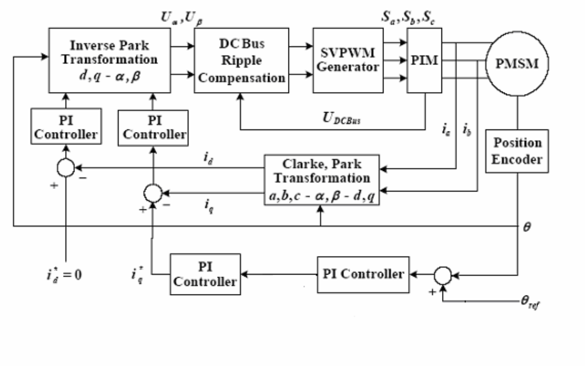

Figure 3: Vector Control of the PMSM

4. DIGITAL MOTION CONTROLLER DESIGN

A PMSM with sinusoidal flux distribution and 4 pairs of poles with the following parameters: R_s=2,75Ω, L_{sd}= L_{sq}=0.0085H, Ψ_M=0.175Wb, J=0.0008Kg.·m^2, was used. Simulation results are presented in the Fig. 4. A disturbance step torque is applied from 3Nm to 10Nm, at the moment t=0.04s. An encoder sensor with a 2000 pulses/rev is used to provide the information required by the speed and position control loops. The rotor position is also required for the coordinate conversion from dq to abc. Stator currents - i_a i_b i_c; speed - ω_m; motor torque - T_e, and PWM voltage – V_{bc} are depicted by the next pictures.

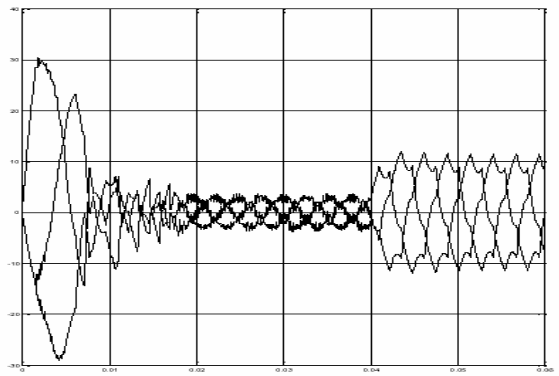

Figure 4a. Stator currents - i_a,, i_b, i_c (A)

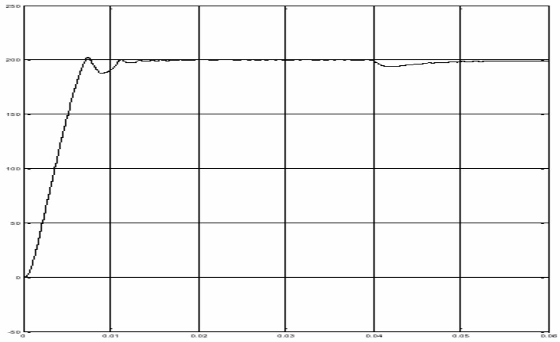

Figure 4b. Rotor speed – ω_m (rad/sec)

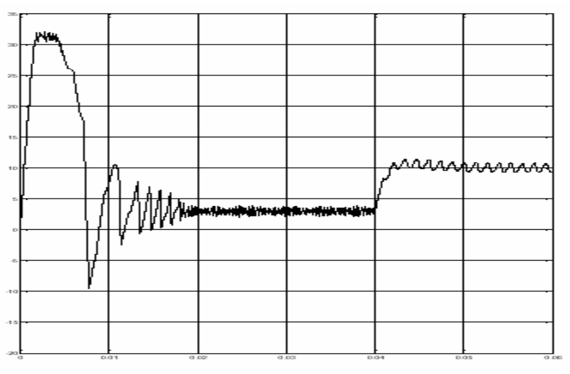

Figure 4c. Motor torque – T_e (Nm)

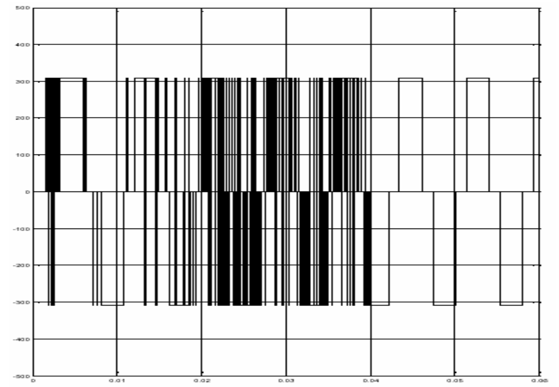

Figure 4c. PWM voltage – V_{BC} (V)

Fig. 5 shows the DSP controller structure based on a DSK243 motion control kit. Main components in the controller include DSP (TMS320F243), FPGA, memories, DAC, etc. The controller directly outputs PWM signals for the PIM (power inverter module) and accepts analog signals (motor currents, analog commands, etc.) and position information (encoder and Hall sensor signals). The controller also has a RS232 interface for on-line tuning. A new version of the controller, which is under development, is based on a TMS320F2407, which will also include Control Area Network (CAN) bus interface.

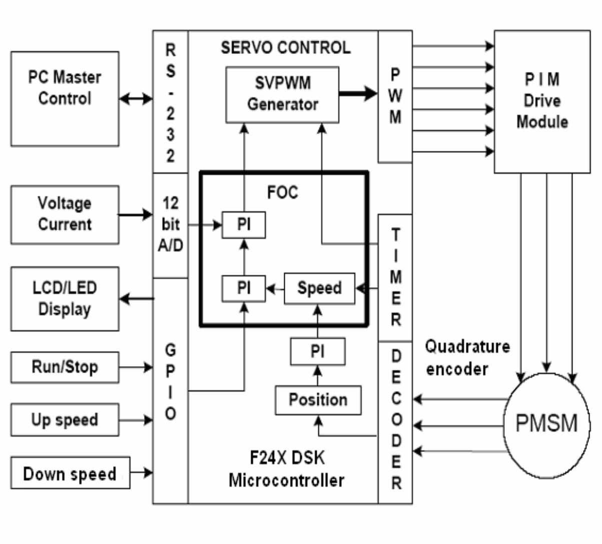

Figure 5: DSP System Structure

5. ROBOT CONTROLLER

In order to investigate the dynamic behavior of the proposed AC servo, an ABB IRB L6/2 industrial robot was considered, Fig. 6.

The robot axes are driven by PMSM servo drive with load torque fed by PWM inverters. In the simulation, the robot is programmed to move its second joint of the arm from $\theta_2 = -30^\circ$ to 30° during 1.5 seconds, and at the same time the third joints is moved from the position $\theta_3 = 45^\circ$ to $\theta_3 = -45^\circ$. The path trajectory to follow by each robot joint is a cubic polynomial function with zero condition for *velocities* and *accelerations* at *t*=0 and *t*=1.5 seconds [7].

The responds for second and third robot's joints, are shown in Fig. 7. Based on the robot arm dynamics the positions (θ_2, θ_3), speeds (ω_2, ω_3), accelerations (α_2, α_3) and torques – (T_2, T_3) for the second and third joint are depicted by the following figures.

Figure 6. ABB IRB L6/2 Industrial Robot

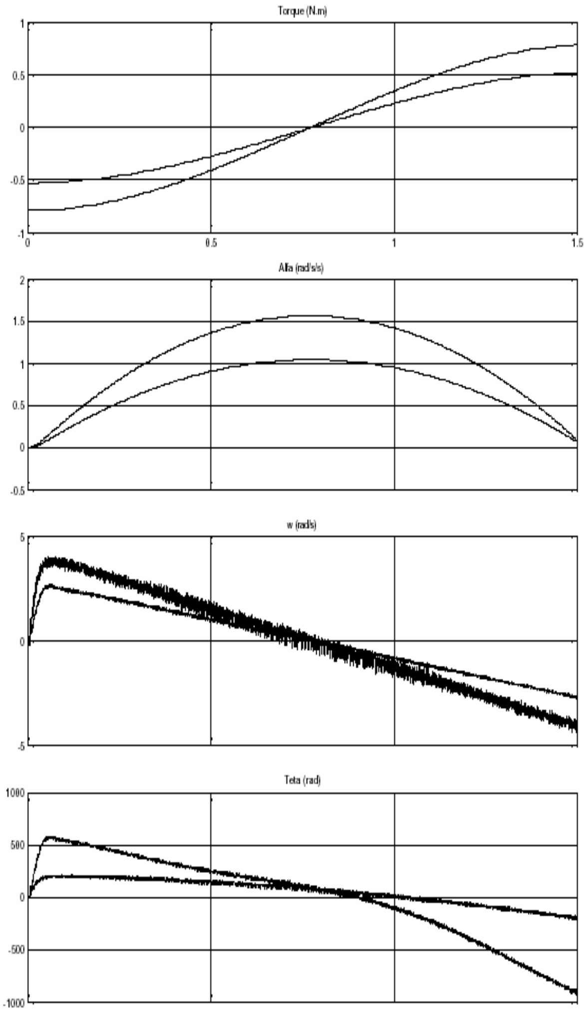

Figure 7. Robot axis (positions, speeds, accelerations and torques)

The behaviors for each servo drives with load torque observer are presented by Fig. 8 and Fig. 9, respectively. The speeds - ω_m; torques - T_e,; and currents - i_a i_b i_c can be compared with previous results.

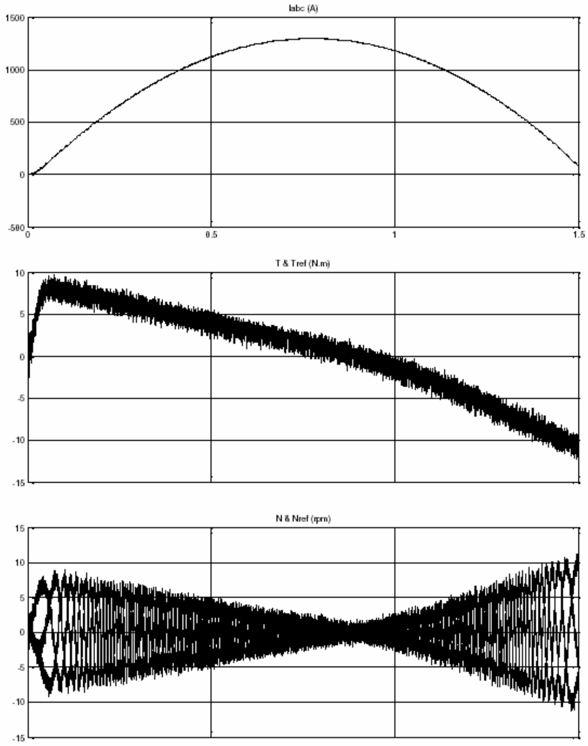

Figure 8. Second joint (speed, torque and stator currents)

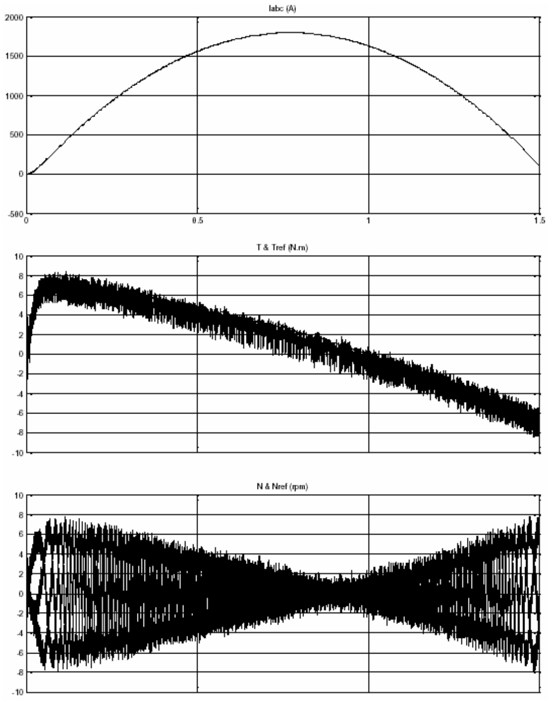

Figure 9. Third joint (speed, torque and stator currents)

CONCLUSION

An AC servo drive with PMSM is proposed for the industrial robot axis. The PM synchronous motor has to supply high torques during a small fraction of the total cycle time. The peak torques during the drive cycle can be substantially higher than the rated torque of the motor. A digital controller based on a DSK243 is used to implement the motion control for the robot axis. The controller drives the PMSM by using the field-orientation control mode. The digital implementation is considered since the controller is much more compact, reliable and flexible. Highly complicated digital algorithms, including vector control, current regulation, and speed/position regulations have been developed. To avoid initial rotor alignment, initial position identification using the Hall sensor signals is implemented. Hardware in loop simulations has proved the efficiency of the controller in motion control multi-axis applications, at a relatively low cost.

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