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Permanent Magnet Synchronous Motor Controller with Load Torque Observer

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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. A controller with load torque observer is proposed against the external disturbances associate with the mechanical and/or electrical subsystem. Digital Signal Processors (DSP) has greatly enhanced the potential of PMSM in servo applications. The 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 for the second and third joints of a robot arm.

Key words: *Motion Control, Servo System, Vector Control, PM Synchronous Motor, Load torque observer.*

Introduction

Industrial robots are widely uses to perform tasks such as welding, machine tending, material handling, grinding, packaging and assemblage. Food industry is also an extensive user of industrial robot technology today. To control a multi-axis industrial robot request to compensate a various kinds of non-linear dynamical forces. The computed torque method requires an exact robot model and a large amount of real time computation for the inverse dynamic. Even for the light robots with low ratio gear transmission, the non-linear and coupling dynamics cannot be considered negligible. These forces can be treated as an unknown disturbance and viewed as a load torque disturbance for the drive system. The electrical drive system becomes an important part of the robot. Robust or adaptive controllers are proffered for each robot joints.

For the most previous applications the drive 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 motors inertia is another important parameter for such 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.

The first industrial robots were equipped with Direct Current drives (DC-motors). But in the last decade, the most of industrial robot drives was replaced by the AC drives with permanent magnet synchronous motors (PMSM). PMSM is today the dominating technology. The benefit of the PMSM, compared to the DC-machine, is its lower price and minimum need of maintenance. But, the control of the PMSM, however, is more complex.

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 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. A load torque estimation method and compensation is used to obtain a robust motion control when the load torque and parameters change.

Position and speed regulations are developed to ensure accurate position control and fast tracking. Current regulation with field oriented vector control is implemented to assure a fast dynamic response.

PMSM Motor Model

For the permanent magnet synchronous machine (PMSM), 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.

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.

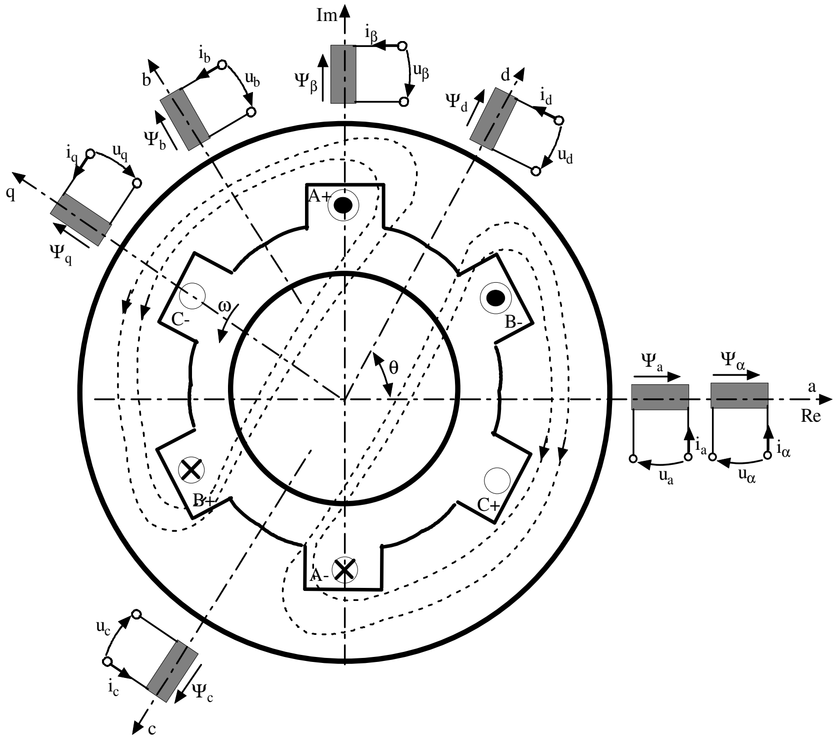

Fig. 1. Rotor oriented coordinate system – dq

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.

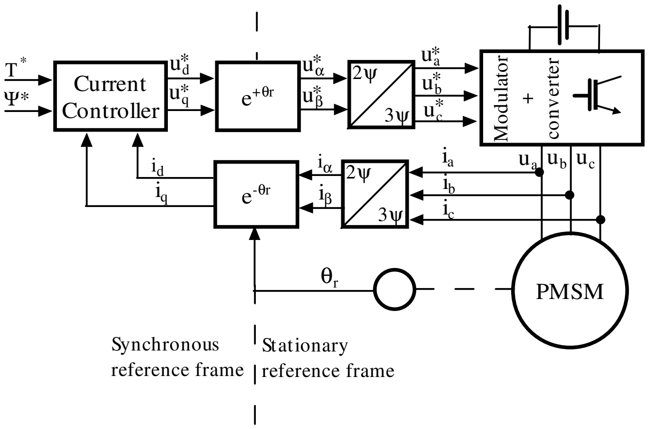

Fig. 2. A current controller in a synchronous frame

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.

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

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

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

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

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

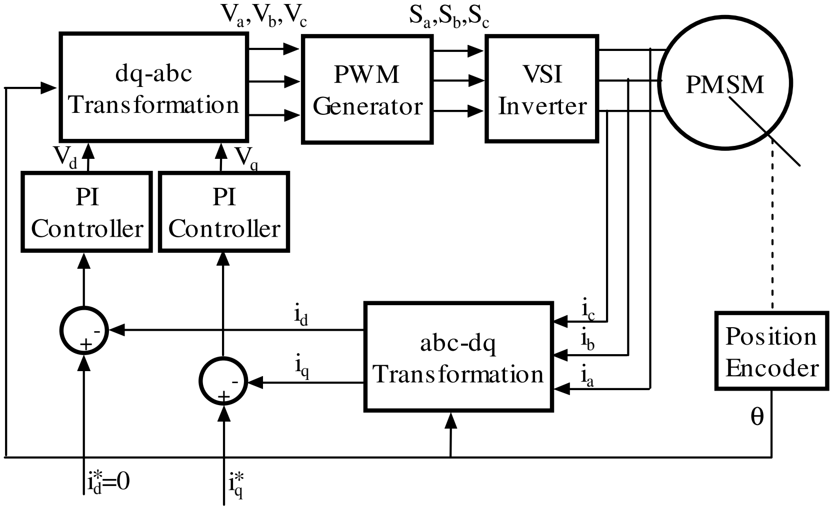

Fig. 3. Vector Control of the PMSM

Controller Design

The q-axis current controller is employed to control the position of the rotor. For this controller we impose an augmented state variable feedback controller based on the linear quadratic law (LQC), given by the equation (3).

The rank of controllability matrix for this system is 3, which means that the steady state value of z variable becomes zero if the input control is given in the form of $u(t) = -\hat{k} \cdot \hat{x}$.

$$\begin{aligned}
\dot{i}_{sq} &= -\frac{R_S}{L_{sq}} \cdot i_{sq} + \frac{1}{L_{sq}} \cdot u_{sq} - \frac{\omega}{L_{sq}} \cdot \Psi_m \\
\dot{\omega} &= \frac{3}{2} \frac{1}{J} \left(\frac{p}{2} \right)^2 \cdot \Psi_m \cdot i_{sq} - \frac{B}{J} \omega - \left(\frac{p}{2J} \right) T_L \\
\dot{\theta} &= \omega
\end{aligned} \tag{7}$$

$$\frac{d}{dt} \begin{bmatrix} \omega \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ y \\ z \end{bmatrix} + \begin{bmatrix} \frac{K_T}{J} \\ 0 \\ 0 \end{bmatrix} \cdot i_{sq} - \begin{bmatrix} \frac{1}{J} \\ 0 \\ 0 \end{bmatrix} \cdot T_L - \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \cdot y_r \tag{8}$$

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \cdot \hat{x}$$

The state feedback controller gain is determined by the optimal control law minimizing the performance index. A large feedback gain is needed for a fast reduction of error caused by the disturbance, which results in a very large current command. If the load torque is known an equivalent current command can be expressed in form of $T_L = K_T \cdot i_{qc}$. In such a way, the disturbance torque is estimated and compensated in order to get a robust controller. The equivalent *q–axis* current will express the load torque variation. Load torque $\hat{T}_L$ is considered to be constant in a sampling interval [4].

The instantaneous speed $\hat{\omega}$ and torque $\hat{T}_L$ estimations are based on extended Luenberger observer. The observer is designed considering T_L as an unknown input. The system equation can be expressed by:

$$\frac{d}{dt}\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{T}_L\end{bmatrix}=\begin{bmatrix}-\frac{B}{J} & 0 & -\frac{p}{2}\cdot\frac{1}{J}\\ 1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{T}_L\end{bmatrix}+\begin{bmatrix}K_T\cdot\frac{p}{2}\cdot\frac{1}{J}\\ 0\\ 0\end{bmatrix}\cdot i_{sq}-$$

$$-\begin{bmatrix}l_1\\ l_2\\ l_3\end{bmatrix}\cdot\left(y-\begin{bmatrix}0 & 1 & 0\end{bmatrix}\cdot\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{T}_L\end{bmatrix}\right) \qquad (9)$$

with l_1,, l_2 and l_3 are the elements of L matrix.

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 500 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.

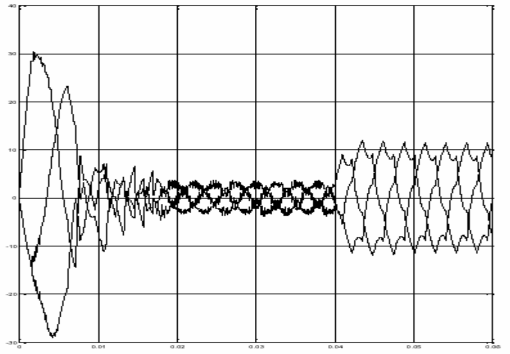

Fig. 4a. Stator currents - i_a,, i_b, i_c (A)

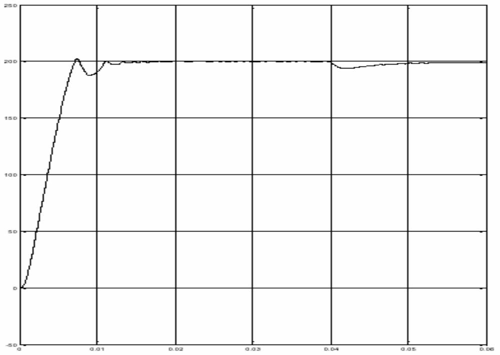

Fig. 4b. Rotor speed – ω_m (rad/sec)

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 IGBT power inverter unit, 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.

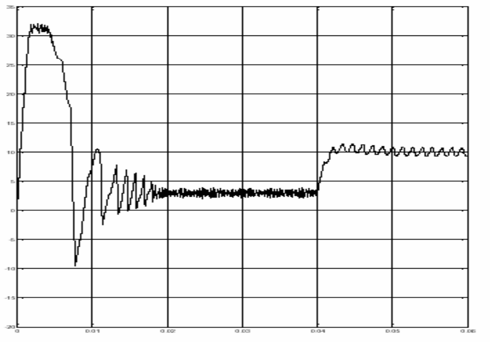

Fig. 4c. Motor torque – T_e (Nm)

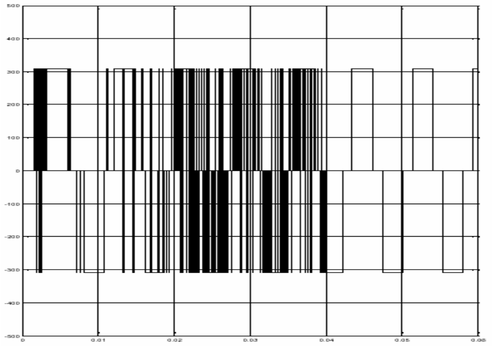

Fig. 4d. PWM voltage – V_{BC} (V)

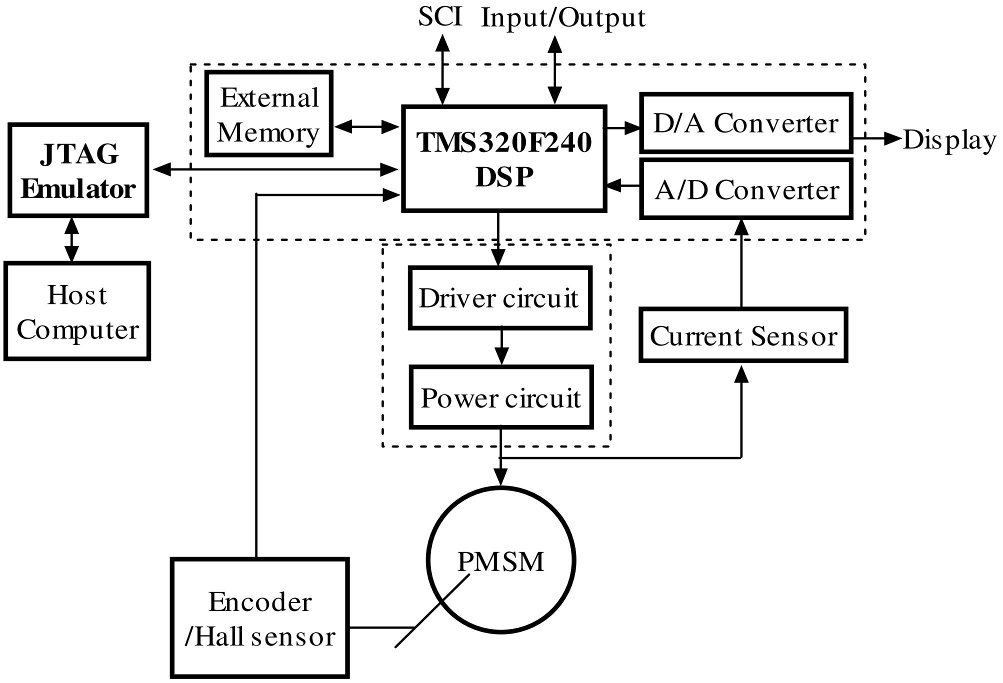

Fig. 5. DSK243 System Structure

Robot Controller

In order to investigate the dynamic behavior of the proposed AC servo, an IRB 1400 ABB industrial robot was considered, (fig. 6). The robot's axes are driven by PMSM with load torque fed by PWM inverters. In the simulation, the robot is programmed to move its second joint of the arm from $\theta_2 = -30°$ to 30° during 1.5 seconds, and at the same time the third joints is moved from the position $\theta_3 = 45°$ to $\theta_3 = -45°$. 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].

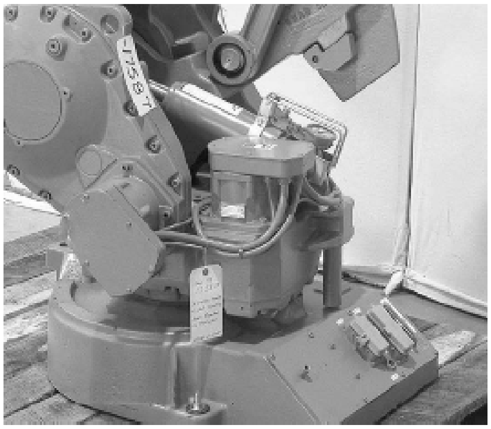

Fig. 6. IRB1400 Robot - PMSM drives

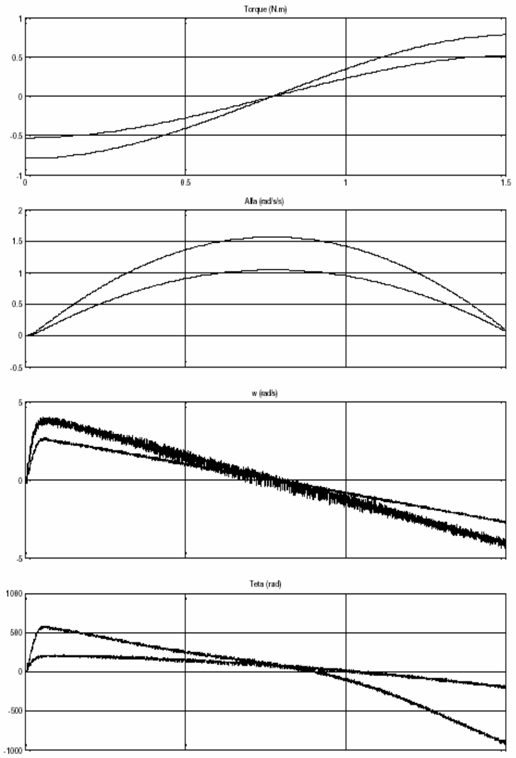

Fig. 7. Robot joints (positions, speeds, accelerations and torques)

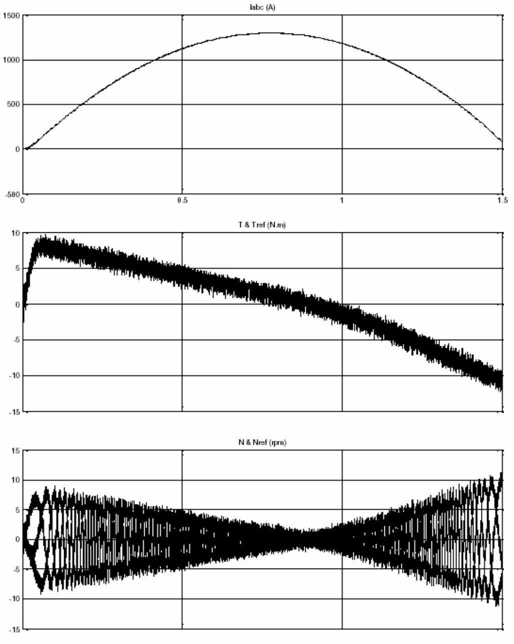

Fig. 8. Second joint (speed, torque and currents)

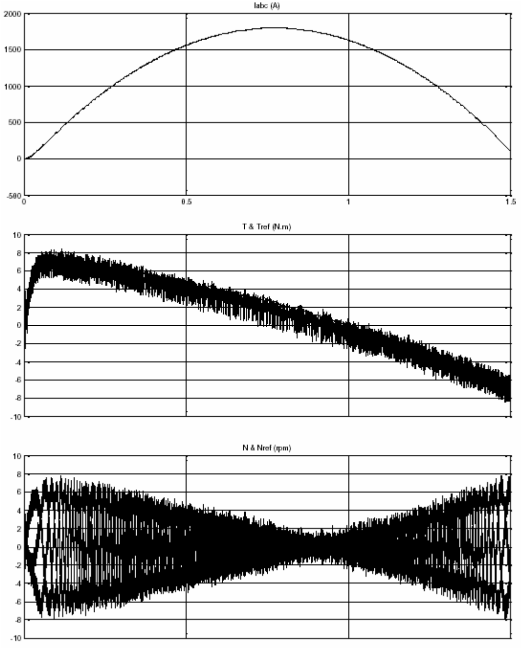

Fig. 9. Third joint (speed, torque and stator stator currents)

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), accelera-tions (α_2, α_3) and torques – (T_2, T_3) for the second and third joint are depicted by the following figures.

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.

Conclusions

A controller with load torque observer is proposed for the industrial robots powered by PMSM servo drives. The controller drives the PMSM by using the field-orientation control mode. External disturbances associate with the mechanical subsystem is estimated and compensated in order to obtain a robust controller.

A digital implementation based on a DSK243 kit 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.

References

1. Chiacchio P., Pierrot F., Sciavicco L., Siciliano B., 'Robust Design of Independent Joint Controllers with Experimentation on a High-Speed Paralleled Robot'., *IEEE Trans on Industrial Electronics,* Vol. 40, No. 4, 1993, pp.393-404.
2. Imecs M., Rusu C., Variable structure control of microrobot servo drive with field-oriented PM step motor, *EPE Chapter*, Lausanne 1994, pp. 301-307.
3. M. P. Kazmierkowski and H. Tunia, *Automatic Control of Converter-Fed Drives*, Amsterdam, The Netherlands: Elsevier, 1994.
4. J. S. Ko, J. H. Lee, S. k. Chung, and M. J. Youn 'A Robust Position Control of Brushless DC motor with Dead Beat Load Torque Observer' *IEEE Transaction on Industrial Electronics,* vol. 40, no. 5, pp. 512-520, 1993
5. D. W. Novotny and R. D. Lorentz, Introduction to field orientation and high performance AC drives, *IEEE-IAS Tutorial Course,* 1986.
6. Rusu C., An adaptive position controller of the hybrid stepper motor drive with load torque observer, *PCIM'98, Nurnberg, Germany, vol. IM Control*, pp.181-189.
7. Spong, M. W., and Vidyasagar, M., *Robot Dynamics and Control,* John Wiley & Sons, New York, 1989.
8. Y. P. Yung and C. F. Fang, Adaptive speed control of AC servo induction with on-line load estimation , *in Conference Rec.* R.O.C. *Automatic Control Conf.,* Taiwan, 1994, pp481-486.
9. M. Fu, L. Xu, A novel sensorless control technique for permanent magnet synchronous motor (PMSM) using digital signal processor, *NEACON, 1997 , Dayton, Ohio,* July, p. 14 - 17.

Controler cu observator de cuplu pentru maşini sincrone cu magneţi permanenţi

Rezumat

Servo sistemele de acţionare cu maşini sincrone cu magneţi permanenţi sunt astăzi larg răspîndite în aplicaţiile industriale, mai cu seamă în acţionarea roboţilor industriali. Controlul mişcării unui sistem robotic multi-axă pretinde compensarea diferitelor tipuri de forţe şi/sau cupluri dinamice neliniare care apar datorită interacţiunilor dintre axele robotului. Aceste cupluri pot fi considerate ca perturbaţii externe pentru servo sistemele electrice de acţionare. In cadrul prezentei lucrări se propune utilizarea *unui controler cu observator de cuplu de sarcină care să compenseze perturbaţiile externe asociate cu subsistemul mecanic al robotului. Utilizarea procesoarelor digitale de semnal permite implementarea algoritmilor de control ce utilizează observatorul de cuplu. Un astfel de controler - DSK243, bazat pe controlul cu orientarea dupa câmpul rotoric pentru maşina sincronă cu magnet permanent este propus pentru acţionarea axelor unui robot industrial de tip IRB1400 ABB. Pentru a arăta viabilitatea acestei soluţii se prezintă rezultatul obţinut în acţionarea articulaţiilor 2 şi 3 ale robotului în situaţia în care profilul vitezei este de tip parabolic.*