Design Implementation of Speed Controller Using Extended Kalman Filter for PMSM

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***Abstract*— A novel design impl[1]ementation of proportional–integral–differential equivalent controller using state observer based Extended Kalman Filter (EKF) for a Permanent Magnet Synchronous Motor (PMSM) is proposed. The EKF is constructed to achieve a precise estimation of the speed and current from the noisy measurement. Then, a proportional integral derivative (PID) controller is developed based on Linear Quadratic Regulator (LQR) to achieve speed command tracking performance. In the present method, the speed and q-axis current are estimated accurately using the EKF algorithm. The steady state and transient state response of the overall system is greatly enhanced and also the speed control is achieved effectively under load disturbance. The experimental results for the speed response and q-axis current as well as the control signal variations when the PMSM is subjected to the load disturbance are presented. The results verify the effectiveness of the proposed method.**

Keywords - Permanent Magnet Synchronous Motor, Extended Kalman Filter, PID, Vector Control.

I. INTRODUCTION

The most utilized motor in the field of variable speed electric drive applications is the Permanent Magnet synchronous Motor (PMSM). The reason for this use is due to its higher full load efficiency and power factor, high torque/inertia ratio, and its wide range of speed control [1-4]. In PMSM drives, the vector control theory is applied in the d-q reference frame where the flux and torque are controlled independently [5-7].

To measure the shaft position of the PMSM the optimal encoder is used. Speed signal is obtained through the discrete differentiation of the encoder position; this signal is very noisy and has an inherent delay. Thus, it adversely impacts the performance of the system. To solve this problem, the speed can be estimated through the EKF algorithm. The estimated speed is very accurate and much better than that obtained using the encoder. The Extended Kalman Filter produces the optimal estimation of the states

based on the least square method. Here, a feedback system control is utilized to estimate the process. The EKF provides good tolerance for the mathematical model error and noises in the measurement.

Many research works have concentrated on speed and position estimation of PMSM using sliding mode method, high frequency signal injection method, adaptive control theory, fuzzy control, state observer, and the EKF approach [8-16]. In all, the EKF method is more attractive as well as popular and is continuously being used in research and applications because it delivers rapid, precise, and accurate estimation. Also, in many applications, the EKF method is implemented because of its low-pass filter characteristics. The feedback gain used in EKF achieves quick convergence and provides stability for the observer.

In this paper a vector control method is developed and implemented by means of the Extended Kalman Filter algorithm to provide the speed control. Here, state space representation of the model and observer is obtained. Utilizing the state space model, a PID controller is designed using Linear Quadratic Regulator (LQR) approach [17]. The accurate estimation of states is very essential to achieve better control and performance of the PMSM drives. Here the EKF is utilized for the precise

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estimation of the rotor speed and stator q-axis current. Since the drive speed and drive current measured directly from the machine terminals contain noise, they are not precise for speed control. In the proposed implementation, the speed and q-axis current are estimated accurately by introducing EKF algorithm theory. The proposed method yields a smooth and quick speed tracking. It also reduces the actual disturbance applied to the system, and provides better control of the control signal variation. The overall system performance under load condition is greatly enhanced.

II. DESCRIPTION OF MOTOR MODEL

The stator voltage and stator flux linkages equations in the rotor references frame are [5]:

$$v_{sd} = R_s i_{sd} + L_s \frac{d}{dt} i_{sd} - \omega_m L_s i_{sq}, \tag{1}$$

$$v_{sq} = R_s i_{sq} + L_s \frac{d}{dt} i_{sq} + \omega_m (L_s i_{sd} + \lambda_{fd}), \tag{2}$$

$$\lambda_{sd} = L_s i_{sd} + \lambda_{fd}, \tag{3}$$

$$\lambda_{sq} = L_s i_{sq} \tag{4}$$

where $v_{sd}, v_{sq}, i_{sd}, i_{sq}, \lambda_{sd}, \lambda_{sq}$ are d-axis and q-axis voltages, currents and flux linkages respectively. R_s and L_s are the stator winding resistance and inductance respectively.

The electromagnetic torque generated and the acceleration is given by:

$$T_{em} = \frac{p}{2} \lambda_{fd} \cdot i_{sq}, \tag{5}$$

$$\frac{d}{dt} \omega_{mech} = \frac{T_{em} - T_L}{J} - \frac{B}{J} \omega_{mech}, \tag{6}$$

$$\omega_m = \frac{p}{2} \omega_{mech} \tag{7}$$

where ω_{mech} is the speed of the motor and p is the number of poles.

Since the torque developed by the motor is directly proportional to the motor drive current, it is difficult to control the drive current directly. Therefore the drive current is indirectly controlled through the input voltage. The simplified model of the PMSM q-axis subsystem is shown in Fig.1. In vector control, assuming i_{ds}=0, the state-space model of the PMSM q-axis subsystem is derived as [18]:

$$\begin{bmatrix} \dot{i}_{sq} \\ \dot{\omega}_{mech} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -(\frac{\lambda_{fd}}{L_s} \cdot \frac{p}{2}) \\ (\frac{p}{2} \cdot \frac{\lambda_{fd}}{J}) & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_{sq} \\ \omega_{mech} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} \\ 0 \end{bmatrix} [v_{sq}] \tag{8}$$

For the speed controller design, the system output is

$$[y] = [0 \quad 1] \begin{bmatrix} i_{sq} \\ \omega_{mech} \end{bmatrix}. \tag{9}$$

If the motor output is considered as the drive current, then the motor output is given by:

$$[y'] = [1 \quad 0] \begin{bmatrix} i_{sq} \\ \omega_{mech} \end{bmatrix}. \tag{10}$$

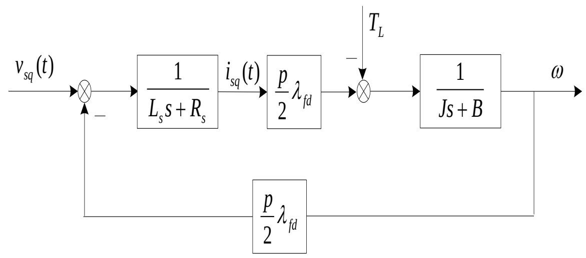

Fig1. Q-axis subsystem of a simplified PMSM

III. PID PARAMETERS TUNING WITH STATE-FEEDBACK AND STATE-FEEDFORWARD LQR

The controller is designed as a single-input–single-output (SISO) system. The following discussion is based on the *q*-axis controller/observer design [18].

The state space model of the simplified PMSM, G1(s), with reference to the q-axis is:

$$\dot{x}_1(t) = A_1 x_1(t) + B_1 u_1(t), \qquad x_1(0) = x_{10} \tag{11a}$$

$$y_1(t) = C_1 x_1(t) \tag{11b}$$

where, $x_1(t) \in R^{2\times1}$, $u_1(t) \in R^{1\times1}$, $y_1(t) \in R^{1\times1}$, and A_1,B_1 andC_1 are constant matrices.

The entire system output is the motor output plus the load disturbance and this is given by:

$$y(t) = y_1(t) + d(t) \tag{12}$$

where $y(t) \in R^{1\times1}$, $d(t) \in R^{1\times1}$.

The state space model of the speed controller, G2(s), can be written as:

$$\dot{x}_2(t) = A_2 x_2(t) + B_2 u_2(t), \qquad x_2(0) = x_{20}, \tag{13a}$$

$$y_2(t) = C_2 x_2(t) = u_1(t), \tag{13b}$$

$$u_2(t) = -y(t) + E_c r(t) \tag{13c}$$

where $x_2(t) \in R^{2\times1}$, $u_2(t) \in R^{1\times1}$, $y_2(t) \in R^{1\times1}$, $r(t) \in R^{1\times1}$, and A_2, B_2, C_2, E_c are constant matrices.

In order to convert the PID tuning problem to an optimal design, we modify the closed loop cascade system into an augmented system with d(t)=0. The result is the following equation:

$$\dot{x}_e(t) = A_e x_e(t) + B_e u_1(t) + E_e r(t), \tag{14a}$$

$$y_e(t) = y_1(t) = C_e x_e(t) \tag{14b}$$

where

$$A_e=\begin{bmatrix} A_1 & 0 \\ -B_2C_1 & A_2 \end{bmatrix},\ B_e=\begin{bmatrix} B_1 \\ 0 \end{bmatrix},\ E_e=\begin{bmatrix} 0 \\ B_2E_c \end{bmatrix},\ x_e=\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix},\ C_e=\begin{bmatrix} C_1 & 0 \end{bmatrix}.$$

The resulting state-feedback LQR for the augmented system is:

$$u_1(t)=-K_e x_e(t)=-K_1x_1(t)-K_2x_2(t) \tag{15}$$

where $K_1 \in R^{1\times 2}$, $K_2 \in R^{1\times 2}$.

The quadratic cost function J for the system is given as:

$$J=\int_0^\infty [x_e{}^T(t)Qx_e(t)+u_1{}^T(t)Ru_1(t)]dt \tag{16}$$

where $Q \ge 0$ is the state variation and $R>0$ is the control energy consumption.

The optimal state-feedback control gain which minimizes the performance index is given by:

$$K_e=R^{-1}B_e^TP \tag{17}$$

where matrix P>0 is the solution of the Riccati equation,

$$PA_e+A_e{}^TP-PB_eR^{-1}B_e{}^TP+Q=0 \tag{18}$$

Let (Ae, Be) be the pair of the given open loop system and h>0 represents the prescribed degree of relative stability. Then the closed-loop system (A_e - $B_eR^{-1}B_e^TP$) has all its eigenvalues lying in the left of the –h vertical line in the complex s-plane.

The solution of the revised Riccati equation is given by:

$$P(A_e+hI)+(A_e+hI)^TP-PB_eR^{-1}B_e{}^TP+Q=0 \tag{19}$$

where $P>0, h>0$.

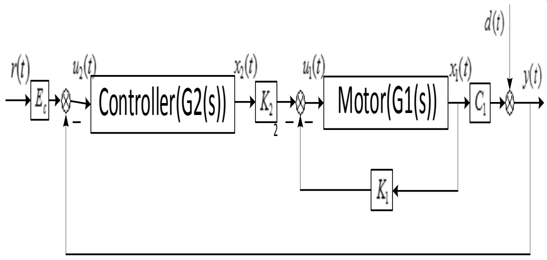

Fig.2. PID controller system

The total control law is equivalent to a PID controller with [$K_1x_1(t)$] acting as proportional and derivative controller and [K2] acting as integral controller.

By choosing the desired values of h and the weighting matrices Q and R, the control gain can be determined. The block diagram of the designed augmented system including the controller is shown in Fig.2.

The calculated control gains are given by:

$$K_1=[0.2241 \quad 0.0030], \tag{20a}$$

$$K_2=[-0.1333]. \tag{20b}$$

IV. STATE OBSERVER BASED EXTENDED KALMAN FILTER

The state space model of the simplified PMSM given by (11a) and (11b) is the non-linear system. To apply the EKF algorithm, the system needs be discretized and linearized [19].

The discrete approximated equation is given by:

$$x_k=(I+AT)x_{k-1}+BTu_k, \tag{21a}$$

$$y_k=cx_k. \tag{21b}$$

The nonlinear stochastic equation is:

$$x_k=f(x_{k-1},u_k,0) \tag{22a}$$

$$y_k=h(x_k,0) \tag{22b}$$

$$f(x_k,u_k)=\begin{bmatrix} (1-\frac{TR_s}{L_s})\, i_{sq}-(\frac{T\lambda_{fd}}{L_s}\cdot\frac{p}{2})\omega_{mech}+\frac{T}{L_s}[v_{sq}] \\ (T\cdot\frac{p}{2}\cdot\frac{\lambda_{fd}}{J})\ i_{sq}+(1-\frac{TB}{J})\omega_{mech} \end{bmatrix} \tag{23a}$$

$$h(x_k,0)=H\cdot x_k. \tag{23b}$$

The Jacobian matrices of partial derivative of f and h with respect to x are given by:

$$A_k=\frac{\partial f(x_k,u_k)}{\partial x}|x_k=\hat{x}_k, \tag{24a}$$

$$H_k=\frac{\partial h(x_k)}{\partial x}|x_k=\hat{x}_k, \tag{24b}$$

From (23)

$$A_k=\begin{bmatrix} 1-\frac{TR_s}{L_s} & -(\frac{T\lambda_{fd}}{L_s}\cdot\frac{p}{2}) \\ (T\cdot\frac{p}{2}\cdot\frac{\lambda_{fd}}{J}) & 1-\frac{TB}{J} \end{bmatrix} \tag{24c}$$

$$H_k=[1 \quad 0]. \tag{24d}$$

The PMSM states x can be estimated by using EKF algorithm during each sampling time interval as follows:

1) Time update step

$$\left.\begin{aligned} \hat{x}_{pk} &= f(\hat{x}_{k-1},u,0) \\ \hat{P}_{pk} &= A_k\hat{P}_{k-1}A_k{}^T+W_kQ_{k-1}W_k{}^T \end{aligned}\right\} \tag{25a}$$

2) Measurement update step

$$\left.\begin{aligned} K_k &= \hat{P}_{pk}H_k{}^T(H_k\hat{P}_{pk}H_k{}^T+V_kRV_k{}^T)^{-1} \\ \hat{x}_{ck} &= \hat{x}_{pk}+K_k(y_k-H_k(\hat{x}_{pk},0)) \\ \hat{P}_{ck} &= (I-K_kH_k)\hat{P}_{pk} \end{aligned}\right\} \tag{25b}$$

where W_k and V_k are zero- mean- white Gaussian process and measurement noise with covariance Q and R.

The important and difficult part in the design of the EKF is choosing the proper values for the covariance matrices Q and R

Variable	Physical Meaning	Value	Unit
R_s	Armature Resistance	0.1127	Ω
L_s	Armature Inductance	3.63e-4	H
J	Moment of Inertia	1.267e-4	$Kg \cdot m^2$
B	Damping Coefficient	2.485e-4	$N \cdot m / rad / s$
λ_{fd}	Stator Flux Linkage	0.0131	$V / rad / s$
p	poles	10	
T_{L0}	Static Friction	0.0237	$N \cdot m$

[20-21]. The change of values of covariance matrices affects both the dynamic and steady-state. By using trial and error method, a suitable set of values of Q and R are selected to insure better stability and convergence time.
The chosen values of Q, R and P are:

$$Q = \begin{bmatrix} 0.008 & 0 \\ 0 & 1.5 \end{bmatrix} \; ; \quad R = [0.02] \tag{26a}$$

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{26b}$$

V. EXPERIMENTAL RESULTS

Experiments are conducted in order to verify and validate the result obtained through simulation. The PMSM speed controller is implemented using DS1104 dSPACE board. The model implementation is achieved in the real time (RTI) in dSPACE board where the simulink code is converted directly into DSP code in the expansion box. The control-desk which acts as user interface is used to regulate the output of the system. The block diagram used in the implementation is as shown in the Fig.3.

The PMSM parameters are given in Table 1. Based on optimal control theory, the desired control gain K1 and K2 are determined and the Kalman filter gain is obtained using EKF algorithm. The output drive current and speed are estimated through the EKF algorithm as previously discussed. The inputs are taken directly from the machine terminals. At the output, the motor response is checked and the speed control is observed.

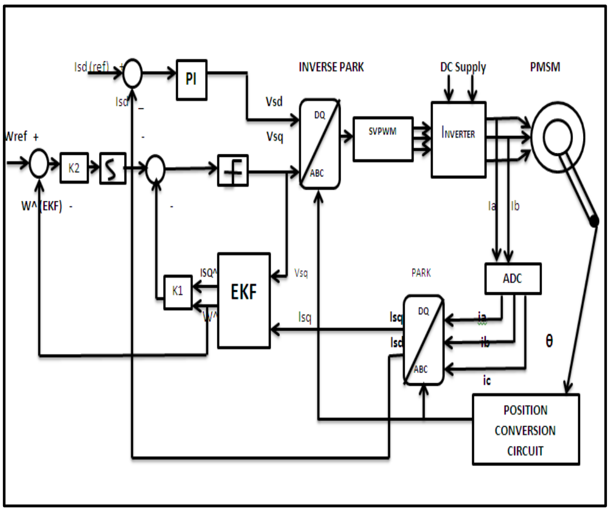

Fig.3. Block diagram of PMSM drive

Table.1
PMSM parameter

The reference speed is changed from 0 to 100rad/sec and the speed, current and control signal responses are recorded under no load condition with non-observer. Fig.4 (a) shows the Speed response, Fig.4 (b) shows the actual Isq current response, and Fig.4(c) shows the control signal Vsq response for the input reference change.

Similarly speed response, actual Isq current response, and control signal Vsq response are observed and recorded under load variations. The experiment results in Fig. 5(a)(b)(c) are shown for when load increase and Fig. 6(a)(b)(c) are shown for when load decrease. It is observed from the results that the speed deviation is around 22rad/sec and control signal variation is nearly 1.26Volts with the transient time of 1.45s. It is also observed that the measured speed signal is too noisy and there is an over shoot in the control signal.

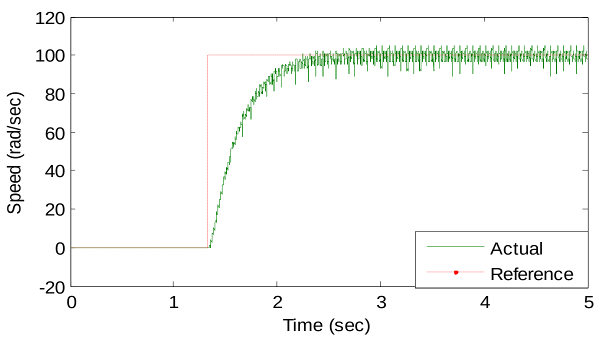

Fig.4(a)

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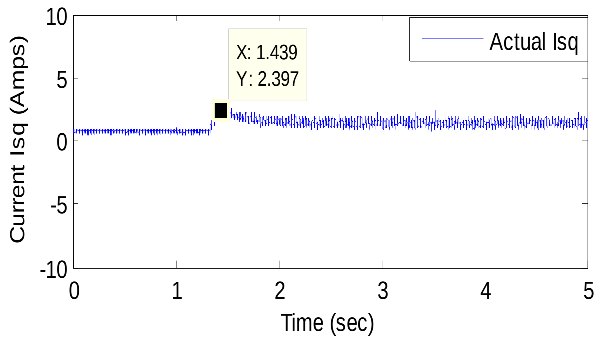

Fig.4 (b)

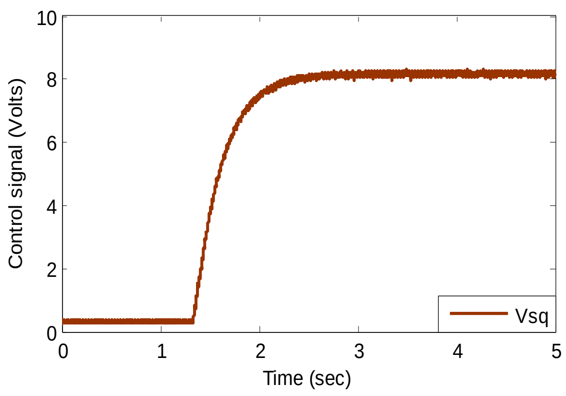

Fig.4 (c)

Fig.4. Experimental results for the input reference change under no load with Non-observer
(a) Speed response (b) Actual Isq current response
(c) Control signal Vsq response

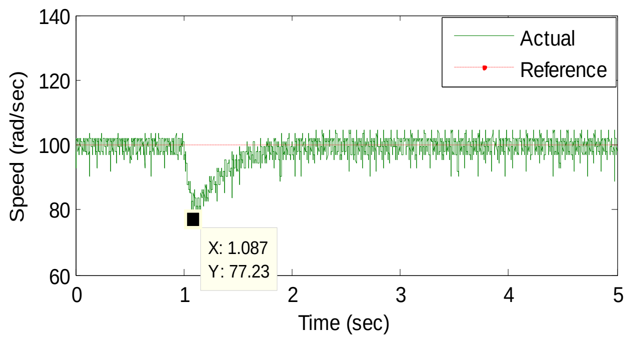

Fig.5 (a)

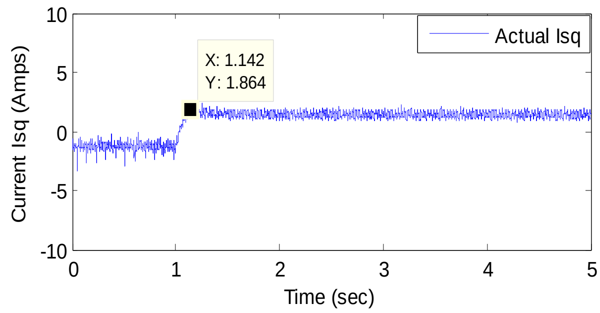

Fig.5 (b)

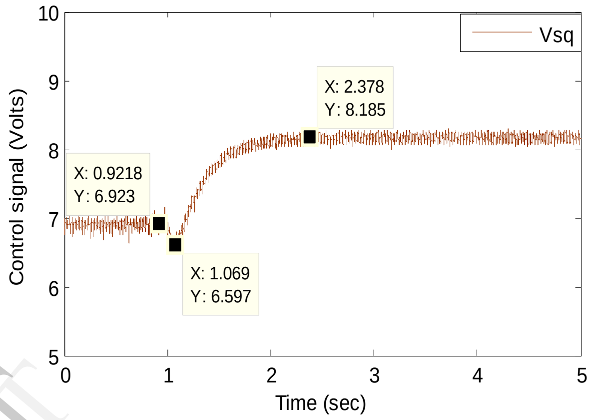

Fig.5 (c)

Fig.5. Experimental results for the load increase with Non observer
(a) Speed response (b) Actual Isq current response
(c) Control signal Vsq response.

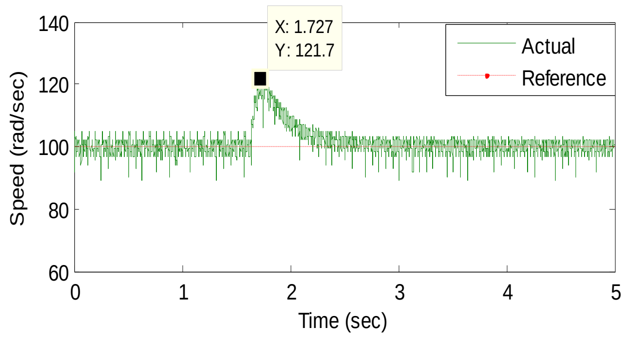

Fig.6 (a)

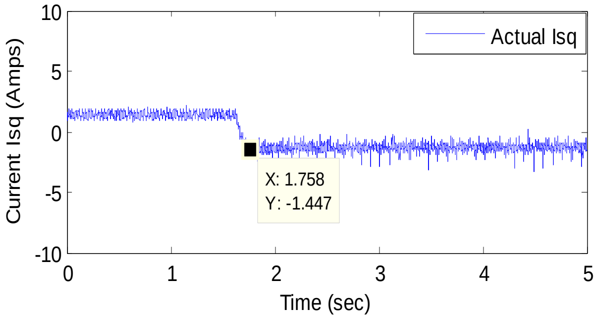

Fig.6 (b)

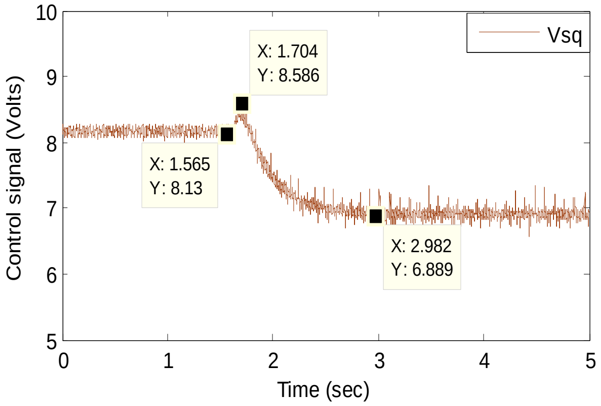

Fig.6 (c)

Fig.6. Experimental results for the load decrease with Non observer
(a) Speed response (b) Actual Isq current response
(c) Control signal Vsq response.

With the reference speed of 100rad/s, the experimental results with the EKF are shown in Fig.7 under no load condition. It is observed that the motor speed tracks the reference speed quickly and smoothly. Fig.7 (a) shows the Speed response, Fig.7 (b) shows the estimated speed response Fig.7 (c) shows the actual Isq current response, and Fig.7 (d) shows the control signal Vsq response for the input reference change. The actual current and estimated current have same value. The control signal variation is also smooth without any overshoots. It is evident that the proposed method estimates the rotor speed and q-axis current exactly.

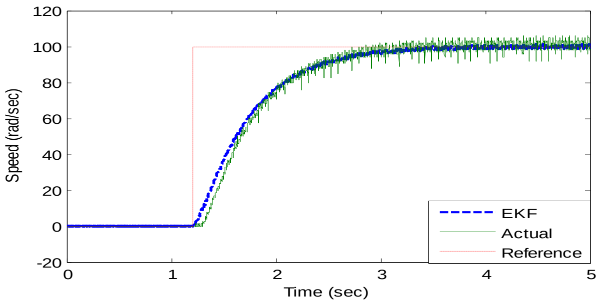

Fig.7 (a)

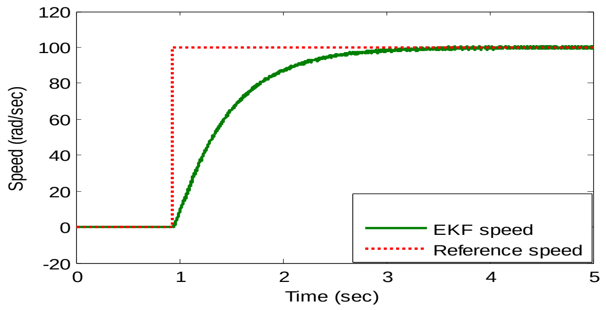

Fig.7 (b)

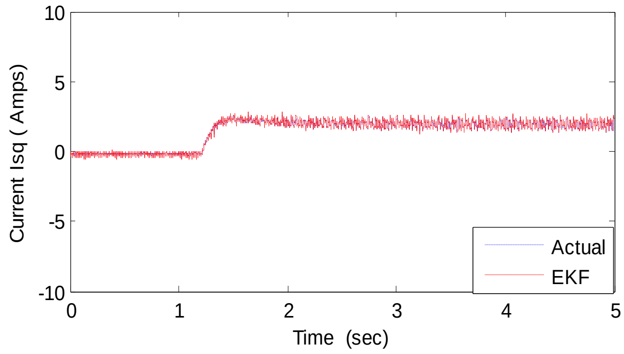

Fig.7 (c)

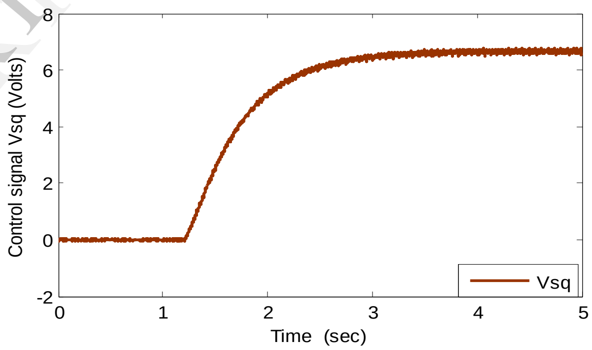

Fig.7 (d)

Fig.7. Experimental results for the input reference change under no load with EKF
(a) Speed response (b) Estimated Speed response
(c) Actual and estimated Isq current response
(d) Control signal Vsq response

The performance of the proposed technique under load disturbance is also verified. The load is varied from - 0.2Nm to 0.2Nm. The Speed response, estimated Speed response, actual Isq current response, and control signal Vsq response are observed and recorded under load variations. The experimental results in Fig. 8(a)(b)(c)(d) are shown for when load increase and Fig. 9(a)(b)(c)(d) are shown for when load decrease. From the results it is evident that speed deviation is reduced from 22 rad/sec to 10 rad/sec and it quickly follows the reference speed. The voltage is also reduced from 1.25v to 0.05v and with less transient time of around 1.2s. The measured speed signal is smooth and contains less noise compared to the non-observer.

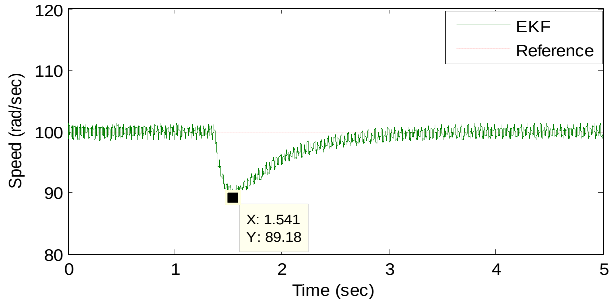

Fig. 8 (a)

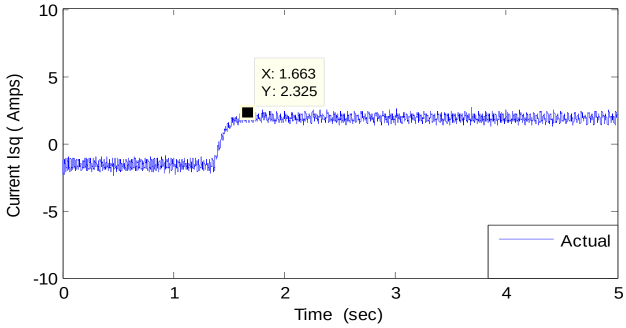

Fig. 8 (b)

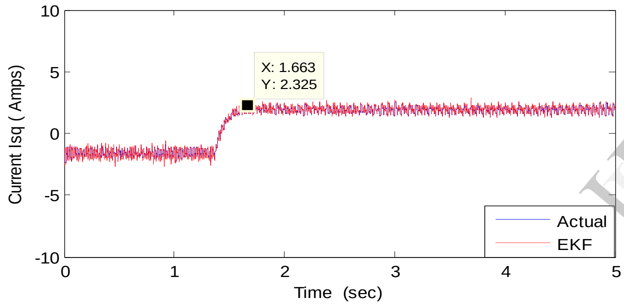

Fig. 8 (c)

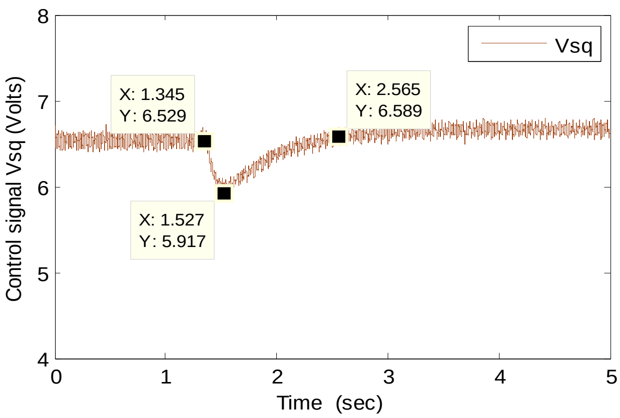

Fig. 8 (d)

Fig.8. Experimental results for the load increase with EKF
(a) Speed response (b) Actual Isq current response
(c)Estimated Isq current response
(d) Control signal Vsq response.

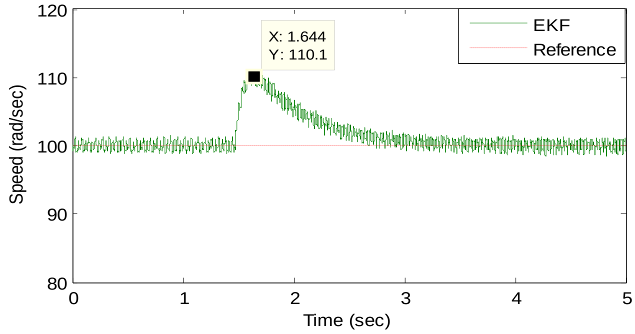

Fig. 9 (a)

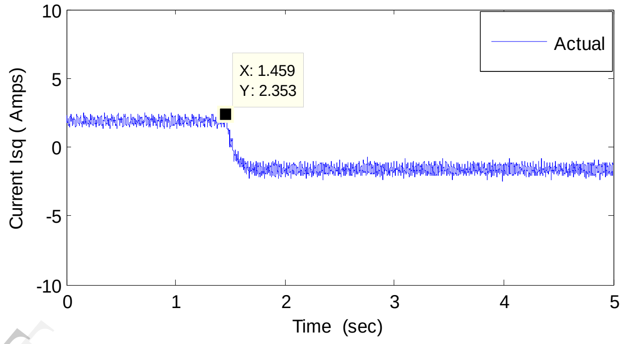

Fig. 9 (b)

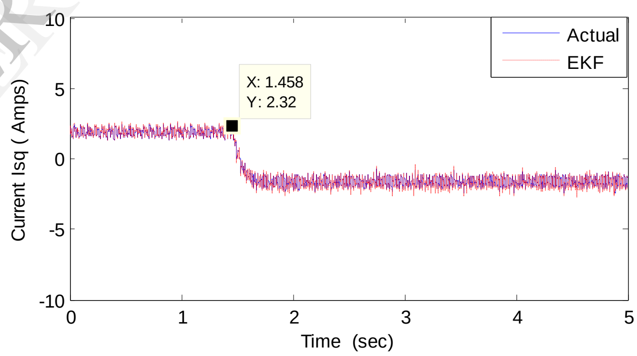

Fig. 9 (c)

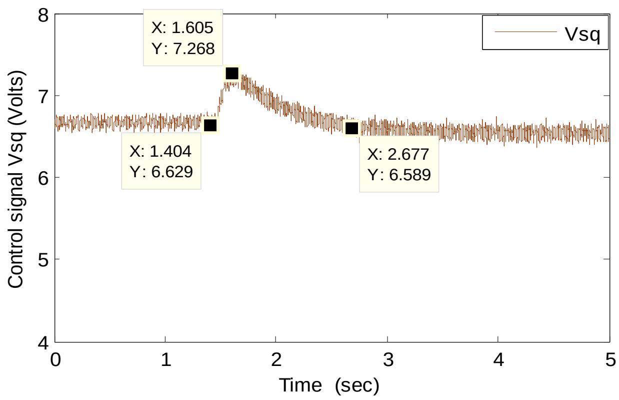

Fig. 9 (d)

Fig.9. Experimental results for the load decrease with EKF
(a) Speed response (b) Actual Isq current response
(c) Estimated Isq current response

(d) Control signal Vsq response.

From the obtained result, it is observed that the speed tracking is smooth and quick. The disturbance is quickly rejected by the system and attains the actual speed. With the implementation of EKF algorithm, the transient time and control signal variation are reduced compare to the non- observer.

VI. CONCLUSION

A novel implementation of proportional–integral–differential equivalent controller using state observer based Extended Kalman Filter (EKF) for a Permanent Magnet Synchronous Motor (PMSM) is proposed. The proposed method accurately estimates the speed and current. Also the proposed approach mitigates speed deviation caused by the load disturbance and attenuates the control signal variation. The steady and transient state responses are also improved. The EKF algorithm method attains good speed tracking. The system performance is enhanced significantly using the proposed method.

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