Position with Force Feedback Control of Manipulator Arm

[1]B. K. Chitra, [2]J. Nandha Gopal, [3]Dr. K. Rajeswari
PG Student, Department of EIE
Assistant Professor, Professor, Department of EEE

***Abstract*— This paper deals with the modeling and simulation of position with force feedback control of manipulator arm. The manipulator is used to collect the potentially hazardous samples and store it. Each joint in the manipulator is actuated by electromechanical actuator. In the proposed work the Electromechanical actuator consists of Permanent Magnet Synchronous Motor (PMSM) with gear box and its accessories. The position control of the manipulator is executed through PMSM motor which is controlled using the vector control technique with the force control loop being added as the outer loop. The entire process is executed using MATLAB SIMULINK software. Simulation results show that the PMSM drive nearly catches the reference signal and we can get the desired speed and position variation according to the reference command. In case of force control some deviations are observed which is due to the environment stiffness parameter.**

***Keywords*— Position Control, Force Control, PMSM, vector control, Electromechanical Actuator, MATLAB/Simulink.**

I. INTRODUCTION

In order to handle the interaction of a robot manipulator with the environment, some control strategies should be employed not only to control the position of the end effector but also the contact force.

There are various control strategies which has been used so far to control the position as well as force of a manipulator arm. Methods showing the relation directly between position and applied force are hybrid position/force control and hybrid impedance control [1]. Hybrid position/force control combines force and torque information with positional data based on two complementary orthogonal workspaces on displacement and force [1]. Methods employing the relation between velocity and applied force are impedance control and admittance control (or accommodation control). According to this strategy, manipulator control system should be designed not to track a motion trajectory alone, but also regulate the mechanical impedance of the manipulator where the relationship between the velocity and applied force is referred to as mechanical impedance [2]. Hybrid impedance control combines impedance control and hybrid position/force control into one strategy [3]. This allowed the designer to control the force and position subspaces independently. Stiffness of the end-effector is controlled in different directions due to the specific task in the active stiffness control. The stiffness of the end-effector depends on the stiffness of the joint servos. Adjusting the stiffness of the servos in the robot joints, desired stiffness of the end-effector can be achieved [4]. Providing the desired stiffness in the selected directions, desired forces can be applied while following the desired position trajectory [4].Admittance control as impedance control uses the relationship between the velocity and the applied force. But in contrast to impedance control, admittance control focuses more on the force tracking control. Force feedback is main feedback signal for this control [5].

Robust force control is used to achieve the target dynamics such as the target impedance, and to preserve the stability robustness in the presence of modeling errors in the robot and in the environment [6]. The design concept of sliding mode is widely used in order to overcome the difficulty to achieve a robust control. Robust control law is usually built by employing Lyapunov’s direct method. The designed robust control guarantees the achievement of the predefined target dynamics, while preserving stability in the presence of modeling errors [6].

Learning algorithm is applied to the hybrid position/force control when the robot performs the same task repeatedly [7]. This algorithm utilizes position, velocity and acceleration errors or force error for learning the command input required to perform tasks. It guarantees the convergence of both position and force tracking errors, as well as robustness, for sufficiently small parameter uncertainties and disturbances [7].

In this work hybrid position/force control with explicit force control technique has been used. Here the position control of the manipulator is done by controlling the motors in the joints. Vector control technique is used to control the motor and hence the position of the manipulator arm. Force control loop is added as an outer loop which tracks the applied and the obtained force.

This paper is organized as follows; Section represents the basic mathematical modeling technique with the help of mathematical equations of PMSM. In section III vector control technique is described. Section IV analyses the results obtained from the simulations.

II MATHEMATICAL MODELLING OF PMSM

The mathematical modeling of PMSM incorporates the d-q model that has been developed on rotor reference frame as shown in Figure 1.

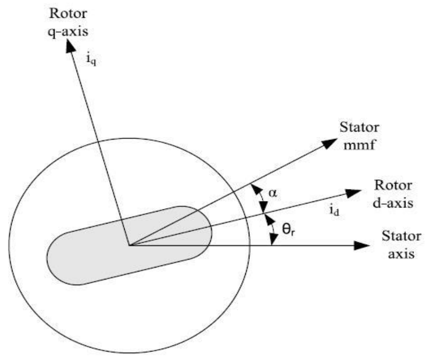

Figure 1. Motor axis

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions [8]:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.

Voltage equations are given by:

$$V_q = r_s i_q + P(\lambda_q) + \omega_r \lambda_d$$

$$V_d = r_s i_d + P(\lambda_d) + \omega_r \lambda_q$$

Flux Linkages are given by

$$\lambda_q = L_q i_q$$

$$\lambda_d = L_d i_d + \lambda_{af}$$

Substituting equations 3 and 4 into 1 and 2

$$V_q = R_s i_q + \omega_r (L_d i_q + \lambda_f) + \rho L_q i_q$$
$$V_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f)$$

Arranging equations 5 and 6 in matrix form

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix}$$

The developed torque motor is being given by

$$T_{em} = \frac{3P}{22}(\lambda_d i_q - \lambda_q i_d)$$

The mechanical Torque equation is

$$T_e = T_L + T_D + B\omega_m + JP\omega_m$$

Solving for the rotor mechanical speed form equation 9

$$\omega_m = \int \frac{(T_e - T_L - B\omega_m)}{J} \mathbf{dt}$$

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right)$$

In the above equations ωr is the rotor electrical speed whereas ωm is the rotor mechanical speed.

A. Parks Transformation and Dynamic d-q Modelling

The dynamic d-q modelling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and currents to dqo variables by using Parks transformation [9].The d-q model offers significant convenience for control system design by transforming stationary symmetrical AC variables to DC ones in a rotating reference frame [10].Converting the phase voltages variables Vabc to Vdqo variables in rotor reference frame the following equations are obtained [11].

$$\begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix} = 2/3 \begin{pmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix}$$

Converting Vdqo to Vabc we get [11].

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{pmatrix} \begin{pmatrix} V_d \\ V_q \\ V_0 \end{pmatrix}$$

III. VECTOR CONTROL OF PMSM

Vector control is also known as decoupling or field orientated control. Vector control decouples three phase stator current into two phase d-q axis current, one producing flux and other producing torque. This allows direct control of flux and torque [12].The scheme of vector control is based on coordinate transformation and motor torque equation by means of controlling stator current to improve the performances of motor, and is widely used in the field of PMSM servo system. In the control of a three phase PMSM system, modulated current is supplied to the A-B-C stator windings to build rotated magnetic field and drive the rotator. The vector control strategy is formulated in the synchronously rotating reference frame. By Clarke–Park transformations and inverse transformations the equivalent relations of currents are built among a,b,c stator coordinates, stationary α, β axis coordinates and rotating d, q axis coordinates [12].

A. *Steps to perform vector control [13]*

1. Measure the motor quantities (phase voltages and currents).
2. Transform them to the 2-phase system (α ,β) using a Clarke transformation.
3. Calculate the rotor flux space vector magnitude and position angle.
4. Transform stator currents to the d-q coordinate system using a Park transformation.
5. The stator current torque- (isq) and flux- (isd) producing components are separately controlled.
6. The output stator voltage space vector is calculated using the decoupling block.
7. An inverse Park transformation transforms the stator voltage space vector back from the d-q coordinate system to the 2-phase system fixed with the stator

IV. SIMULATION AND RESULTS

The position-force control implemented in this work combines the robustness properties of a position controller with the ability to follow position and force references of a hybrid controller. It has two cascaded control loops: a position control is implemented as an inner control loop; a force control loop is used as an external loop control. The force controller modifies the desired position trajectory in order to limit the contact force to a specified maximum value.

The position control loop comprises of three internal loops. The outer most loop is the position control loop, followed by speed control and current control loops. This control uses two proportional-integral (PI) control modules, one for speed and one for current control. A current controller is employed to linearize the current- voltage relation of the actuator. A PI controller is adopted to improve current response. It receives torque commands and position information, and outputs desired current set points to the motor. The actuation of the manipulator is provided by PMSM motor and a gearbox. With these regulators, along with the PMSM motor, the position control is obtained.

The MATLAB SIMULINK model for position control of manipulator is shown in the figure 2. The stator currents, speed and torque are being sensed to get the reference d-q axis components which are further processed by Park and Clark transformation. Reference speed and position signal is given to the motor to obtain the motor parameters using the vector control strategy.

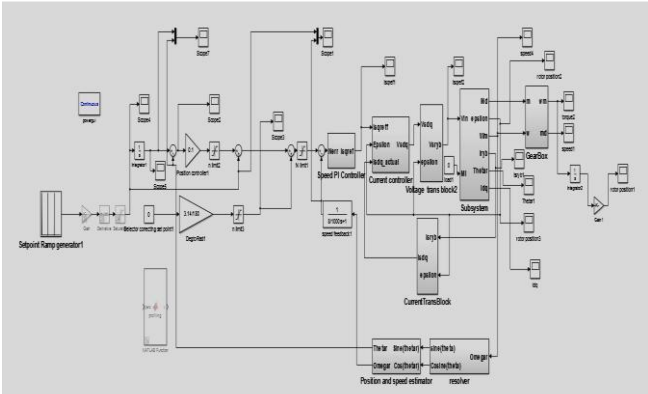

Figure 2. MATLAB SIMULINK model of inner position control loop.

To verify the feasibility the simulation is carried out and above model is simulated by giving some reference signals. The simulation is carried out for the reference position as shown in figure 3.

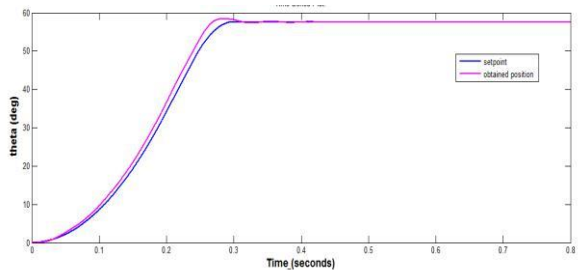

Figure 3. Comparison of reference and obtained position.

Simulation results show that the PMSM drive nearly catches the reference signal and we can get the desired speed variation according to reference command.

A proportional-integral speed controller is implemented to regulate the rotor speed by comparing the reference speed with the estimated speed. The PI controller delivers an output current reference i_{sqref}, while the direct current reference i_{sdref} is set to zero in normal operation to obtain the maximum torque-to-current ratio. The simulation results obtained between the reference and actual speed is shown in figure 4 . As shown in the figure it can be seen that the there is a very small fluctuation and the speed is well tracked.

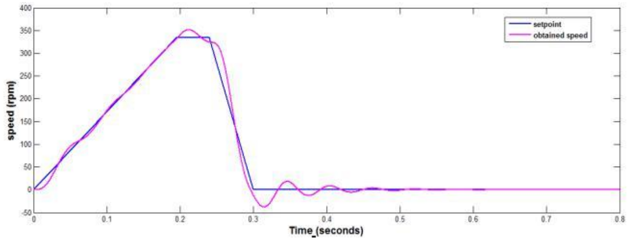

Figure 4. Comparison of reference speed and actual speed

The vector control model of PMSM is implemented by sensing the stator currents, speed and torque to get the reference d-q axis components. This is further processed by Parks and Clark Transformation. The mathematical implementation of conversion of V_{dq} to i_{dq} is shown in the figure 5 and the torque generation block is shown in the figure 6.

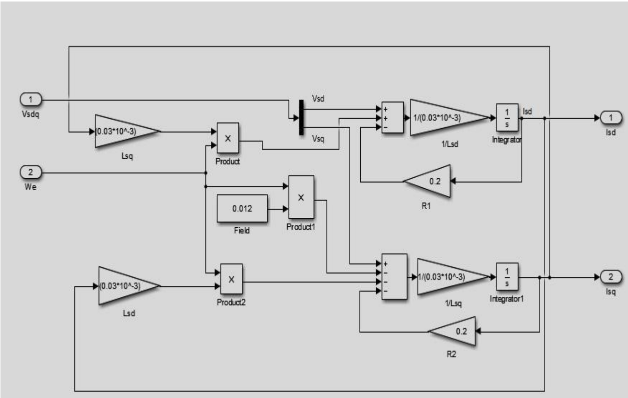

Figure 5. Generation of i_d, i_q currents through mathematical blocks

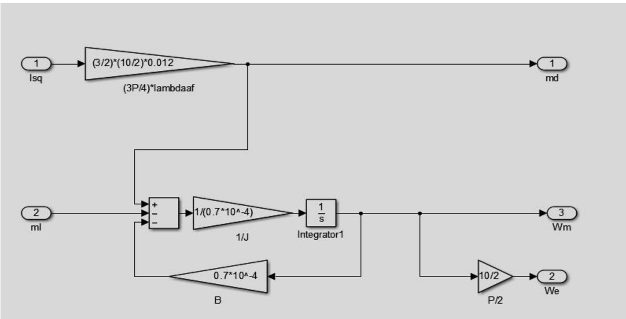

Figure 6. Torque generation block

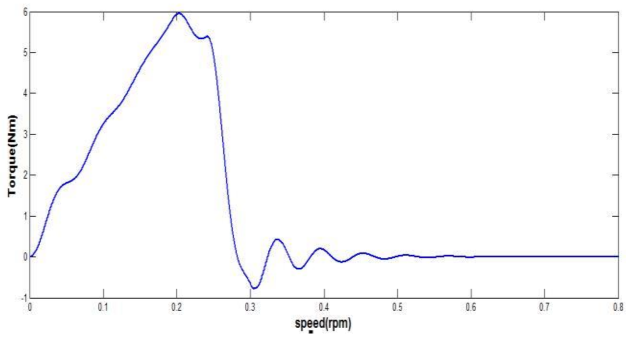

Figure 7. Obtained torque

The simulation block diagram for the force control loop with inner position control is shown in the figure 8. It comprises a number of components and subsystems. The force controller modifies the desired position trajectory , in order to limit the contact force to a specified maximum value. The force reference has the meaning of a limiting value to the force the end-effector may apply to the environment. The contact force saturation behavior is obtained by the use of limited integrators on the force control loop.

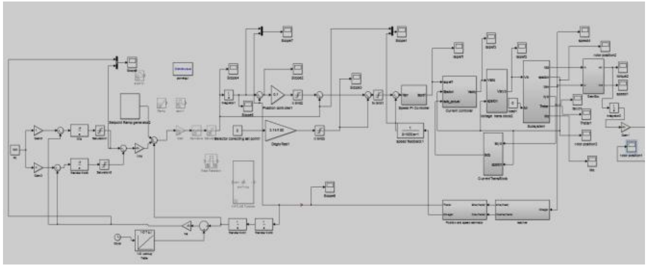

Figure 8. Position/Force control

The output of the force control loop is shown in the figure 9. The two lines represent the desired and the obtained outputs. The deviation observed between the actual and obtained is due to the environment stiffness parameter inclusion of which in the current model will require extensive trial and error and there by result in widening the scope of this work.

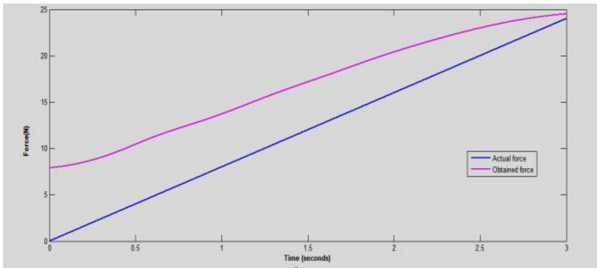

Figure 9. Comparison of Actual and obtained force

V. CONCLUSION

In this paper, Simulink-based simulation of position with force feedback control of manipulator is implemented. A common way of causing a manipulator to move from here to there in a smooth, controlled fashion is to cause each joint to move as specified by a smooth function of time. Commonly, each joint starts and ends its motion at the same time, so that the manipulator motion appears coordinated. Here the manipulator is equipped with Permanent Magnet Synchronous Motor which directly executes a desired trajectory. In this work position tracking has been executed and from the results it can be seen that the PMSM drive nearly catches the reference trajectory and the desired speed and position variation according to reference command is obtained.

Force control has also been attempted in this work. Here the contact force saturation behavior is obtained by the use of limited integrators on the force control loop. The results obtained shows that we were able to attain upto 90 percent of the set point.

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