Field Oriented Sensorless Position Control of a Hybrid Stepper Motor with Extended Kalman Filter

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***Abstract*— This paper describes the sensorless position control of a hybrid stepper motor. Extended Kalman filter algorithm is used for sensorless control. The extended Kalman filter estimates the position and speed required for the field oriented control. The currents and voltages of the two phases of stepper motor is sensed and used for the state estimation using extended Kalman filter. The estimated position is compared with the desired position and motor is stopped at the desired position. Sensorless control eliminates the need for mechanical sensors. Simulation is done in MATLAB. ARM LPC2148 processor is used for the hardware implementation of steady state Kalman filter.**

Keywords— Arm LPC2148, Extended Kalman filter (EKF), Field oriented control (FOC), MATLAB, Position control, Sensorless control, Stepper motor.

I. INTRODUCTION

Stepper motors work considerably well in open loop, but closed loop control is preferred for precise positioning applications. Position or speed is fed back in closed loop control of stepper motors. In the conventional closed loop position control techniques mechanical sensors are used to measure the speed and position of stepper motor. This will increase size of the system and also they are expensive. The reliability of the system is reduced because the sensor measurements are influenced by humidity, temperature etc.

Sensorless control is done using extended Kalman filter algorithm. Kalman filter can be used for estimation in linear systems and extended Kalman filter can be used for non linear systems. Extended Kalman filter (EKF) algorithm can estimate the parameters and states of a nonlinear stochastic system. State estimation can be done using continuous time and discrete time extended Kalman filter. Here discrete time EKF algorithm is used for state estimation as the system is non linear.

The currents and voltages of the motor are used by the extended Kalman filter to estimate the speed and position. Using the estimated speed and position a field oriented feedback control is implemented. By using field oriented control the flux and torque of the stepper motor can be controlled separately. The dynamic performance of the system can be improved by FOC. The steady state Kalman filter gain obtained from the simulation is used in hardware implementation.

Rotor position and the speed of a hybrid stepper motor can be estimated using steady state Kalman filter [1]. Unscented Kalman filter has less computations and less estimation error compared to extended Kalman filter. But with noisy measurements in real time implementation extended Kalman filter gives better results [2]. In [3] the field oriented control of a hybrid stepper motor is presented using encoder. Sensorless control of different types of motor with vector control was done using extended Kalman filter [4], [5], [6]. In this paper field oriented position control of a hybrid stepper motor is implemented using extended Kalman filter algorithm without the use of mechanical sensors.

II. STEPPER MOTOR

The working of stepper motor depends upon the rate of input pulses and speed of the motor depends upon the frequency of the pulses. The hybrid stepper motor has small size, high stepping rate and high torque than variable reluctance and permanent magnet stepper motors. The dynamic equations for a two phase hybrid stepper motor are given below [7].

$$\frac{di_a}{dt}=\frac{v_a-Ri_a+K_m\omega\sin N_r\theta}{L} \tag{1}$$

$$\frac{di_b}{dt}=\frac{v_b-Ri_b+K_m\omega\cos N_r\theta}{L} \tag{2}$$

$$\frac{d\omega}{dt}=\frac{K_m i_b\cos N_r\theta-K_m i_a\sin N_r\theta-T_L-B\omega}{J} \tag{3}$$

$$\frac{d\theta}{dt}=\omega \tag{4}$$

where v_a and v_b are the phase voltages(V), i_a and i_b are the currents(A) in two phases, ω is the rotor speed(rad/sec), Θ is the rotor(rad) and T_L is the load torque(Nm). The parameters of the motor are phase resistance R=1.13Ω, phase inductance L=3.6mH, torque constant K_m=0.458Nm/A, number of rotor teeth per phase N_r=50, inertia of motor J=0.000048Kg/m^2 and coefficient of viscous friction B=0.0014N.m.s/rad.

For field oriented control, the model in d-q frame is used. The voltages and currents are transformed by Park transformation using the following equations.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & \sin(N_r\theta) \\ -\sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{6}$$

The electrical and mechanical equations of a hybrid stepper motor in d-q frame are given below [8].

$$\frac{di_d}{dt} = \frac{v_d - Ri_d}{L} + N_r\omega i_q \tag{7}$$

$$\frac{di_q}{dt} = \frac{v_q - Ri_q - K_m\omega}{L} - N_r\omega i_d \tag{8}$$

$$\frac{d\omega}{dt} = \frac{K_m i_q - T_L - B\omega}{J} \tag{9}$$

$$\frac{d\theta}{dt} = \omega \tag{10}$$

III. STATE ESTIMATION USING EXTENDED KALMAN FILTER

Extended Kalman filter is used to estimate the states of a nonlinear system. It can estimate the present and future state of the system. For an observable system the EKF algorithm can estimate the state variables from the system inputs and outputs. It uses the measurements containing noise for estimation. The recursive EKF algorithm uses the mathematical model of the system. The discrete system model in the state space form is given by the following equations.

$$x_{k+1} = x_k + t.f(x_k, u_k) + c_k \tag{11}$$

$$y_k = h(x_k) + d_k \tag{12}$$

where $x_k = [i_{dk}\ i_{qk}\ \omega_k\ \Theta_k\ T_{Lk}]^T$ is the state vector, $u_k = [u_{dk}\ u_{qk}]^T$ is the input vector, $y_k = [i_{dk}\ i_{qk}]^T$ is the output vector. c_k is the process noise vector and d_k is the measurement noise vector. c_k and d_k are taken as random matrices in the simulation. For the proper working of motor, sampling time t should be small compared to the electric time constant of the motor. Sampling period is taken as 0.00002 seconds. As the sampling time is small load torque will not change.

The EKF algorithm has 2 phases, prediction phase and correction phase. Prediction phase also known as time update equations project forward the error covariance estimate and current state from time step k to next time step $k+1$. Correction phase also known as measurement update equations compare the actual measurement with the estimated one to improve the estimate. The estimate of the state vector and the error covariance matrix, related to the initial estimate of state vector should be initialized at the beginning. First the state variables are estimated. Then error covariance matrix, P is estimated. Then the Kalman filter gain, K is computed. Using the value of Kalman filter gain the state estimate is updated and finally the error covariance estimate is updated. The algorithm is repeated using the previous estimate to predict the next estimate. The equations of EKF are given below [9].

$$\hat{x}_{k+1/k} = \hat{x}_{k/k} + t.f(\hat{x}_{k/k}, u_k) \tag{13}$$

$$P_{k+1/k} = F_k P_{k/k} F_k^T + Q_k \tag{14}$$

$$K_{k+1} = P_{k+1/k} H_k^T \left(H_k P_{k+1/k} H_k^T + R_k\right)^{-1} \tag{15}$$

$$\hat{x}_{k+1/k+1} = \hat{x}_{k+1/k} + K_{k+1}\left(y_{k+1} - H_k \hat{x}_{k+1/k}\right) \tag{16}$$

$$P_{k+1/k+1} = P_{k+1/k} - K_{k+1} H_k P_{k+1/k} \tag{17}$$

The Jacobian matrices of system and output are denoted by F and H respectively. The values of initial error covariance matrix P_0 and Q, which is the covariance matrix of c_k and R, the covariance matrix of d_k used in the simulation are given below. Microstepping mode of excitation was used in simulation. The values of the covariance matrices were optimized after doing several simulations.

$$P_0 = \begin{bmatrix} 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0 \\ 0 & 0 & 100 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0.01 \end{bmatrix}$$

$$Q = \begin{bmatrix} 10^{-4} & 0 & 0 & 0 & 0 \\ 0 & 10^{-4} & 0 & 0 & 0 \\ 0 & 0 & 10^{-6} & 0 & 0 \\ 0 & 0 & 0 & 10^{-6} & 0 \\ 0 & 0 & 0 & 0 & 10^{-6} \end{bmatrix}$$

$$R = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.01 \end{bmatrix}$$

Actual speed and estimated speed using EKF is shown in Fig. 1. Actual speed is plotted in green color and estimated speed is plotted in red color. The error in the estimated speed is plotted in Fig. 2. Error in the estimated speed is less than 0.15 rad/sec.

Actual position and estimated position using EKF is shown in Fig. 3. Actual position is plotted in green color and estimated speed is plotted in red color. The error in the estimated position is plotted in Fig. 4. Error in the estimated position is less than 0.0004 rad.

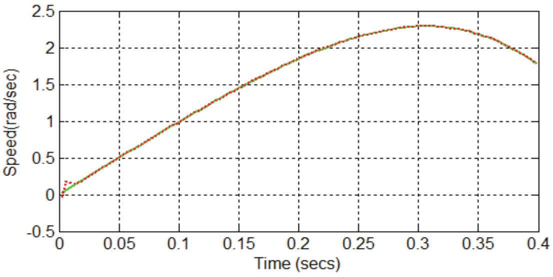

Fig. 1. Actual speed and estimated speed

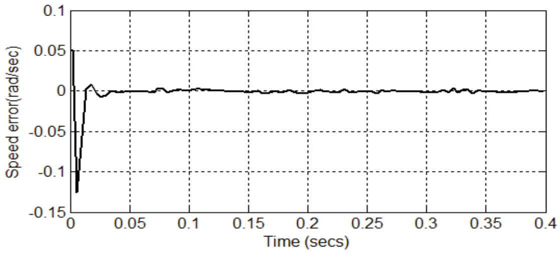

Fig. 2. Error in the estimated speed

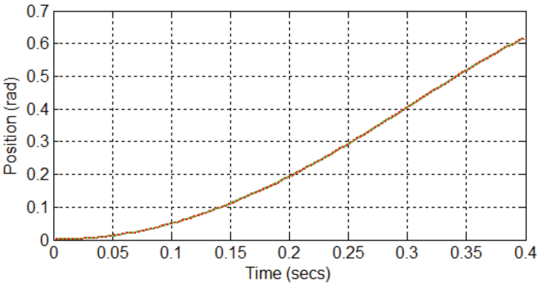

Fig. 3. Actual position and estimated position

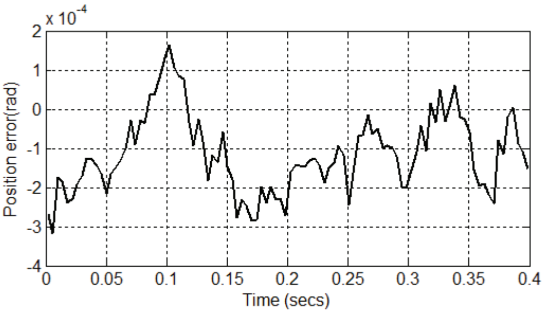

Fig. 4. Error in the estimated position

IV. Position Control using EKF

The block diagram of sensorless position control of the hybrid stepper motor using extended Kalman filter is given in Fig. 5.

The hybrid stepper motor (HSM) can be controlled like a DC motor in d-q frame. Flux is aligned with the direct axis (d) and torque is controlled by controlling the current in quadrature axis (q). The value of reference current for direct current i_d is set to zero. Then the value of quadrature current i_q is varied to control the torque.

The outputs of the two current PI controllers are the linear components i.e. v_d^{ln} and v_q^{ln} of the d and q axis voltages. The decoupling components i.e. v_d^{de} and v_q^{de} of the d and q axis voltages should be added to these linear components to get the actual v_d and v_q. The linear components of v_d and v_q are the following.

$$v_d^{\ln} = Ri_d + L\frac{di_d}{dt} \tag{18}$$

$$v_q^{\ln} = Ri_q + L\frac{di_q}{dt} \tag{19}$$

The decoupling components of v_d and v_q are the following.

$$v_d^{de} = -LN_r\omega i_q \tag{20}$$

$$v_q^{de} = LN_r\omega i_d + K_m\omega \tag{21}$$

The voltages v_d and v_q are transformed back to the a-b frame using inverse Park transformation with the equations given below.

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} \cos(N_r\theta) & -\sin(N_r\theta) \\ \sin(N_r\theta) & \cos(N_r\theta) \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{22}$$

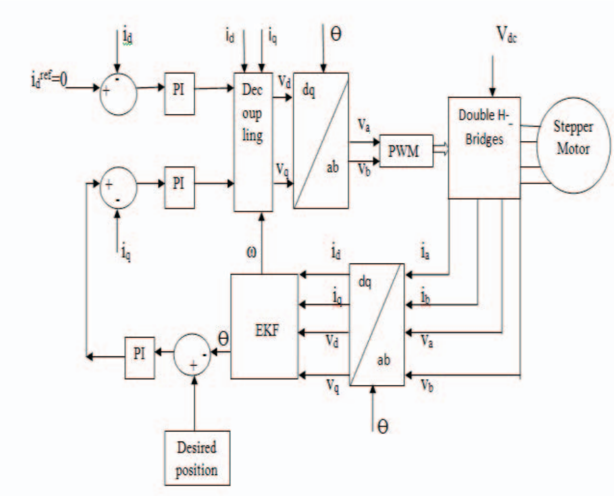

Fig. 5. Block diagram of position control using EKF

V. HARDWARE IMPLEMENTATION

A. Experimental Setup

The block diagram of experimental setup is shown in Fig. 6. The experimental setup is shown in Fig. 7. A keypad is used to enter the desired position. The entered value will be displayed in the LCD display. The current and voltages are sensed and given to the ARM LPC2148 processor. LPC2148 is a high performance 64 pin microcontroller. It is a 32 bit ARM7 processor. For high speed applications it enables up to 60MHz operation. It has two 10 bit ADCs with 14 channels and a PWM unit with 6 channels.

Based on the field oriented control and extended Kalman filter algorithm coded in the processor, gating pulses are generated. These gating pulses are given to the switches through the driver circuit. H- bridge is used to drive the motor. Two current sensors ACS712 are used for current sensing. Four IR2110 MOSFET drivers are used in the circuit. To switch the MOSFETs in 1 leg of H-bridge, a IR2110 MOSFET driver is used. At a time only 1 MOSFET in a leg of H-bridge will be turned on. IRF 740 MOSFETs are used. For the operation of stepper motor only 2 switches in a H-bridge is turned on at a time. A 12V, 2.8A, 1.8^0 step angle hybrid stepper motor is used for hardware implementation.

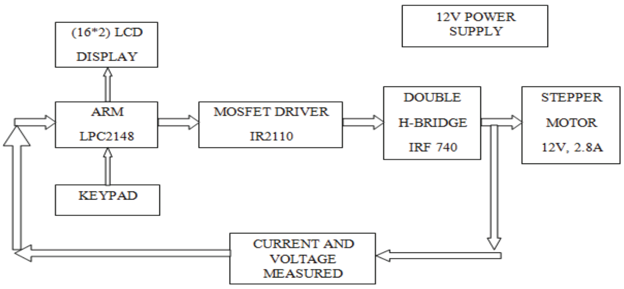

Fig. 6. Block diagram of experimental setup

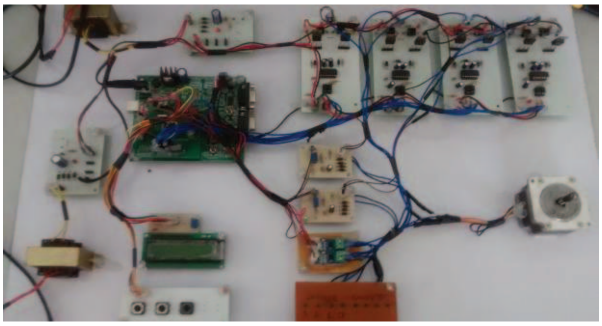

Fig. 7. Experimental setup

B. Experimental Results

Steady state extended Kalman filter method is used in hardware implementation. The computation time will be reduced by this method. The Kalman gain matrix computed from simulation is used in real time algorithm. So in real time implementation only two equations, (13) and (16) are used.

The position of stepper motor at starting is shown in Fig. 8. Microstepping was achieved in the hardware implementation. The position when the desired angle is given as 180^0 is shown in Fig. 9.

Fig. 8. Stepper motor position at starting

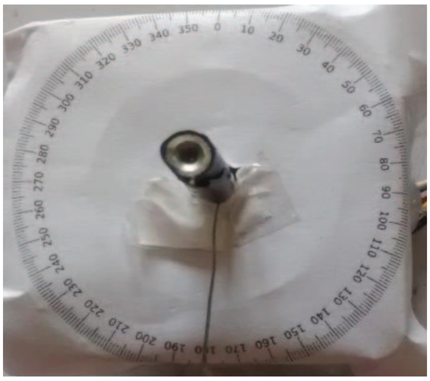

Fig. 9. Stepper motor position at 180^0

VI. CONCLUSION

The estimation of state variables in MATLAB using extended Kalman filter gives satisfactory results. The error in the estimation is very less. From the results, it can be concluded that extended Kalman filter is an effective tool for sensorless control. The sensorless position control with field oriented control is implemented in real time using steady state Kalman filter. The use of steady state Kalman filter reduces the computation time required by the processor. Mechanical sensors are not used so that the volume and cost of the system is reduced and the reliability is increased. The online computation of Kalman filter gain can be done using a high speed DSP.

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