Experimental Investigation of Five-Phase Induction Motor Drive Using Extended Kalman-Filter

M. Rizwan Khan[1]   Atif Iqbal[2]

Abstract — In this paper extended Kalman filter (EKF) is reviewed for estimating the rotor position/speed of a vector controlled five-phase induction motor drive. The basic configuration of the Kalman filter is studied and the system vectors and matrices are explained. The EKF equations are made from a d-q-axis model of the five-phase induction motor by considering the rotor speed as a state variable. The simulation and experimental results show that the EKF is capable of tracking the actual rotor speed. Care should be taken in the selection of elements of the covariance matrices. The performance of the EKF is acceptable even in the presence of noise.

Keywords - Induction motor, Sensorless control, Kalman filter, Five-phase.

I. INTRODUCTION

Three-phase induction machine in industry is mostly used for speed control. For speed control ac drives are used which require a power electronic converter for their supply (mostly an inverter with a dc link), therefore number of machine phases is effectively unlimited. Multi-phase ac drive applications have increases enormously, since multiphase machines tender many advantages over their three-phase counterparts. A number of multi-phase machine research results have been reported [1-8].

Main advantages of multi-phase machine over three-phase machine are superior torque density, better efficiency, low torque pulsations, better fault tolerance, and reduced rating per inverter leg. Furthermore, noise performances of the drive improve as well. The limitation of multi-phase machine is that it needs a power electronic converter for phase conversion because three-phase supply is only easily available.

In most drive systems (speed and torque controlled), closed loop control is used in which shaft encoder is used for measurement of speed/position of the motor. However, in a compact drive system it is very difficult and expensive to use speed sensors for speed measurement (e.g. submarine applications). The cost of system can be reduced by eliminating the speed sensor and connection cables, and so the consistency and ruggedness of the overall drive system increases. A series of speed sensorless control techniques for induction motor has been reported in the last decade. The motor speed is estimated using these techniques and used as a feedback signal for closed-loop speed control.

Kalman filter is a unique observer which offers best possible filtering of the noise in measurement and of the system if the noise covariances are known. If rotor speed considered as an extended state and is incorporated in the dynamic model of an induction machine then the extended Kalman filter can be used to relinearize the nonlinear state model for each new value of estimate. As a result, the extended Kalman filter is measured to be the best solution for the speed estimation of an induction machine [9]. The extended Kalman filter has been applied to the vector control system [10-12] and for a direct control system or a constant Volt per Hertz. Few publications has been reported for the choice of the covariance matrices of the Kalman speed estimator. In this paper, the Kalman speed estimator for a vector controlled five-phase induction motor drive system is studied.

II. KALMAN FILTERS

Kalman filter takes care of the effects of the disturbance noise of a control system and the errors in the parameters of the system are considered as noise. The Kalman filter can be expressed as a state model [13]:

$$\dot{x} = Ax + Bu + U(t)w(t) \quad \text{(System equation)} \quad (1)$$

$$y = Cx + v(t) \quad \text{(Measurement equation)} \quad (2)$$

where

$U(t)$ = weight matrix of noise

$v(t)$ = noise matrix of output model (measurement noise)

$w(t)$ = noise matrix of state model (system noise)

$U(t)$, $v(t)$, and $w(t)$ are assumed to be stationary, white, and Gaussian noise, and their expectation values are zero. The covariance matrices Q and R of this noise are defined as:

$$Q = \text{cov } ariance(w) = E\{ww'\} \quad (3)$$

$$R = \text{cov } ariance(v) = E\{vv'\} \quad (4)$$

where $E\{.\}$ denotes the expected value.

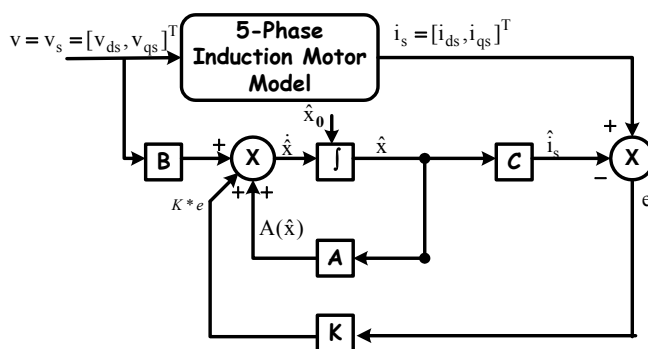The basic configuration of the Kalman filter is shown in Fig. 1.

Fig. 1: The basic configuration of the Kalman filter observer.

The state equations of the Kalman filter can be made as follows:

$$\dot{\hat{x}} = (A - KC)\hat{x} + Bu + Ky \qquad (5)$$

The Kalman filter matrix is based on the covariance of the noise and denoted by K. The measure of quality of the observation is expressed as follows:

$$L_x = \sum E\left\{[x(k) - \hat{x}(k)]^T [x(k) - \hat{x}(k)]\right\} = \min \qquad (6)$$

The value of K should be such that as to minimize L_x. The result of K is a recursive algorithm for the discrete time case. The discrete form of Kalman filter may be written by the following equations, in which all symbols denote matrices or vectors [13]:

(i)　System state estimation:

$$x(k+1) = x(k) + K(k)(y(k) - \hat{y}(k)) \qquad (7)$$

(ii)　Renew of the error covariance matrix:

$$P(k+1) = P(k) - K(k)h^T(k+1)P(k) \qquad (8)$$

(iii)　Calculation of Kalman filter gain matrix:

$$K(k+1) = P^*(k+1)h^T(k+1)[h(k+1)P^* \\ (k+1)h^T(k+1) + R]^{-1} \qquad (9)$$

(iv)　Prediction of state matrix:

$$f(k+1) = \frac{\partial}{\partial x}(A_d x + B_d v)\Big|_{x=\hat{x}(k+1)} \qquad (10)$$

(v)　Estimation of error covariance matrix:

$$P^*(k+1) = f(k+1)\hat{P}(k)f^T(k+1) + Q \qquad (11)$$

Discretization of (1) and (2) yields:

$$\qquad (12)$$

$$x(k+1) = A_d(k)x(k) + B_d(k)u(k)$$

$$y(k) = C_d(k)x(k) \qquad (13)$$

where $K(k)$ is the feedback matrix of the Kalman filter. $K(k)$ gain matrix calculates how the state vector of the Kalman filter is updated when the output of the model is compared with the actual output of the system. The Kalman filter algorithm can also be used for nonlinear systems (e.g. induction motor). However, the optimal performance may not be obtained and it is impractical to verify the convergence of the model. To realize the recursive algorithm of the extended Kalman filter, a state model of the induction motor is required. After knowing the matrices A_d, B_d, and C_d, the matrices $x(k)$ (state prediction) and $y(k)$ (output prediction) can be calculated.

III. Design Of Extended Kalman Filter For Five-Phase Induction Motor Drive

When rotor speed is considered as a state variable in the induction motor model, then an extended induction motor model is obtained and the rotor speed is considered as an extended state. The discrete induction motor model defined in (12) and (13) can be implemented in the extended Kalman filter algorithm.

If the system matrix, the input and output matrices of the discrete system are denoted by A_d, B_d, and C_d, while the state and the output of the discrete system are denoted by $x(k)$ and $y(k)$, then

$$A_d = \begin{bmatrix} 1 - T/T_s'^* & 0 & TL_m/(L_s'L_rT_r) & \omega_r TL_m/(L_s'L_r) & 0 \\ 0 & 1 - T/T_s'^* & -\omega_r TL_m/(L_s'L_r) & TL_m/(L_s'L_rT_r) & 0 \\ TL_m/T_r & 0 & 1 - T/T_r & -T\omega_r & 0 \\ 0 & TL_m/T_r & T\omega_r & 1 - T/T_r & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B_d = \begin{bmatrix} T/L_s' & 0 \\ 0 & T/L_s' \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C_d = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$x(k) = [i_{ds}(k) i_{qs}(k) \psi_{dr}(k) \psi_{qr}(k) \omega_r(k)]^T$$

$$u(k) = [u_{ds}(k) u_{qs}(k)]^T$$

$$y(k) = [i_{ds}(k) i_{qs}(k)]^T$$

where $L_s' = \sigma L_s = (1 - \frac{L_m^2}{L_s L_r})L_s$,

$$T_s'^* = \frac{L_s'}{R_s + R_r(L_m/L_r)^2}$$ and T is the sampling time.

The essential matrices and vectors for the recursive algorithm of the extended Kalman filter can be calculated, with the discrete system model. With the help of Matlab/Simulink program, speed estimation algorithm of the extended Kalman filter can be simulated, as shown in Fig. 2. The execution of the S-function block is based on an M-file written as MATLAB code.
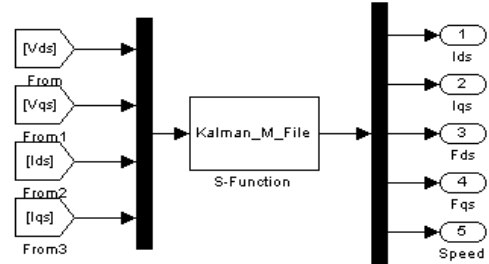

Fig. 2: Simulink based extended Kalman filter speed estimator.

IV. Sensorless Operation Of Five-Phase Induction Motor Drives

The developed model of a five-phase induction motor [4] indicates that an observer (Kalman Filter) used for three-phase machines can be easily extended to multi-phase machines. For multi-phase machines observer-based speed estimator requires only d and q components of stator voltages and currents. From the model of a five-phase induction machine [4], it is shown that the stator and rotor d and q axis flux linkages are function of magnetizing inductance Lm and stator and rotor d and q axis currents, where as the x and y axis flux linkages are function of only their respective currents. Therefore in speed estimation for multi-phase machine the x and y components of voltages and currents are not required. The speed can be estimated using only d and q components of stator voltages and currents.

The proposed extended Kalman filter-based vector controlled five-phase induction motor drive structure with current control in the stationary reference frame is shown in Fig. 3 (Appendix).
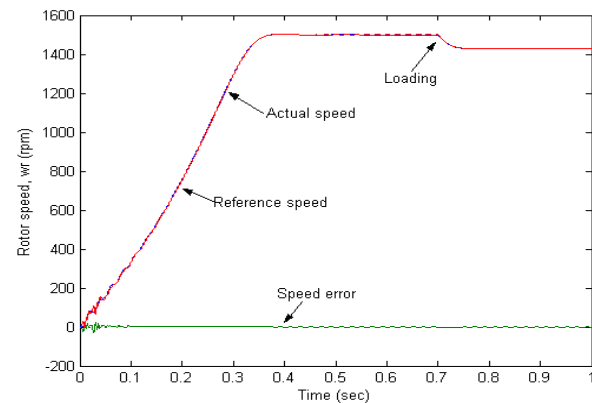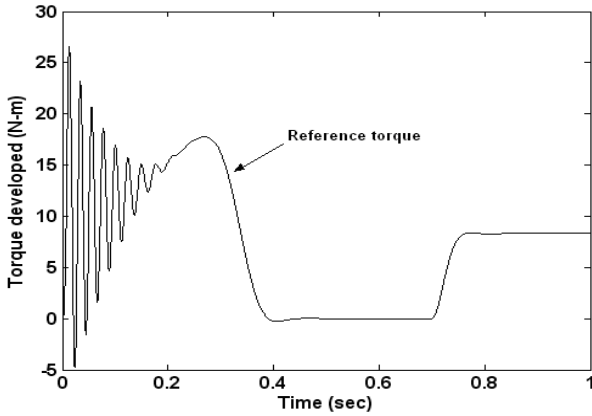
V. SIMULATION RESULTS

Fig. 4: Five-phase induction motor torque and speed characteristics for fixed voltage and fixed frequency fed supply ($g_1 = q_1$ =1e-6, $g_2 = q_2$ =1e-2).
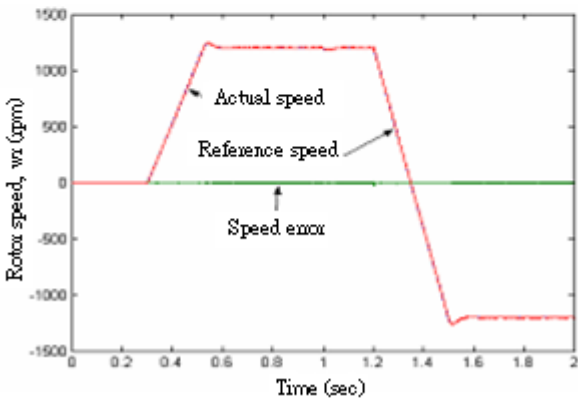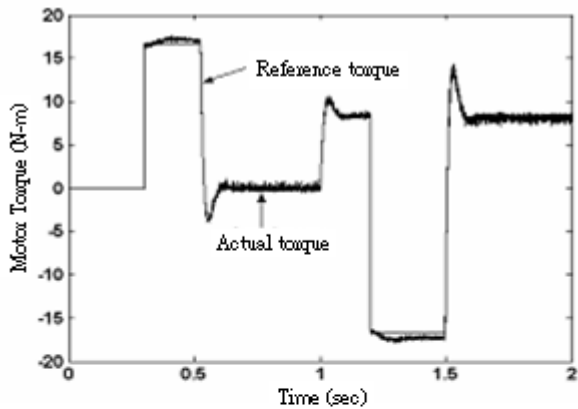

Fig. 5: Five-phase induction motor torque and speed characteristics for vector control ($g_1 = q_1$ =1e-6, $g_2 = q_2$ =1e-2).
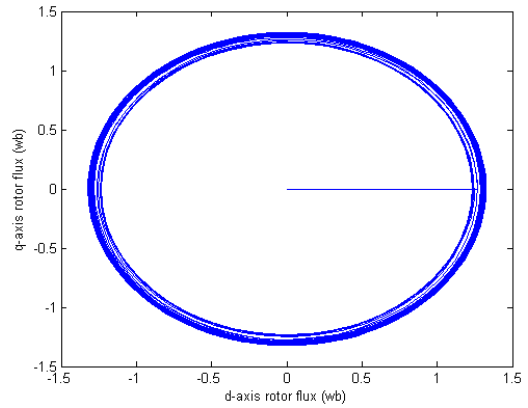

Fig. 6: Locus of rotor d- and q-axis fluxes.

The proposed drive is operated in speed mode with speed feedback is taken from kalman filter speed estimator. Fig. 4 displays the results for torque and speed characteristics of the induction motor when motor is fed with fixed voltage and fixed frequency supply. The simulation time is t=1 sec. and a rated torque is applied at t=0.7 sec. For vector control, the total simulation time is t=2 sec. Speed command of 1200 rpm is functional at t=0.3 sec in a ramp wise mode from $t = 0.3$ to $t = 0.35$ sec and is further kept unaffected. Operation takes place under no-load and load conditions. Interruption dismissal properties of the drive are investigated next. A load torque equal to the motor rated torque is functional in a step-wise mode at $t = 1$ sec. In the last, reversing transient is examined. The command for speed reversal is given at $t = 1.2$ sec. The results, obtained for these periods, are shown in Fig. 5. It is concluded from the results that, the actual speed and torque closely follow the reference. Fig. 6 displays the locus of rotor fluxes.

The error covariance matrix P of the Kalman filter is taken as a unit matrix and the measurement noise covariance matrix R of the extended Kalman filter is assumed as follows:

$$P = diag(1,1,1,1,1) \text{ and } R = diag(1e-3,1e-3)$$

Selection of covariance matrix:
The configurations of the state noise covariance matrices G and Q are of highest importance for the superior performance of the Kalman filter algorithm. They are expressed as follows:

$$G = diag(g_1, g_1, g_1, g_1, g_2) \quad \text{and}$$
$$Q = diag(q_1, q_1, q_1, q_1, q_2)$$

Fig.7 illustrates that the speed estimation of the extended Kalman filter is sensitive to the covariance matrices G and Q.
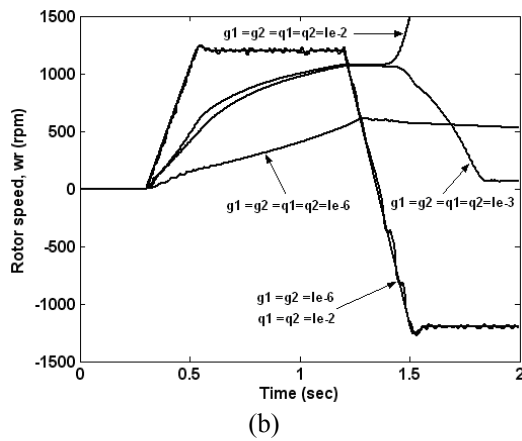

(a)

(b)
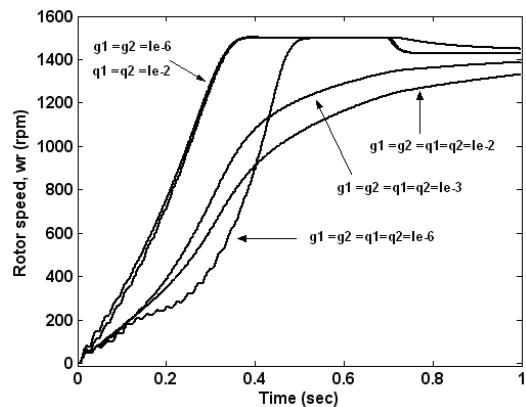
Fig. 7: Estimated speed with various covariance matrices for (a) fixed voltage and fixed frequency fed supply (b) vector control five-phase induction motor drive.

The precision of speed estimation with various G and Q may be find by the mean squared error between the actual rotor speed and the estimated speed. From Fig. 7, it is observed that when $g_1 = q_1$ =le-6, and $g_2 = q_2$ =le-2, the extended Kalman filter gives a more accurate result. When $g_1 = g_2 = q_1 = q_2$, the extended Kalman filter gives poor speed estimation results. For obtaining superior estimation results, the design principle is that the values of g_2 and q_2 in the covariance matrices G and Q should be greater than the values of g_1 and q_1.

VI. EXPERIMENTAL RESULTS

With the advent of high-performance digital signal processors (DSPs) dedicated for motion control applications, it is now possible to control motors without speed sensors. This is obtained by algorithms/programs that estimate the desired quantities in real time, based on the electrical signals in the motor windings. The advantages are cost savings and improved consistency due to reduced component used.

The motor used in both the experiment and simulation is same. The simulation results shown in Fig. 4 to Fig. 7 have been obtained under an 8.41 N-m load. The real-time control and observer program are implemented by using the software of digital signal processor (DSP) TMS320F2812. An eddy-current machine is coupled to the shaft of the IM as a load. A feedback control system is applied to the vector controlled IM drive system. In the inner loop of the control system, a standard proportional plus integral (PI) controller is used for current control and another PI controller is used in the outer loop for speed control. The parameters of the PI controller are tuned to obtain ample performance of the control system. A PC is used for data logging, data communication, and downloading. The stator currents are detected through Hall-effect sensors. The performance of the Kalman observer is tested in the implementation for trapezoidal references. The trapezoidal references are selected to show the performance of the proposed method in both directions at variable and constant speeds. The various experimental results are shown in Fig. 8 to Fig. 11.
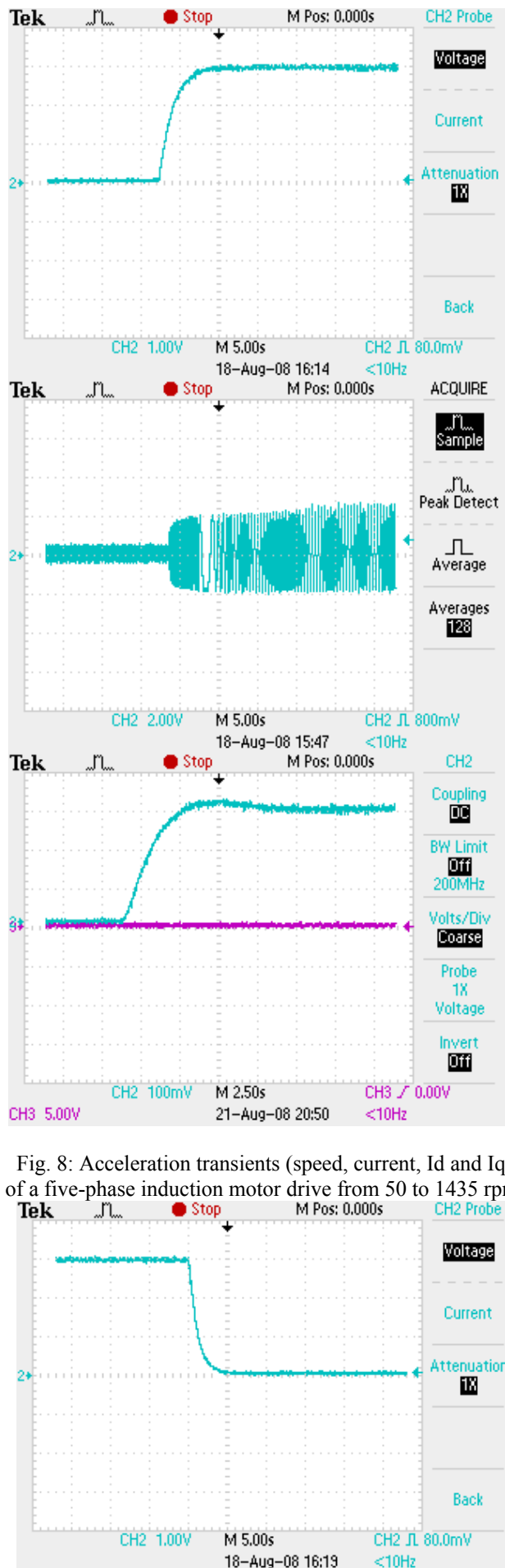

Fig. 8: Acceleration transients (speed, current, Id and Iq) of a five-phase induction motor drive from 50 to 1435 rpm.
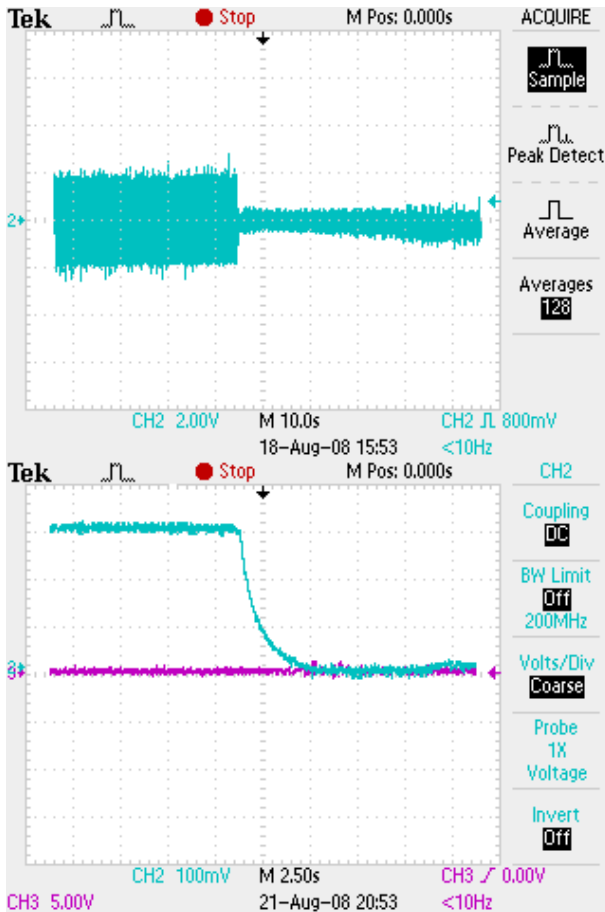
Fig. 9: Deceleration transients (speed, current, Id and Iq) of a five-phase induction motor drive from 1435rpm to 50 rpm.
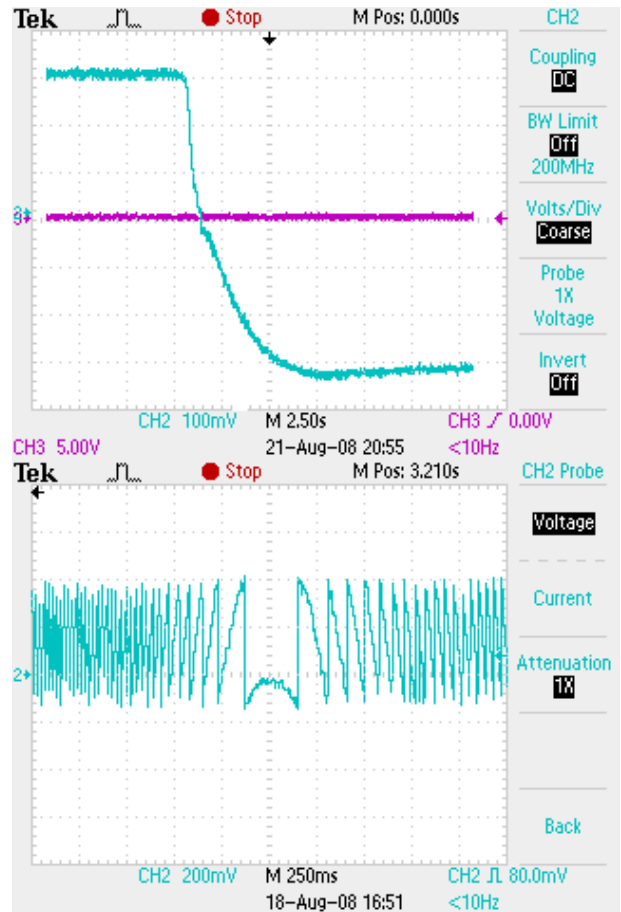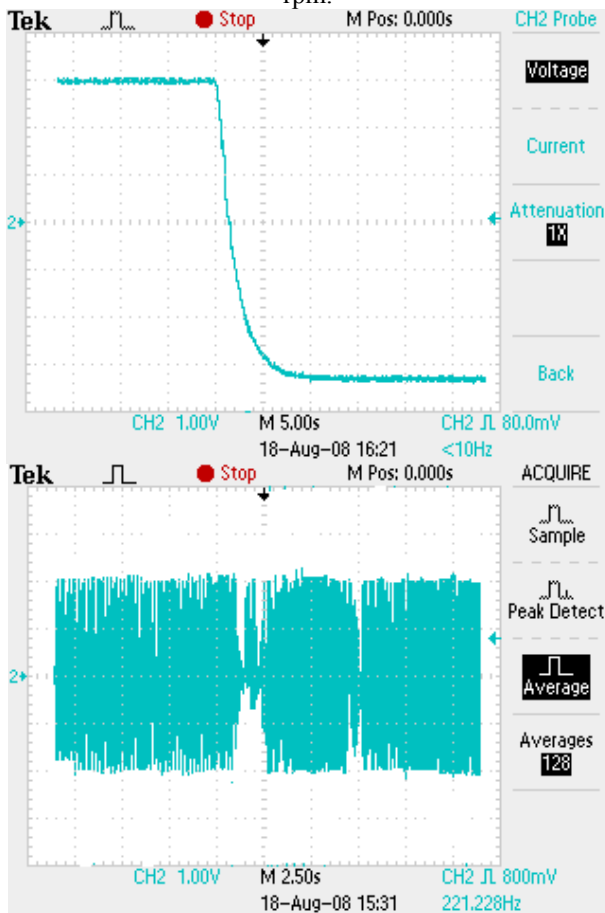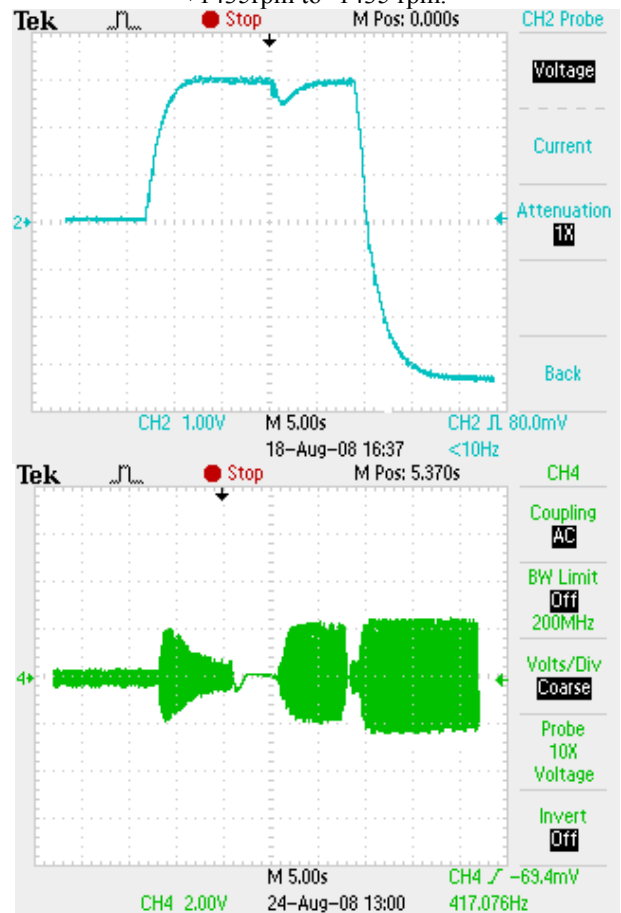
Fig. 10: Reversing transients (speed, current, Id & Iq, rotor position) of a five-phase induction motor drive from +1435rpm to -1435 rpm.
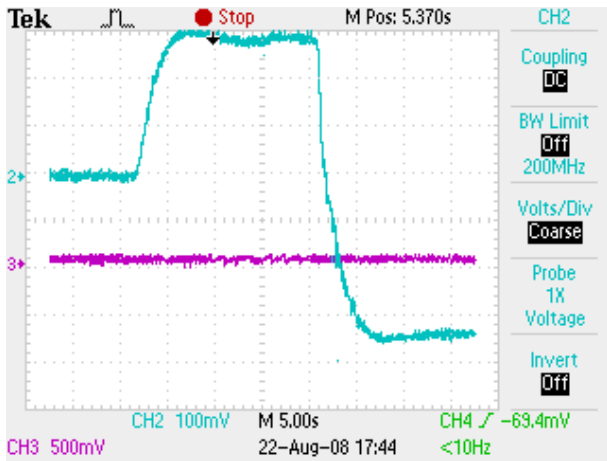
Fig. 11: Acceleration and reversing transients (speed, current, Id and Iq) of a five-phase induction motor drive under no-load and load from 50rpm to 1435rpm to -1435 rpm.

VII. Discussion

The results of the experimental study are illustrated for all transients by displaying the speed response, actual phase current and stator d- and q-axis current references. A step speed command is initiated in all the cases. There is no inertia wheel fitted to the motor. It can operates under no load and load conditions. All the transients are taken from the DAC outputs of DSP TMS320F2812. Acceleration transients, starting from 50 rpm, are shown in Fig. 8. The step speed command is 1435 rpm. Typical behavior of sensorless control of vector controlled five-phase induction motor is observed, with rapid stator q-axis current reference build up corresponding to almost instantaneous torque build up. Three different types of characteristics speed, current and Id and Iq are shown in Fig. 8.

The second test is a deceleration transients illustrated in Fig. 9. The motor is decelerated from 1435 rpm to 50 rpm speed.

The same quality of performance as for the acceleration transient is obtained. The speed, current and Id and Iq characteristics are shown in Fig. 9. Next, reversing performance of the drive is investigated. Transition from 1435 rpm to –1435 rpm, is depicted in Fig. 10. Prolonged operation in the stator current limit results in all the cases, leading to rapid change of direction of rotation. The speed, current, Id and Iq and rotor position characteristics are shown in Fig. 10 when motor is reversing.

One more transition is performed in three steps. First, motor will accelerate from 50 rpm to 1435 rpm at no-load. Second a step loading is applied to motor in steady-state period. Lastly, motor is reversing from +1435 rpm to -1435 rpm. All the corresponding transients are shown in Fig. 11.

VIII. Conclusion

In this paper, an extended Kalman filter is designed to estimate the rotor speed of a vector controlled five-phase induction motor drive. Effects of the covariance matrices of the Kalman filter are studied and a suggestion for selecting the covariance matrices is also given. Simulation results shows that the extended Kalman filter has excellent noise rejection properties. The attainable performance are examined by simulation and compared. It is shown that the dynamic behavior, obtainable with the indirect vector control, is the same as obtained with three-phase machine. Results are also obtained by experiments and compared with the simulation results. Experiment results show that proposed technique is well suited for speed sensorless estimation of five-phase induction machine. Same technique can be extended to multi-phase multi-motor drive system.
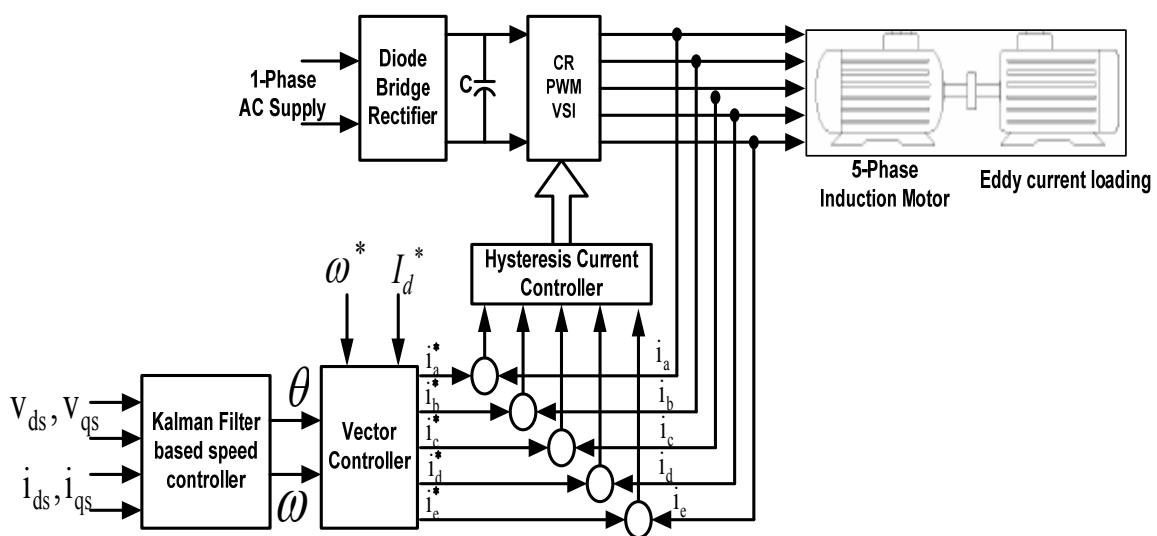
APPENDIX

Fig. 3: A vector controlled five-phase induction motor with extended Kalman filter speed estimation algorithm

REFERENCES

[1] E. Levi, "Multi-phase electric machines for variable speed applications", IEEE Trans. On Ind. Electronics, Vol. 55, No. 5, 2008, pp. -1893-1909.

[2] E. Levi, R. Bojoi, F. Farina, H.A. Toliyat and S. Williamson ,"Multi-phase induction motor drives-A technology status review", IET Electr. Power Appl. Vol. 1, No. 4, 2007, pp. 489-516.

[3] M.Jones and E.Levi, " A literature survey of state-of-the-art in multiphase ac drives", Proc. 37th Int. Universities Power Eng. Conf. UPEC, Stafford, UK, 2002, pp. 505-510.

[4] A. Iqbal, S.N. Vukosavi and E.Levi, "Vector control of a five-phase induction motor drive," Proc. 38th UPEC, Thessoloniki, Greece, 2003, CD-ROM paper No. EMDII, pp.57-60.

[5] M. Rizwan Khan, Atif Iqbal and Mukhtar Ahmad, "MRAS-Based Sensorless Control of A Vector Controlled Five-Phase Induction Motor Drive" Electric Power Systems Research, Volume 78, No. 8, August 2008, pp. 1311-1321.

[6] M. Rizwan Khan and Atif Iqbal "MRAS-Based Sensorless Control Of Series-Connected Five-Phase Two-Motor Drive System " Korian Journal of Electrical Engineering and Technology , Vol. 3, No. 2, 2008, pp. 224-234.

[7] M. Rizwan Khan and Atif Iqbal, "Speeds Estimation of Series-Connected Five-Phase Two-Motor Drive System Using Adaptive Flux Observers" Asian Power Electronics Journal Vol. 2, No.1, April 2008, pp. 45-54.

[8] M. Rizwan Khan, Atif Iqbal and Mukhtar Ahmad, "Artificial Intelligence -Based Sensorless Control of A Vector Controlled Five-Phase Induction Motor Drive" IEEE International Conf. on Recent Advancement and Applications of Computer in Electrical Engineering (RACE), 24-25 March, 2006, Bikaner, India, CD_ROM paper.

[9] C. Manes, F. Parasiliti, M. Tursini, "A Comparative Study of Rotor Flux Estimation in Induction Motors with a Nonlinear Observer and the Extended Kalman Filter", IECON 94 Conference, 1994, pp.2149-2154.

[10] G. Henneberger, B.J. Brunsbach, Th. Klepsch, "Field-Oriented Control of Synchronous and Asynchronous Drives without Mechanical Sensors using a Kalman Filter", Sensorless Control of AC Motor Drives, IEEE Press, 1996, pp.207-214.

[11] Y. R. Kim, S.K. Sul, M.H. Park, "Speed Sensorless Vector Control of Induction Motor Using Extended Kalman Filter", Sensorless Control of AC Motor Drives, IEEE Press, 1996, pp. 2 15-223.

[12] L. Salvatore. S. Stasi, S. and L. Tarchioni, "A New EKF-based Algorithm for Flux Estimation in Induction Machines", IEEE Transactions on Industrial Electronics, Vol.40, No.5, 1993, pp.496-504.

[13] F. L. Lewis, "Applied Optimal Control & Estimation", Prentice Hall, Inc., 1992.

[14] M. Chee, "Dynamic Simulation of Electric Machinery Using Matlab/Simulink" PrenticeHall, Inc., 1998.

BIOGRAPHIES

M. Rizwan Khan received his B.Sc. Engineering, M.Tech. (Electrical) and Ph.D. degrees in 1998, 2001 and 2009 respectively, from the Aligarh Muslim University, Aligarh, India. He is an Asstt. Professor in the Department of Electrical Engineering, Aligarh Muslim University, Aligarh since 2001. His principal area of research interest is Power Electronics, Artificial Intelligence and Multi-phase motor drives.

Atif Iqbal received his B.Sc. and M.Sc. Engineering (Electrical) degrees in 1991 and 1996, respectively, from the Aligarh Muslim University, Aligarh, India and PhD in 2005 from Liverpool John Moores University, Liverpool, UK. He has been employed as Lecturer in the Department of Electrical Engineering, Aligarh Muslim University, Aligarh since 1991 and is currently working as a Reader in the same university. He is recipient of Maulana Tufail Ahmad Gold Medal for standing first at B.Sc. Engg. Exams in 1991, AMU and research fellowship from EPSRC,UK for pursuing Ph.D. studies. His principal area of research interest is Power Electronics and Multi-phase machine drives.