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Experimental Verification of the Speed Performance of PMSM Using DS1104 dSPACE with Load Disturbance

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Abstract: A novel design implementation of Extended Kalman Filter (EKF) combined with state observer for a Permanent Magnet Synchr onous Motor (PMSM) is proposed. The precise speed estimation is achieved using kalman algorithm and the Linear Quadratic Regulator (LQR) technique is used to tune the PID controller parameters. The disturbance rejection is achieved using observer based PID controller and its error is retained and will act as immune to disturbance rejection. The proposed methodology combines the best features of EKF estimator and that of the observer based PID controller and greatly enhances the PMSM speed control performance compared to the case when an EKF and observer acting alone. The PMSM speed controller is implemented using MATLAB/SIMULINK and DS1104 dSPACE board. The experimental results for the speed response variations when the PMSM is subjected to the load disturbance are presented. The experimental results verify the effectiveness of the proposed method.

Keywords: Permanent magnet synchronous motor; Extended kalman filter; Observer; PID; Vector control

I. INTRODUCTION

Permanent Magnet synchronous Motors (PMSM) are popular because they are efficient, compact and highly reliable, exhibits high torque/inertia ratio. Therefore it has become the choice of excellence in the field of variable speed electric drive applications. The PMSM drives with the vector control theory demonstrate the high performance and controls the flux and torque independently, similar to the DC motor. Although the vector control is a complex control technique, the progresses in the development of fast semiconductors switches and cost efficiency micro-controller has made the vector control feasible.

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. In order to avoid adverse effect on the performance of the system, the speed can be estimated through the Extented kalman filter (EKF) algorithm. The Extended Kalman Filter produces the optimal estimation of the states based on the least square method. Though the design of the observer is simple, it does not calculate the optimal estimation of the states unlike in Kalman Filter. Since, the fast dynamics demands for a high estimator gain which in turn causes noisy states. Hence, the Kalman Filter gives a better approach to state estimation because it is easier to tune the filter in terms of process and measurement noise variances than in terms of eigenvalues of the error- model.

Many research works have been done on speed and position estimation of PMSM. The observer and EKF approaches are well utilized in developing speed, position and torque control [1-8]. Also the disturbance rejection is achieved based on a multi-objective observer [9-11]. Due to the precise and accurate estimation, the EKF method is more attractive as well as popular and is continuously being used in research and applications. The feedback gain used in EKF achieves quick convergence and provides stability for the observer [12-16]. Here the best features of observer based PID and Extended Kalman Filter are combined to achieve better speed controller and to react quickly for the load disturbances.

To realize the better performance, the vector control theory requires the knowledge of the rotor position and speed of the motor. The first goal of the proposed method is to find the optimal method to estimate the angular speed of the motor. Since the rotor position is estimates through using sensors, it is essential to estimate the speed accurately under noisy nature to attain the speed tracking performance. It is effectively handled by designing the Extended Kalman Filter (EKF). The EKF is precisely

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estimate the angular speed by considering the noise in the measurement. The basic idea is to realize simple tracking algorithm and it is achieved in the proposed method. The second goal is to design a PID controller, which is quickly react to the variation of the reference input and to develop an observer to achieve disturbance rejection. Finally in this paper, implementation of a drive system by observer based PID controller combined with the EKF is achieved. In the proposed implementation, the speed and q-axis current are estimated accurately by introducing combined observer and EKF algorithm theory.

The proposed method yields a smooth and quick speed tracking. In addition, the noises in the signals are mitigated substantially. The actual disturbance applied to the system is reduce significantly, and provides better control of the control signal variation. The overall system performance during use is greatly enhanced. The experimental results justify the effectiveness of the proposed controller.

II. DESCRIPTION OF MOTOR MODEL

The vector control theory is utilized in PMSM drives in which the resulting state-feedback LQR for the augmented system is:
3-ɸ stationary frame transforms into 2-ɸ synchronously rotating rotor reference frame to control the flux and torque independently.

The stator voltage equations in the rotor references frame are [17,18]:

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

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

The stator flux linkages equations are:

$$\lambda_{sd} = L_s i_{sd} + \lambda_{fd}, \qquad (3)$$

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

Rs and Ls are the stator winding resistance and inductance. The electromagnetic torque generated and the acceleration is given by:

$$T_{em} = \frac{p}{2} \lambda_{fd} \cdot i_{sq}, \qquad (4)$$

$$\frac{d}{dt}\omega_{mech} = \frac{T_{em} - T_L}{J} - \frac{B}{J}\omega_{mech} \qquad (5)$$

III. PID CONTROLLER WITH EXTENDED KALMAN FILTER DESIGN AND STATE SPACE OBSERVER

The state space model of the simplified PMSM with reference to the q-axis is:

$$\dot{x}_1(t) = A_1 x_1(t) + B_1 u_1(t), \qquad (6)$$

$$y_1(t) = C_1 x_1(t) \qquad (7)$$

The state space model of the speed controller can be written as:

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$$\dot{x}_2(t) = A_2 x_2(t) + B_2 u_2(t), \qquad (8)$$

$$y_2(t) = C_2 x_2(t) = u_1(t), \qquad (9)$$

$$u_2(t) = -y(t) + E_c\, r(t) \qquad (10)$$

The entire system output with the motor output plus the load disturbance is:

$$y(t) = y_1(t) + d(t) \qquad (11)$$

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

$$u_1(t) = -K_e x_e(t) = -K_1 x_1(t) - K_2 x_2(t) \qquad (12)$$

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

$$J = \int_0^\infty [x_e^{\ T}(t) Q\, x_e(t) + u_1^{\ T}(t) R\, u_1(t)] dt \qquad (13)$$

where $Q \geq 0$ 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:

$$K_e = R^{-1} B_e^T P \qquad (14)$$

The total control law is equivalent to a PID controller with $\{K_1 x_1(t)\}$ acting as proportional and derivative controller and {K2} acting as integral controller.

The design of an observer, whose dynamic function is the same as that of the motor, is

$$\dot{\hat{x}}_1(t) = A_1 \hat{x}_1(t) + B_1 u_1(t) - J_o [C_1 \hat{x}_1(t) - y(t)] \qquad (15)$$

Where, $\hat{x}_1(t)$ is an observed state and $x_1(t)$ is the real state.

The state space model of the simplified PMSM is:

$$x_k = (I + AT) x_{k-1} + BT u_k, \qquad (16)$$

$$y_k = c x_k \qquad (17)$$

The nonlinear stochastic equation is:

$$x_k = f(x_{k-1}, u_k, 0) \qquad (18)$$

$$y_k = h(x_k, 0) \qquad (19)$$

$$f(x_k, u_k) = \begin{bmatrix} (1 - \frac{TR_s}{L_s})\, i_{sq} - (\frac{T\lambda_{fd}}{L_s} \cdot \frac{p}{2})\omega_{mech} + \frac{T}{L_s}[v_{sq}] \\ (T \cdot \frac{p}{2} \cdot \frac{\lambda_{fd}}{J})\ i_{sq} + (1 - \frac{TB}{J})\omega_{mech} \end{bmatrix} \quad \text{and } h(x_k, 0) = H \cdot x_k. \qquad (20)$$

The PMSM states x can be estimated by using EKF algorithm during each sampling time interval as shown in the Figure 1. The estimated current acts as an input to the state observer, while the estimated speed is compared with the reference speed.

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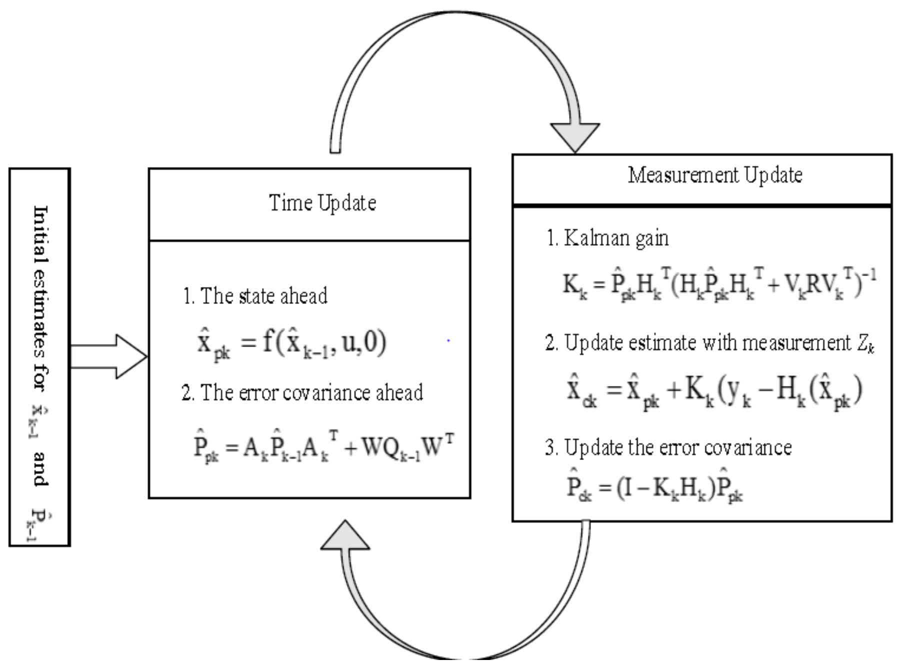

Figure 1: The Kalman filter algorithm.

The wise choice of the covariance matrices Q and R insures the better stability and convergence time. The overall system block diagram using EKF combined with state observer is as shown in the Figure 2.

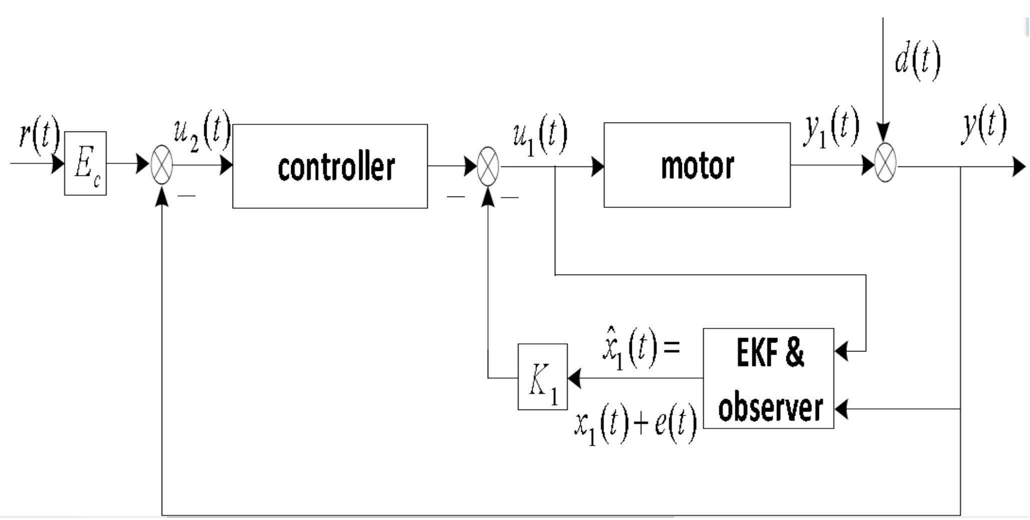

Figure 2: The block diagram of speed controller using the EKF combined with the state observer.

IV. EXPERIMENTAL RESULTS

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point DSP. 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 CP1104I/O board is an input-output interface board between the power electronic The experiments are conducted in order to verify and validate the results [19,20]. The PMSM speed controller is implemented using DS1104 dSPACE board. The DS1104 dSPACE controller board is built around the TI TMS320F240 floating drive board and dSPACE controller board. The block diagram used in the implementation is as shown in the Figure 3.

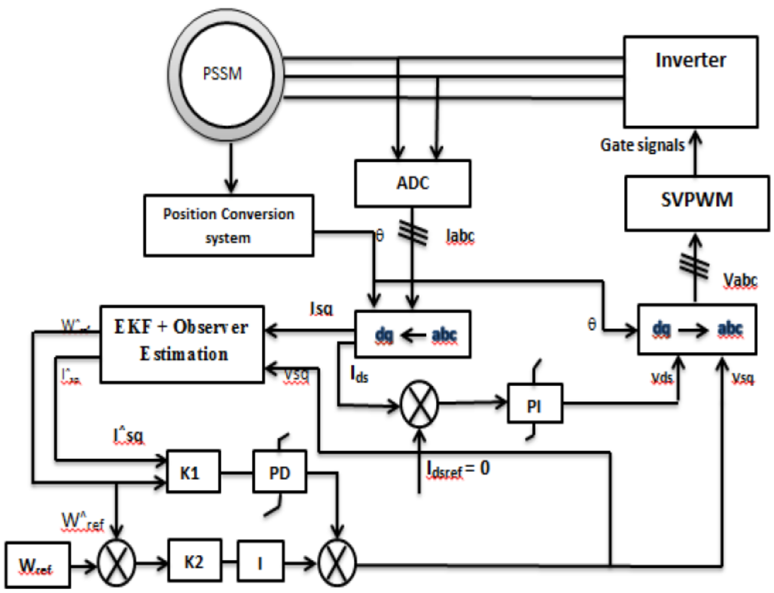

Figure 3: Experimental setup of PMSM speed controller.

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.

The experimental results are recorded with the Non-observer under no load condition with the reference speed of 100 rad/s.

It is observed from the Figures 4a and 4b that the measured speed signal and current signals are too noisy and there is an over shoot in the current signal.

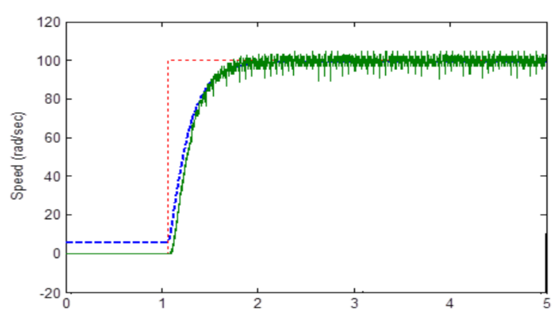

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Figure 4a: Speed response of the PMSM without the controller under no load.

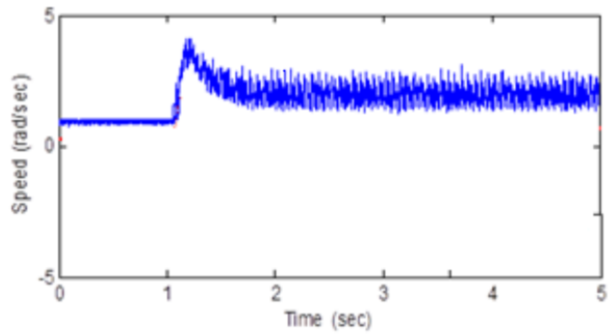

Figure 4b: Current response of the PMSM without the controller under no load.

The experiment is repeated with the proposed controller under no load and the speed and current responses are also recorded as shown in the Figures 5a and 5b respectively.

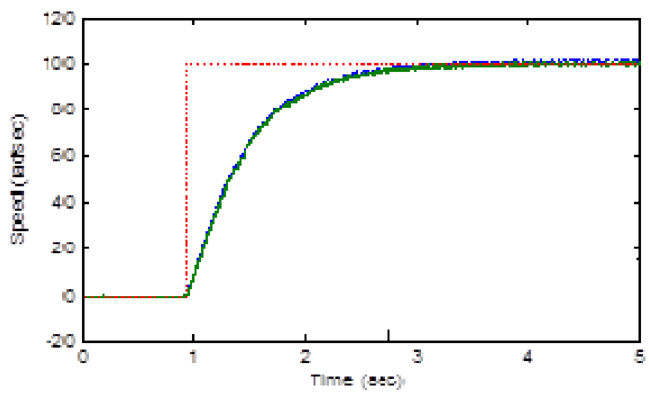

Figure 5a: Speed response of the PMSM with the proposed controller under no load.

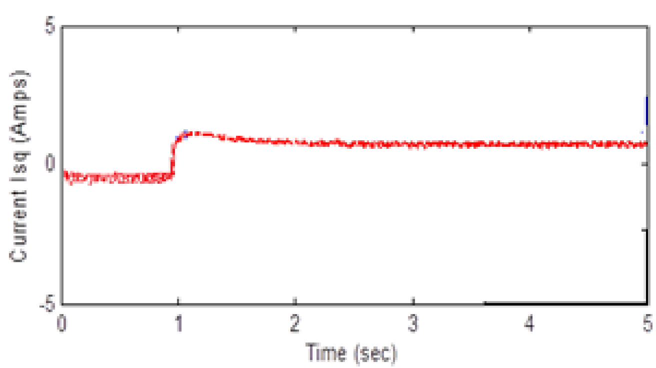

Figure 5b: Current response of the PMSM with the proposed controller under no load.

To verify for the speed estimation performance of the proposed method for a step change in steady state operation of PMSM; the load is varied from -0.2 Nm to 0.2 Nm. The experimental results are shown in the following figures for the increasing load. The estimated speed and current are compared with the actual values and are validated. Figures 6a and 6b shows the actual and

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estimated speed responses and the Figures 7a and 7b shows the actual and estimated current responses respectively.

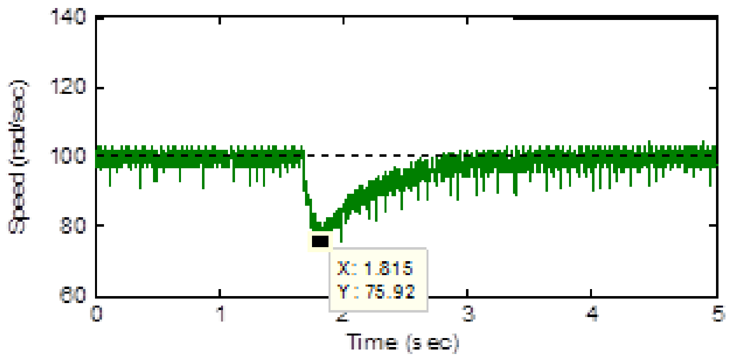

Figure 6a: Speed response of the PMSM without the controller under increasing load.

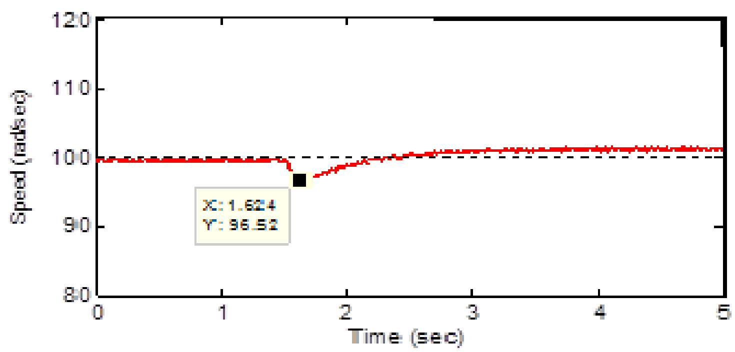

Figure 6b: Speed response of the PMSM with the proposed controller under increasing load.

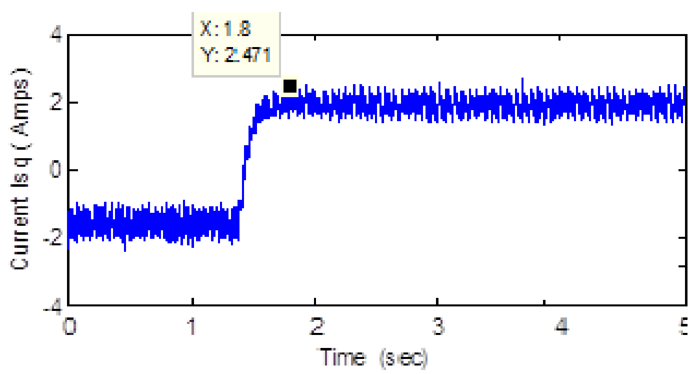

Figure 7a: Current response of the PMSM with the proposed controller under increasing load.

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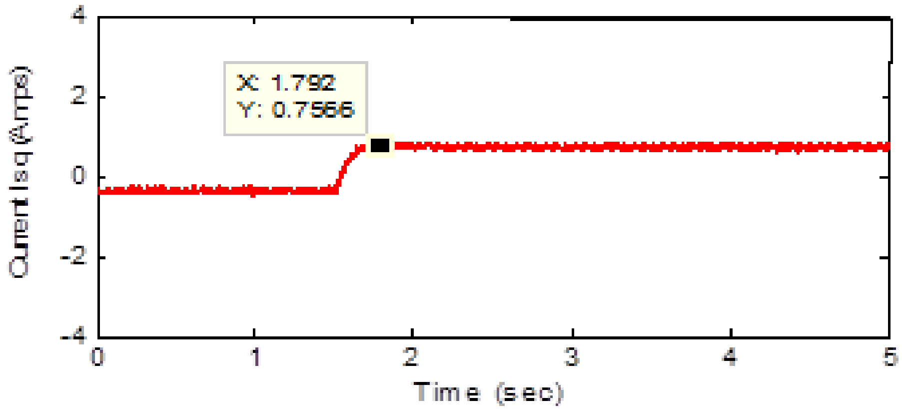

Figure 7b: Current response of the PMSM with the proposed controller under increasing load.

The experiment is repeated for the decreasing load and the actual and estimated speed is as shown in the Figures 8a and 8b.

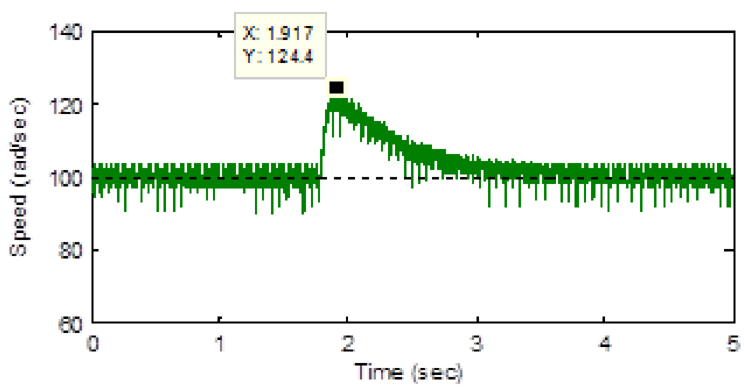

Figure 8a: Speed response of the PMSM without the controller under decreasing load.

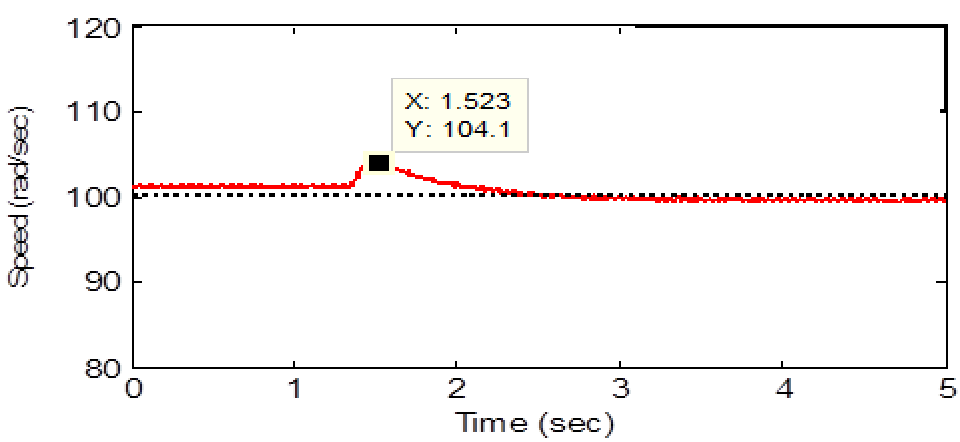

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Figure 8b: Speed response of the PMSM with the proposed controller under decreasing load.

The actual current and estimated current are as shown in Figures 9a and 9b. The obtained results are verified and validated.

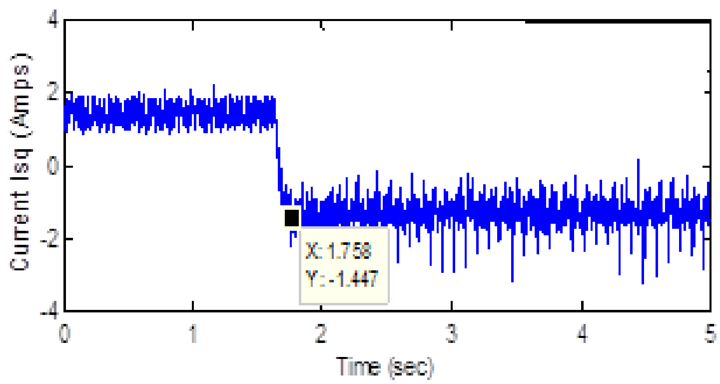

Figure 9a: Current response of the PMSM without the controller under decreasing load.

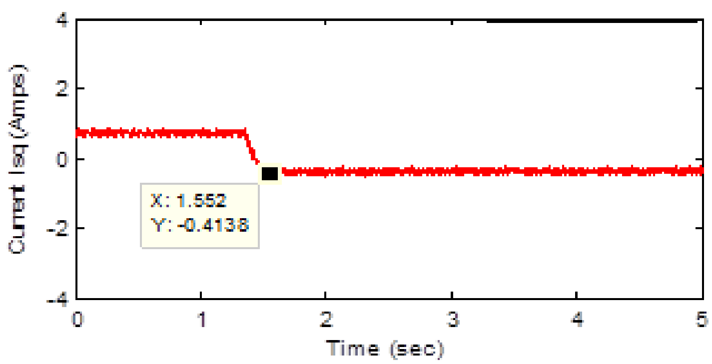

Figure 9b: Current response of the PMSM with the proposed controller under decreasing load.

From the experimental results it is observed that the speed deviation is around 5 rad/sec and the speed recovers quickly after the load disturbance with less transient time of around 0.8 secs. The measured speed signal is smooth and contains less noise compared to the conventional methods. The significant reduction in the transient input signal variation is noticed, which intern help to reduces the risk of potential input signal saturation, and prevents the deterioration of the system performance.

V. CONCLUSION

A novel design implementation of speed controller for a Permanent Magnet Synchronous Motor (PMSM) with disturbance rejection using conventional observer combined with Extended Kalman Filter (EKF) is proposed. The PID controller parameters are tuned using LQR technique in q-axis subsystem by considering the PMSM model as a decentralized multivariable system. Through the EKF, the accurate speed estimation as well as the excellent speed tracking is achieved. The EKF algorithm method attains good speed tracking and the observer based PID controller design provides the disturbance compensation. By combining the EKF and observer, the steady and transient state responses are improved considerably. The overall system performance is

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also enhanced significantly using the proposed method. Also, as the experimental results show, the input signal variation is reduced with less noise in the speed measurement. The proposed approach mitigates speed deviation caused by the load disturbance variations and there is an improvement in the efficiency of the overall system.

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