Estimation of Speed and Rotor Position of Brushless Dc Motor by Application of Extended Kalman Filter

Nabiya Ellahi
Lab Engineer, Institute of Electrical, Electronics & Computer Engineering, University of the Punjab
MS Electrical Engineering, University of Engineering & Technology, Lahore Lahore, Pakistan

Abstract:- This research basically focuses on a technique to estimate speed and rotor position with enhanced performance. For this purpose numerous techniques including Sensorless methods were taken into account and new developments were also made. Some advanced methods were also introduced for this purpose along with their associated merits and demerits. This research includes detailed study of all the methods which can be used for the purpose of speed and rotor position estimation including back-EMF sensing method which was an obsolete technique. Some other methods which can be used for this purpose are position estimation by inductance and flux, back-EMF zero crossing and integration of voltage. But all these methods were obsolete and had disadvantages associated with them so in this research, the main aim is to utilize latest technique which can give accurate results and is also up to date. For this purpose Extended Kalman Filter is employed for the purpose of state estimation while PID controller is utilized to synchronize system state following the reference signal. The proposed solution will control the harmonic generated in speed and position of Brushless DC motor and ultimately performance of the motor will get improved.

Keywords:- *Sensorless, Extended Kalman Filter, PID controller, speed and rotor position estimation, back-EMF zero crossing.*

I. INTRODUCTION

There are numerous advantages associated with Brushless Direct Current (BLDC) motor which includes reduced harmonic operation, improved torque versus speed features, elimination of sparking and robust construction. Various studies and researches were performed on proper commutation, enhanced speed diversity, reduction of ripples or disturbances generated in torque and powering the phases of BLDC motor [1].Previously, various sensorless techniques were suggested by the experts to eliminate the costly and feeble sensing of position of BLDC. These techniques include many methods such as back-EMF zero crossing of voltage, back-EMF integration, approximation of flux, and motor moderation techniques. But all these techniques, didn't worked well for various operating speed ranges and there were some issues associated with those techniques including complexity and reliability problems for different operational speeds [2].These methods were inadequate to provide continuous information regarding estimation of rotor position and speed and for improved accuracy a method was required which can provide continuous information regarding rotor position after every instant of time when the motor will change its position or will perform switching not only after 60 electrical degrees as the old techniques were performing this task for limited time span [3]. Undoubtedly all the previous methods had quite a lot of benefits associated with them and also they can be utilized to accurately estimate rotor position. But apart from all these merits, all these techniques ultimately fell short when it came to test the performance of motor at low speeds, other cons which were associated with these techniques include varying ranges of speed of all these techniques requires betterment. Most of the times, therewere issues of disturbances and perturbations in mechanical control objects[4].Designing and modeling of motor parameters were also complicated, so considering all the above mentioned shortcomings these methods are not applied currently and frequently, as they hadnumerous disadvantages linked with them[5]. Because of all the above mentioned reasons there was a requirement to overcome these problems by introducing a technique which had the audacity to deal with these problems. An advanced method will be described in detail in this research article whose ultimate aim is to efficiently and accurately perform approximation of speed and rotor position with enhanced accuracy. The method which will perform this task with great accuracy is the Extended Kalman Filter. This is one of the latest and cost friendly method which is adopted currently to enhance motor performance.Estimation of parameters will take place by the utilization of line voltages of stator and phase currents [6]. Certain parameters needs consideration for the purpose of estimation and those variables are described in detail in the forthcoming paragraphs and some other parameters which needs considerationare rotor position and speed[7]. Extended Kalman Filter is an iterative process for non-linearized systems that gets disturbed by noise, in the which first step is to predict about system state and next step involves correction of predicted estimated state by utilization of a recent measurement process so that an estimation of the next state can be generated [8]. Basically this method involves the online estimation of state variables so that speed and rotor position can be approximated by utilization ofcalculated values of voltages and currents of permanent magnet

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

synchronous motor [9] in the absence of position sensorExtended Kalman Filter will perform online estimation in which maximum steady state error between estimated and actual speed of motor will get reduced.

II. ESTIMATION OF SPEED EMPLOYING EXTENDED KALMAN FILTER

This is an online estimation technique that approximates the system state by the application of signals that gets disturbed by noise ripples. Extended Kalman Filter will approximate the unidentified variableslike stator resistance R_s and afterwards it will perform the task of parameter estimation. The deterministicobserver that has no noise is luenberger and that can be applied to time-invariant linear systems[10]. EKF considers thatthe noise sources have certain inaccuracies associated with them in measurements and modeling. Generally for linear systems Kalman Filter is utilized and for the systems that are subjected to disturbances Extended Kalman Filter is applied for those systems[11].

Normally the machine model is shown below:

$$\frac{dx}{dt} = Ax + BV_s$$

$x=[ids, iqs, \Psi dr, \Psi qr]^T$

$V_s=[Vds, Vqs, 0, 0]$

Where
- ids, iqs= Stator current
- Ψdr Ψqr= Rotor flux
- vds,vqs = stator voltage
- Vs= Input Vector
- ωr= Rotor speed

$$\begin{bmatrix} & \frac{-(L_m^2R_r+L_r^2R_s)}{\sigma L_s L_s^2} & \frac{0}{\sigma L_s L_s^2} & \frac{L_m R_r}{\sigma L_s L_s} \\ 0 & \frac{-(L_m^2R_r+L_r^2Rs)}{\sigma L_s L_s^2} \quad \frac{}{Lr\ Lr} & \frac{-L_m R_r}{\sigma L_s L_s} & \frac{L_m R_r}{\sigma L_s L_s^2} \\ 0 & \frac{L_m R_r}{} & & \frac{\omega_r - R_r}{L_r\ L_r} \end{bmatrix}$$

Description of Variables:
- L_m=magnetizing inductance
- R_r=Rotor resistance
- R_s= Resistance of Stator
- σ = Position of Rotor
- ω_r = Rotor Speed
- L_r= Inductance of Rotor

III. MATHEMATICAL MODEL OF EXTENDED KALMAN FILTER

The Extended Kalman Filter employs dynamic machine model which considersspeed a state as well as a parameter.

$Y = CX$

$X=[ids, iqs, \Psi dr, \Psi qr, \omega_r]$

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

$Y= [ids \ \ iqs] = i_s$

Speed ω_r can be considered a state as well as a parameter. If there are no changings in the speed $d\omega_r/dt=0$[12]. This is quite justified consideration because time of sampling is lowor inertia of the load has high value. If the consideration is that speed ω_r is a parameter of constant value then nonlinear model of EKF can be considered linear

IV. IMPLEMENTING EXTENDED KALMAN FILTER DIGITALLY

For the implementation of Kalman filter in digital mode, the model should be discretized first and [13] there are some noise sources associated with the model which are designated as V and W so in the discrete mode, the model can be defined in the form of following equation.

- $X(K+1)= A_dX(k) + B_dU(k)+ V(k)$
- $Y(k) = Cd\ X(k)+ W(k)$

All these variables have no dependence over each other. For the purpose of noise and statistics measurement covariance matrices are employed which are denoted by P, Q, and R. The process of Extended Kalman Filterinvolves two which are prediction and correction.In the first steppredicted values (k+1) are obtained on the basis of machine model and previous values of the estimated states. In the second step filtering starts from vector Q in which estimated state (K+1) is found from the previous prediction state with the addition of the factor, which is ek where eis basically be the variance between predicted and estimated state and k is Kalman gain. This gain is basically utilized to optimize errors in estimation. For the purpose of calculations of EKF, a correction term is involved which is designed in such a manner that it always remains close to zero. Following steps are involved for designing of Extended Kalman Filter[14].

$L_m \omega_r$

A=$L_m R_r$ 0 -R_r -ω_r

A. *Extended Kalman Filter Steps*

Step 1 Initialization of state vector and other matrices
$X(0), Q_o, R_o, P_o$

Step 2 Prediction of state vectors
$X(k+1,K) = X(k+1) = A_dX(k) + B_dU(k)$

Step 3 Estimation of P(k+1) which is covariance matrix
$P(k+1)=f(k+1)\ P(k)f^T(k+1)+Q$

Step 4 Computation of Kalman Filter Gain
$K(k+1)= P(k+1)h(k+1)[h(k+1)\ P(k+1)\ h^T(k+1)]^{-1}$

Step 5 Estimation of state vectors
$\widehat{X}\ (K+1)=X(k+1)+K(k+1)[Y(k+1)]$

Step 6 Updating $\widehat{P}(K+1)$ of covariance matrices
$\widehat{P}(K+1)=P(K+1)-K(k+1)h(k+1)P(k+1)$

B. Block Diagram with Extended Kalman Filter

Complete representation of experimental setup of Extended Kalman Filter is shown in the form of block diagram which is drawn in the form of figure below [15]. The blocks consists of different components including DC input, inverter for the purpose of switching, current sensors, brushless dc motor and an Extended Kalman Filter is used for the purpose of estimation of speed and rotor position.

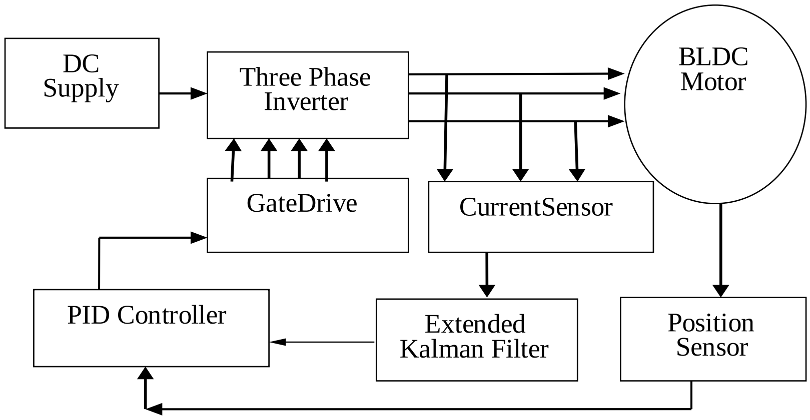

Fig. 1: Block Diagram of BLDC Motor for Position and Speed Estimation

The research employs a brushless DC motor which is utilized in the form of synchronous motor. In order to energize the motor, trapezoidal input is given to the motor, which can be done by switching motor at proper instants of time by using analogy of switching. First of all, dc input is given to the motor and afterwards, the dc input is fed to the MOSFET, which will serve the purpose of inverter, and convert the DC input into AC and ultimately the motor will run. Kalman Filter will generate estimation of voltages and currents from the terminals of the motor. Once these values are obtained, they are fed to the PI controller and afterwards to the logic table, which will perform the function of switching. The controller will make electromagnetic torque as a reference. Sensors will provide step input to the MOSFET, which will work on the position of the rotor and stator. The sensor will take into account the position of stator and rotor by detection of the electromagnetic force, which will be obtained by the positions of the stator and rotor[16]. Afterwards, the stator and rotor positions will be fed into zero and ones and afterwards to the proportional-integral controllers via analog to digital converters. The non-linear system will take these values as reference and will perform switching of the motor. The Extended Kalman Filter model can be made linearized about an estimator of current mean and covariance. In the case of well-defined and transitioned model of EKF, generated values of estimated flux linkage of the stator andoriginal velocity of the rotorwill be obtained by utilizing values of voltage and current from the terminals of the motor. With the help of these values, the ripple generation in the torque will be controlled by the PI controller and ultimately, the ripple will be minimized[17].

V. SIMULINK MODEL WITHOUT EXTENDED KALMAN FILTER

The motor model to obtain estimation of motor speed without involving Extended Kalman Filter is depicted below.

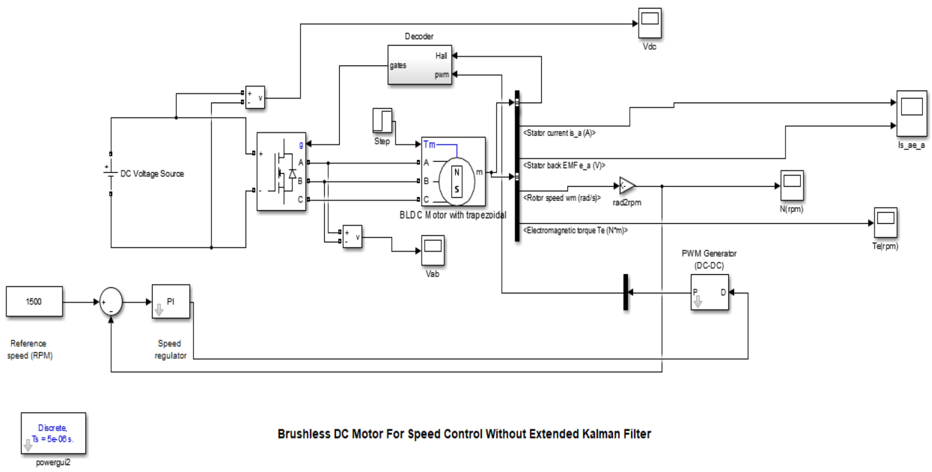

Fig. 2: Simulation of BLDC Motor withoutExtended Kalman Filter

VI. PROPOSED SIMULINK MODEL EMPLOYING EXTENDED KALMAN FILTER

The motor model to obtain speed and rotor estimation applying Extended Kalman Filter is shown below:

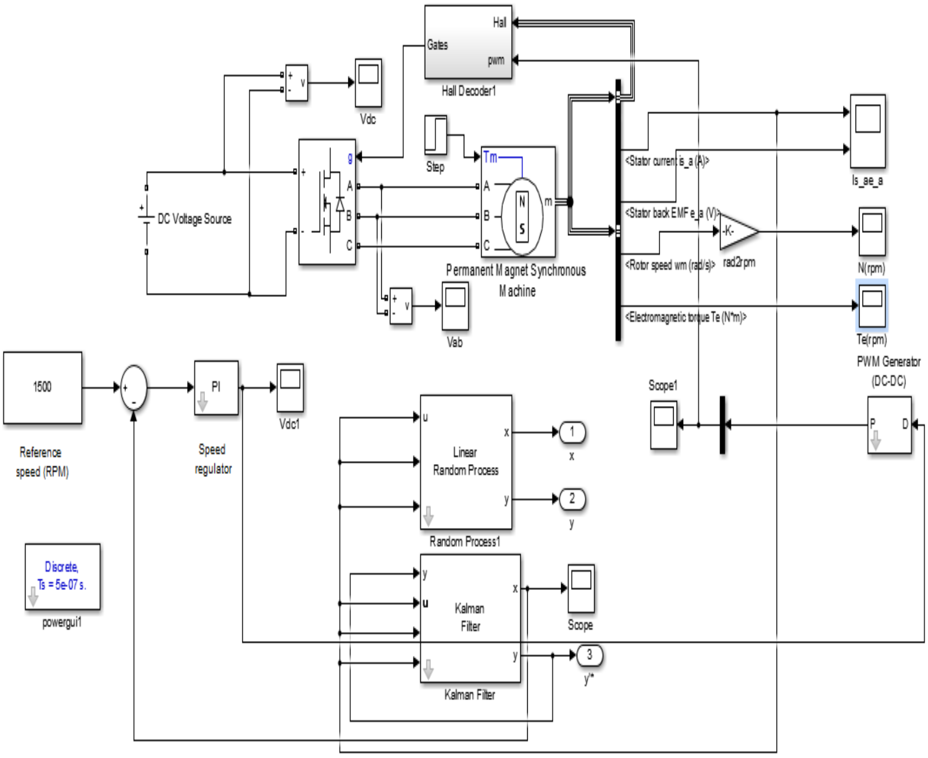

Fig. 3: Simulation of BLDC Motor with Extended Kalman Filter

VII. COMPARISON OF RESULTS

Comparison of motor speeds with and without Extended Kalman Filter are shown in the below results. Constant and steady-state speed cannot be obtained as the ripple generation in the toque is quite high. In this scenario, reference speed is kept close to 1000 rpm. In the first case as no estimation technique is present so the value of speed slightly increase from the reference speed of 1000 rpm and there is also ripple generation in this case. Whereas, in the second case motor runs smoothly without torque generation in speed as estimation technique of Extended Kalman Filter is used.

A. Motor Speed Without Extended Kalman

Motor speed without application of Extended Kalman Filter is shown in the below diagram

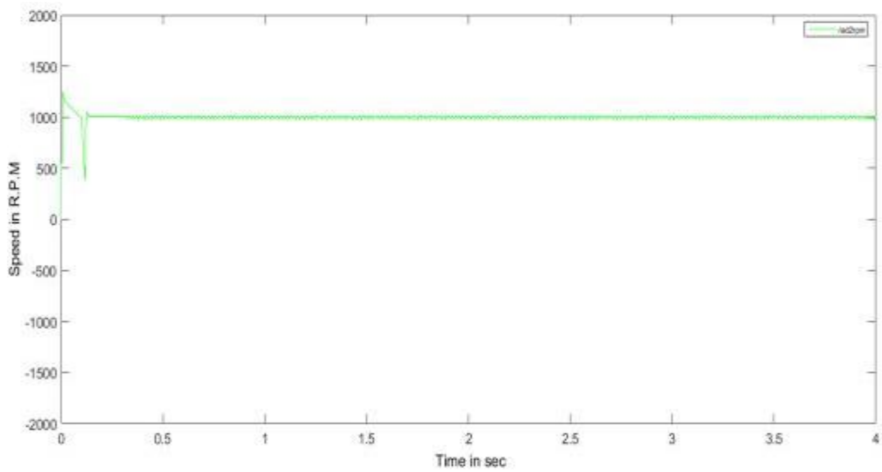

Fig. 4: Motor Speed without Extended Kalman Filter

B. Motor Speed With an Extended Kalman Filter

Torque ripple generated in motor speed is much improved after employing Extended Kalman Filter as shown in the below figure

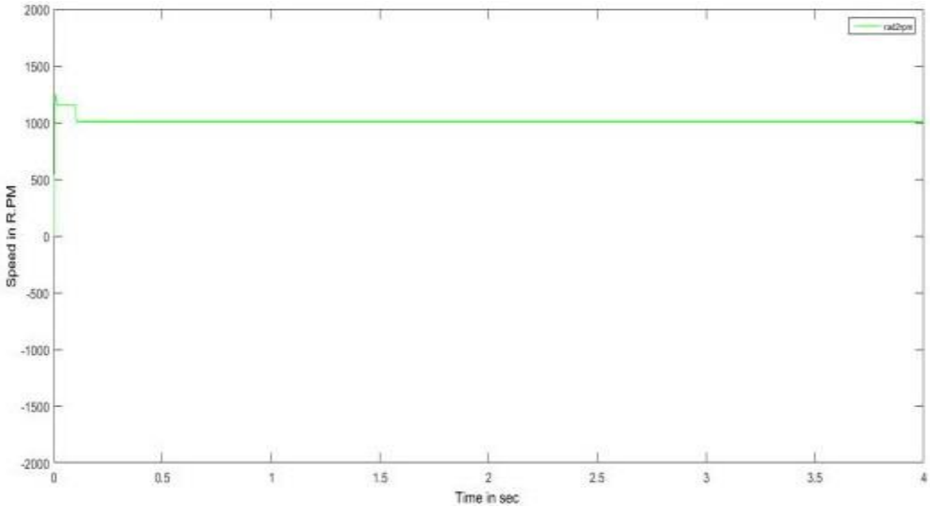

Fig 5.Motor Speed with Extended Kalman Filter

VIII. TORQUE RIPPLE IN BLDC MOTOR AND ITS IMPROVEMENT

Ripple generated in torque is due to various problems in the motor including cogging of torque, the interaction of flux in the air gap, magneto motive force and disturbances, which ultimately cause mechanical imbalance. As consequence of thesereasons motor speed usually gets reduced. So Extended Kalman Filter technique will be used to getan estimation. This technique is specially designed to control torque ripple generated in the motor, and utilizing the application of this technique, ripple can get managed in the system and by controlling torque, ripple generation in speedcan be reduced. Torque ripple reduces of motor rated speed. The torque ripple can be obtained by many ways, including varying input voltage, current control algorithm, and control of frequency, unipolar and bipolar method. In this research, an Extended Kalman Filter will be employed to minimize ripple in the torque and speed. A comparison between the results of torque ripple generated in a BLDC motor is drawn and it can be clearly viewed from the results that the torque ripple is controlled significantly after the application of Extended Kalman Filter which ultimately lead to better performance of BLDC motor and problems of noise in the motor were also reduced after the utilization of Extended Kalman Filter.

A. Torque Ripple without Extended Kalman Filter:

Motor shows high torque without an Extended Kalman Filter as there was no estimation technique to control torque ripple generated in the motor. This can be shown in the figure below:

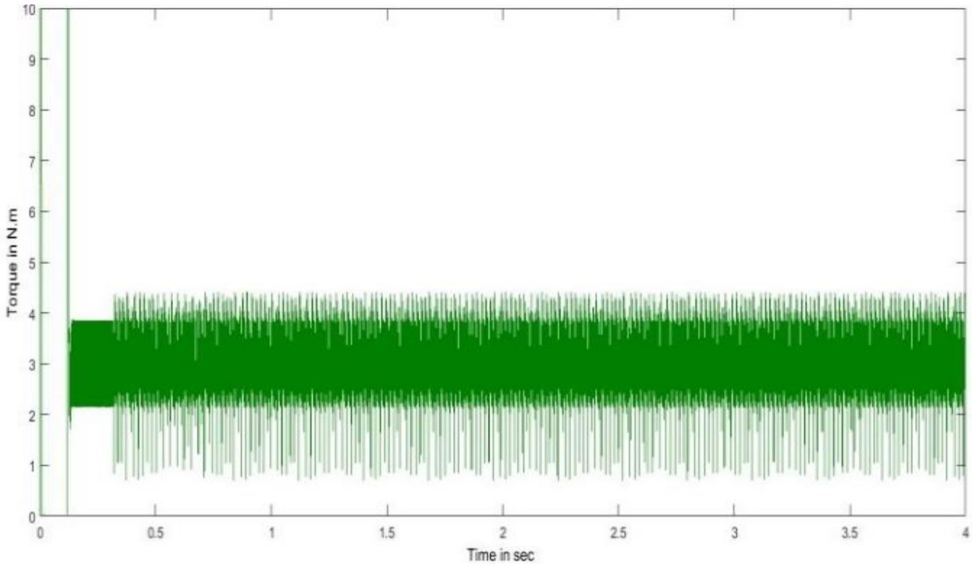

Fig 6: Torque Ripple in BLDC Motor without Extended Kalman Filter

B. Improvement in Motor Torque after applying Extended Kalman Filter

Motor Performance shows significant improvement after application of Extended Kalman Filter as it can also be viewed from the below figure.

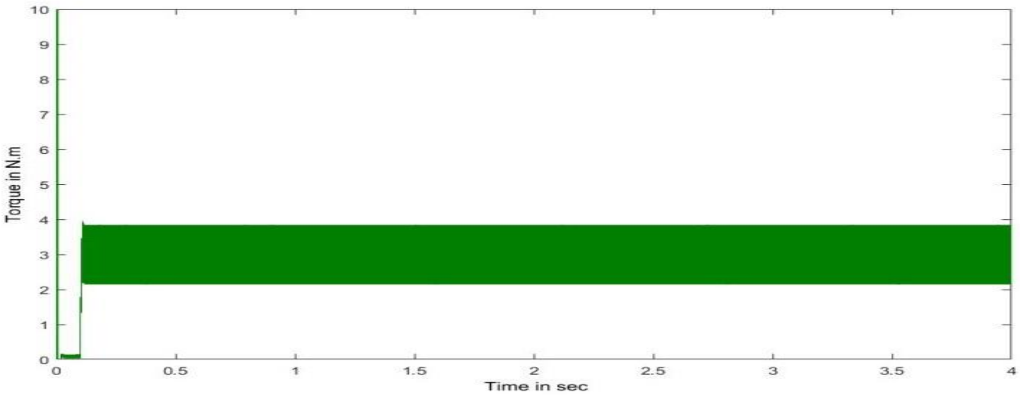

Fig. 7: Torque Ripple with Extended Kalman Filter

C. Stator Currents and Back-EMF in a BLDC Motor

Switching is generated in the motor at the instant when stator currents and back-EMFchanges there Position from one instant of time to another switching positions are shown in the below figure

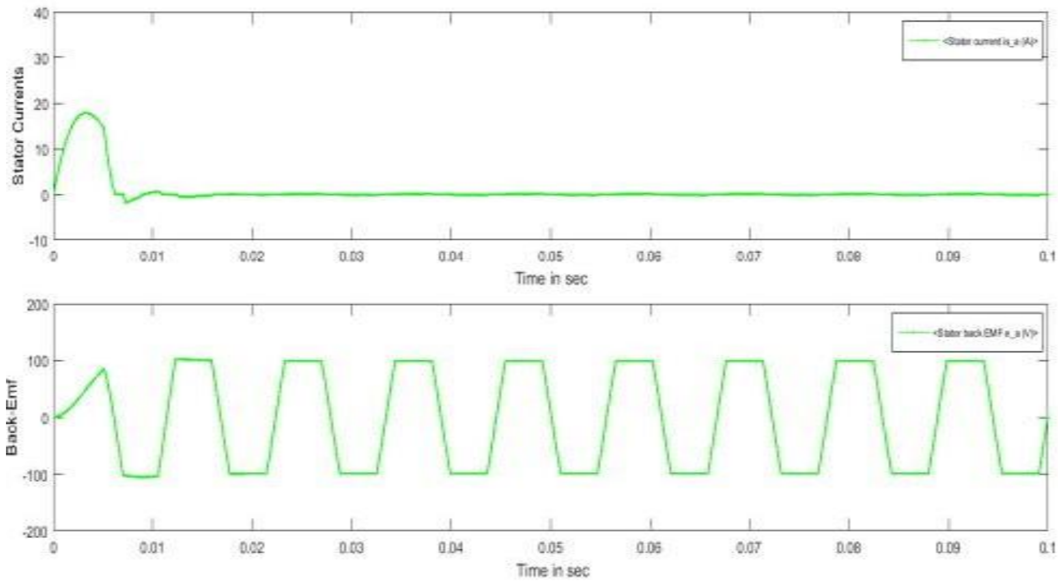

Fig. 8: Stator Currents and back-EMF of BLDC motor with Extended Kalman Filter

IX. CONCLUSION

Undoubtedly, Extended Kalman Filter is widely applied in various fields and is the most accurate methods for position estimation of the BLDC motor. But there are also some limitations of this technique, which include properinitialization of machine model parameters, the complexity of computation difficulty in the calculation of parameters, and modeling errors. Due to these reasons, the usage of EKF is limited on a larger scale. Still, if these shortcomings can be overcome then it has quite a lot of benefits and applications, including accurate estimation of rotor speed and due to reason, it is applied in this research.

ACKNOWLEDGMENT

I am thankful to all Professors and other faculty members of University of Engineering & Technology, Lahore for their constant support and encouragement. I also want to pay my gratitude to my parents, husband and siblings for their constant support, guidance and appreciation, for they taught me the worth of hard work, dedication and perseverance.Last but not the least, I would like to render my thanks to my friends who’s ever helping nature and suggestions helped me to complete this laborious task.

REFERENCES

[1.] K. Mohri, M. Kano, H. Uzuhashi, M. Kano, T. Endo, , “Microcomputer control for sensorless brushless motor,” IEEE Trans. Ind. Application.

[2.] R. C. Beccerra, M. Ehsani, and T. M. Jahns, , “Sensorless Four Quadrant BLDC Motor,” IEEE APEC’91, 1991, pp. 210–215.

[3.] H. Akagi and Su S. Ogasawara, “A perspective to sensorless drive for position of brushless dc motors,” in Conf. Rec. IEEEIAS, 1980,pp. 453–457.

[4.] M. C. Moeira, “Indirect sensing of flux position for rotor of permanent magnet AC motors operating in different speed range,” in Annu. Meeting, 1984, pp. 411–417.

[5.] P. P. Acarnley and N. Ertugrul , “A procedure for sensorless functioning of permanent magnet motors,”. Ind. Applicat., vol. 40,

[6.] G. Henneberger and B. J. Brunsbach , “Field-oriented control of AC motor drives without mechanical sensors utilizing a Kalman filter,” in EPE’94, vol. 3, Florence, Italy, 1981, pp.

[7.] T. Klepsch, G. Henneberger and H. Brunsbach, , , “Position controlled permanent magnet synchronous motor without sensors,” in, Brighton, U.K., 1983, pp. 28–33.

[8.] R. Dhaouadi, and L. Norum, “Implementation of an extended Kalman filter for the state estimation of a permanent magnet motor,” IEEE Trans. Power Electron., vol. 6, pp. 491–497,

[9.] D. M. Brod, “Current control of Voltage Source Inverter and Pulse Width Modulation inverters,”IEEE Trans., vol. IA-21, pp. 572–580, June/July 1975.

[10.] L. Loron, “Extended Kalman filter for parameters estimation of DC motors,” in Proc. EPE’93,

[11.] https://www.researchgate.net/figure/Electronically-commutated-BLDC-motor-drive-16_fig27_45267009

[12.] G. Laliberte, “Extended Kalman filter to variable estimation of induction motors,” in, U.K., 1995, pp. 75–80. J. Moore

[13.] B. Anderson, Optimal Filtering. Englewood Cliffs, NJ:Prentice-Hall, 1979.

[14.] R. Krishnan, “Initial algorithm of a PM DC brushless motor drive with zero position sensor,” in Proc. IEEE PESC’89, 1989, pp. 815–821

[15.] L. Cardolleti, “Sensorless position and speed control of a brushless DC motor from starting to normal speed,” EPE J., vol. 4, pp. 35–44, Mar. 1982.

[16.] a-novel-techniques-for-speed-and-rotor-position-estimation-of-brushless-dc-motor-with-an-extended-kalman-filter-by-using-matlab-simulation-IJERTV5IS050587

[17.] Ellahi, Nabiya (2021). EXTENDED KALMAN FILTER BASED BRUSHLESS DC MOTOR FOR ROTOR POSITION AND SPEED CONTROL. Techrxiv. https://doi.org/10.36227/techrxiv.17208848.v1

BIBLIOGRAPHY

Nabiya Ellahi received her BS degree in Elec Electrical Engineering from University of Punjab, Lahore and her MS degree in Elec-trical Engineering from UET, Lahore. She is currently working as an academician in the Institute of Electrical Electronics & Computer Engineering since 2020. She has work experience of 3 years. Her research interests includes Power, Electronics, control systems and renewable energy.