Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı 42, S. 6-13, Ekim 2022
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Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 42, pp. 6-13, October 2022
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Research Article

Speed-Sensorless DTC of BLDC Motor with EKF-based Estimator Capable of Load Torque Estimation for Electric Vehicle

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(2nd International Conference on Engineering and Applied Natural Sciences ICEANS 2022, October 15 - 18, 2022)

(**DOI:** 10.31590/ejosat.1190197)

ATIF/REFERENCE: İnan, R., & Üzüm, O.M., (2022). Speed-Sensorless DTC of BLDC Motor with EKF-based Estimator Capable of Load Torque Estimation for Electric Vehicle. *European Journal of Science and Technology*, (42), 6-13.

Abstract

This study presents the simulation of brushless DC (BLDC) motor control in MATLAB/Simulink simulation environment with model-based and direct torque control (DTC) method with extended kalman filter (EKF). In this study, a control method based on DTC method is tested to control a nonlinear BLDC motor with extended kalman filter. In this method, an accurate control can be made thanks to the load moment estimation, which is not found in the literature. As a result of the tests have carried out at low and high speeds, it is concluded that the system can lead to real-time systems.

Keywords: Speed-sensorless BLDC Motor, Kalman Filter, Direct Torque Control.

Elektrikli Araç için BLDC Motorun Yük Momenti Kestirimi Yapabilen EKF Tabanlı Hız-Algılaycısız DTC'si

Öz

Bu çalışma, MATLAB/Simulink simülasyon ortamında fırçasız DC motor (BLDC) kontrolünün model tabanlı ve doğrudan tork kontrolü (DTC) yöntemi ile genişletilmiş kalman filtresi (EKF) ile simülasyonunu sunmaktadır. Bu çalışmada, doğrusal olmayan bir BLDC motoru genişletilmiş kalman filtresi ile kontrol etmek için DTC yöntemine dayalı bir kontrol yöntemi test edilmiştir. Bu yöntemde literatürde bulunmayan yük moment tahmini sayesinde doğru bir kontrol yapılabilmektedir. Düşük ve yüksek hızlarda gerçekleştirilen testler sonucunda sistemin gerçek zamanlı sistemlere öncülük edebileceği sonucuna varılmıştır.

Anahtar Kelimeler: BLDC Motor, Kalman Filtresi, Model Tabanlı Öngörülü Kontrol, Doğrudan Tork Kontrolü, BLDCM Simülasyonu.

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1. Introduction

Today, electric motors are used in a wide variety of fields. One of these motors is called brushless direct current (BLDC) motor are used in many fields today especially in electric vehicle and hybrid electric vehicle include drones, electric cars, etc. The advantages of BLDC motor can be listed as follows;

- Speed control can be done with constant torque.
- Their yields are high.
- Due to their brushless structure, there is no friction, no arcing, no carbon dust production.
- Its dimensions are smaller than other motors and its torque is higher.
- It works without problems at high revs.
- They work silently.
- They get very little hot.
- They last much longer.
- They don't need care.

The disadvantages of BLDC motor can be listed as follows;

- They have a complex control circuit.
- They need position sensors.
- Their cost is high.

The torque-current characteristics of BLDC motors are similar to DC motors. BLDC motor works similarly to a synchronous motor [1]. BLDC motors are more popular today than conventional DC motors, but the development of this type of motor has only been possible since the 1960s, when semiconductor electronics were developed [2]. It is a type of motor that provides the commutation process electronically. BLDC motors have been produced in order to get rid of the brush and collector assembly by preserving the torque-speed characteristics of DC motors.

In brushed DC motors, electrical transmission to the windings in the rotor is provided by the brush-collector structure, which causes problems such as sparking, maintenance and wear on the brushes.

An electronic controller takes over the task of the brush-collector assembly in BLDC motors.

A brushless direct current motor consists of two main parts, a stator and a rotor. The rotor is a bipolar permanent magnet. The stator consists of regular coils as shown in Figure 1.

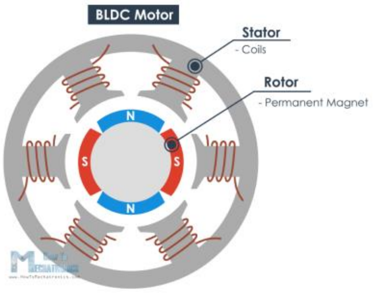

Fig. 1. BLDC Motor

The controller must follow the rotor at an appropriate speed and know the rotor position so that the rotation of the motor is not interrupted. Hall effect sensors are generally used for this (Figure 2).

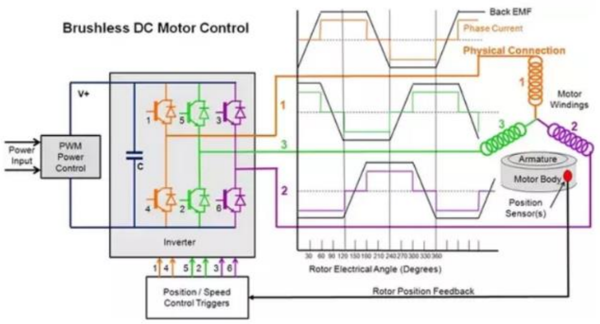

Fig 2. Schematic representation of BLDC Motor Control

BLDC motors consist of:
•The stator with its windings
•Permanent magnet rotor
•Position sensors
•Driver circuit

BLDC motors are of two types according to their internal structure:

In inner rotor BLDC motor, the rotating part of the motor, namely the rotor, is inside the motor. The body (stator) is fixed. These motors generally have higher speeds than the other type, the outer rotor. On the other hand, the torque produced by the motors per volt is less. Having the rotor inside provides many ease of use. They are similar in appearance to standard brushed motors.

Outrunner Brushless Motors have a mechanical arrangement unlike inrunner motors. The rotor of the motor is on the outside. In other words, the body of the motor is inside the rotating fixed part. They are more difficult to cool because the coil part is in the center. They are used more frequently in flying projects (helicopter, quadrotor, plane…) due to the lower speed of outrunner motors and higher torque.

BLDC motor is of two types according to the sensor condition:

Sensored brushless motors precisely detect where the coil is in the housing. With a suitable motor driver circuit, no lost power occurs from the motor.

Sensorless brushless motors are widely available. They decide that the wave sent from the motor driver circuit to the coil will be changed, with the electrical signal (signal generated by the eddy current) occurring in the coil without current. Sensorless motors do not reach speeds and accelerations as high as sensor motors.

BLDC motors are especially used for radio controlled projects. Since their unit energy densities are better, they are used in RC cars, helicopters, photocopiers, printers, tape drives, optical scanners and medical devices that require high power [3].

As a result of the literature review on BLDC motor control, many articles and papers have been researched.

Li et al. have mentioned the advantages of DC motors in their study. They have tried the six-step control and field-oriented control method on BLDC motors and carried out simulation studies. They have examined torque fluctuations and power losses [4].

Rekioua et al., in their study, have presented a new approach to field-oriented control of brushless direct current motor and applied this approach to permanent magnet synchronous motor. According to the results they obtained, it has determined that the current and speed showed a significant improvement in no-load and loaded conditions [5].

Gujjar and Kumar have showed the performance analysis of the field-oriented control (FOC) of BLDC motor using sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) techniques in their study. They have performed control by changing the motor parameters in the d-q axis of the current going to the motor. They have simulated the system in the MATLAB Simulink simulation environment and determined that space vector pulse width modulation is more performant than sinusoidal pulse width modulation [6].

Kumar and C.M.C have presented a comparison of sinusoidal field oriented control (FOC), field oriented control (FOC), and hysteresis control of a BLDC motor primarily in terms of output torque ripple. They have simulated the algorithm of the three control methods [7].

Irimia et al., in their study, have performed a comparative study between simultaneous sinusoidal modulation (SSM) and space vector modulation (SVM). In order to achieve efficient results, vector or field-oriented control is applied as a control method. They have developed a comprehensive mathematical model equivalent to the power steering/brake system that can be successfully integrated into today's vehicle platforms and applied this model to the MATLAB Simulink simulation environment [8].

Islam et al., in their study, have explained the field-oriented control method for BLDC motor with space vector pulse width modulation technique with current and speed sensor. In this method, they have introduced the PI controller and as a result, they observed that this control method has good speed response and performance [9].

Tatar et al., in their study, have determined the rotor position of the BLDC motor using hall-effect sensors. They describe the development of a field-oriented control method based on the space vector pulse width modulation method with the Labview FPGA module for a BLDC motor. They have simulated the system in MATLAB Simulink environment [10].

Sandre-Hernandez et al., in their study, have presented sensorless field-oriented control of a BLDC motor using a sliding mode observer to determine phase currents. They also have used a back EMF observer to determine the position of the rotor. They have supported their work with numerical simulations [11].

De Almeida et al., in their study, have explained the vector control of a BLDC motor with trapezoidal waveform of the estimated back EMF through the kalman filter [12].

In their study, Reddy and Murali have proposed an algorithm to obtain a uniform rotor angle with hall signals. In the proposed algorithm, they have aimed to avoid unnecessary multiplication and division operations in the FPGA module and implemented it in Microsemi SmartFusion ® 2 SoC FPGA [13].

Hui et al., have mentioned different control techniques of permanent magnet brushless direct current motor used as compressor motor. They have focused on the bridge 3 phase inverter circuit technique with sensorless back-EMF detection. The methods are simulated on PSIM software [14].

Lee et al., in their study, have focused on the comparison of commutation methods of permanent magnet brushless direct current motor. They have focused on trapezoidal, sinusoidal commutation and field-directed control techniques. They have made use of Hall-effect sensors. As a result of their analysis, they have seen that the best of these techniques is field-directed control [15].

Noroozi et al., in their study, have mentioned direct torque control in brushless permanent magnet direct current motors. They have studied the details of two-phase and three-phase transmission modes. They have wanted to control the motor in MATLAB Simulink environment using twelve voltage vectors. With the simulation results, they have obtained the data they expected [16].

Li et al., in their study, have suggested that direct torque control of brushless permanent magnet direct current motor should be done to reduce torque fluctuations. For this, they have proposed a hysteresis torque control with pulse width modulation. In addition, two-phase 120 electrical degree control is proposed. Motor control is performed with MATLAB [17].

Singh and Singh (2016), in their article, have performed the speed control of a permanent magnet brushless direct current motor, three of the control methods, Back-EMF, sinusoidal pulse width modulation (SPWM), and space vector pulse width modulation using the MATLAB Simulink simulation environment. They have compared these control methods. According to their results, they have seen that the space vector pulse width modulation technique is more efficient than the others [18].

Aktas et al., have compared indirect field oriented control and direct torque control of a brushless permanent magnet direct current motor. While examining these methods, they have focused on PI controller, fuzzy logic and sliding mode speed controller [19].

To control BLDC motor and phase flux and currents, there are certain sensors used to measure. Using these sensors imposes a burden on both the motor and the driver in terms of cost and ease of operation.

In the following studies, the control forms of the BLDC motor with the kalman filter are mentioned.

Mazaheri and Radan have mentioned three main and basic algorithms of motor control methods and they studied on BLDC motor: Extended, Unscented and Cubature Kalman filtering. They have done various studies on the application of these algorithms in estimating the angular position of the rotor at low speeds. When they have applied the measurements to a 3-phase low voltage BLDC motor, they have observed that the Unscented Kalman filter and Cubature Kalman filtering techniques gave better results and performance than the Extended Kalman filter. They have determined that it is better in terms of accuracy [20].

Kettle and Murray, in their study, have obtained estimates for position and velocity based on back EMF from the trapezoidal motor with an algorithm based on an extended kalman filter. In this study, they have made sensorless measurements and worked with a DSP controller without stator current measurements [21].

Terzic and Jadric have studied the extended kalman filter application of a brushless direct current motor in their study. They have used this filter to estimate motor state variables. The speed and rotor position of the motor and motor parameters is used in the estimation algorithms. They have carried out this study on a 1.5 kW motor and observed that it is predicted with sufficient performance in steady and dynamic condition [22].

Nair et al., in their study, have presented electromagnetic torque prediction using a Kalman filter with direct torque control of a BLDC motor with trapezoidal back-EMF. They have used the PWM technique with the voltage vector they have had previously determined to obtain a faster torque response. They have determined an error by comparing the estimate with the reference electromagnetic torque and applied the appropriate voltage vector [23].

Lv et al., in their study, have proposed a sensorless control technique working with an odorless kalman filter to a BLDC motor. In this algorithm, they have wanted to predict the position and speed of the motor by measuring the terminal voltages and three-phase currents. According to the simulation results, they have observed the accuracy of the algorithm [24].

Ejlali and Soleimani, in their study, have carried out the active learning method with the extended Kalman filter. They have made estimation of stator voltage and current and state variables and observed with simulation results [25].

Aishwarya and Jayanand, in their study, have made a prediction algorithm with an extended kalman filter for the estimation of the speed and rotor position of the BLDC motor. The reason they use the extended kalman filter is because the BLDC motor is a non-linear system. The state variables of the motor are predicted using a kalman filter with measurements of stator voltages and currents [26].

As a result of the literature review, the following information can be given about the importance of the study:

As a result of this study, the most efficient use of BLDC motor is determined by simulating the BLDC motor, which is frequently used in electric vehicles, loaded and unloaded, and also with kalman filter algorithm. It is ensured that it can be used with a more logical control method and a simple control method with both economic and energy efficiency.

Unlike the above studies, the load moment must also be estimated in model-based estimators.

In this study, 3 phase current, flux, electrical position of the rotor, load torque and mechanical angular rotor speed are estimated with the extended kalman filter, which can also predict the load torque, unlike the studies mentioned above. For the performance of model-based estimation performance, this extended Kalman filter has been tested on direct torque control (DTC) created in the MATLAB/Simulink simulation environment.

2. Material and Method

Despite the simple structure of the BLDC motor, it is necessary to operate the BLDC motor with a complex control structure in order to control it properly.

In this section, the mathematical and MATLAB/Simulink block diagram model of the BLDC motor will be given. Then, in this study, direct torque control and extended kalman filter application, which is one of the sensorless control methods used to control BLDC motor, are discussed.

2.1. Mathematical Model of BLDC Motor

The mathematical model of BLDC motors is similar to conventional brushed DC motors. The creation of the mathematical model is done separately for each phase. The effect of the phases on each other should also be added to the model. Each phase of the motor can be modeled with a resistor, a coil and a DC voltage source connected in series. Fig. 3 show this model.

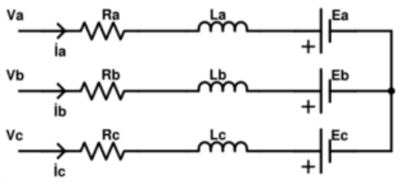

Fig. 3. BLDC Motor Equivalent Circuit

Some assumptions are made in order to write the mathematical model of the engine. These are respectively;

- The engine is not saturated.
- Stator windings have fixed resistance, self-inductance and common inductance.
- The back electromotive force in all phases has a sinusoidal shape.
- Iron losses, eddy currents and hysteresis effects in the motor are neglected [27].

The equivalent mathematical model of the motor is given in Fig. 3. According to this model, the voltage equations of the motor are;

$$v_a = R_a . i_a + L_a \frac{d}{dt} i_a + L_{ab} \frac{d}{dt} i_b + L_{ca} \frac{d}{dt} i_c + E_a \quad (1)$$

$$v_b = R_b . i_b + L_b \frac{d}{dt} i_b + L_{ab} \frac{d}{dt} i_a + L_{bc} \frac{d}{dt} i_c + E_b \quad (2)$$

$$v_c = R_c . i_c + L_c \frac{d}{dt} i_c + L_{ca} \frac{d}{dt} i_a + L_{bc} \frac{d}{dt} i_b + E_c \quad (3)$$

In the above equations;

- v_a, v_b, v_c: Stator phase voltages
- i_a, i_b, i_c: Stator phase currents
- R_a, R_b, R_c, R: Stator phase resistors
- L_a, L_b, L_c, L: Stator phase inductances
- L_{ab}, L_{bc}, L_{ca}, M: Common inductance between stator phase windings
- E_a, E_b, E_c: Opposite electro-motor force means.

If the stator windings are considered to be balanced;

$$R_a = R_b = R_c = R \quad (4)$$

$$L_a = L_b = L_c = L \quad (5)$$

$$L_{ab} = L_{bc} = L_{ca} = M \quad (6)$$

Accordingly, the voltage equations are rewritten as:

$$v_a = R_a . i_a + L_a \frac{d}{dt} i_a + M \frac{d}{dt} i_b + M \frac{d}{dt} i_c + E_a \quad (7)$$

$$v_b = R_b . i_b + L_b \frac{d}{dt} i_b + M \frac{d}{dt} i_a + M \frac{d}{dt} i_c + E_b \quad (8)$$

$$v_c = R_c . i_c + L_c \frac{d}{dt} i_c + M \frac{d}{dt} i_a + M \frac{d}{dt} i_b + E_c \quad (9)$$

The matrix representation of the stator voltages is given in (10).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (10)$$

$$\boldsymbol{A}\big(\boldsymbol{x}(k)\big)=\begin{bmatrix}-\frac{R_s}{L_s}T+1 & 0 & 0 & -\frac{p_p\psi_{ra}T}{L_s} & 0 & 0\\ 0 & -\frac{R_s}{L_s}T+1 & 0 & -\frac{p_p\psi_{rb}T}{L_s} & 0 & 0\\ 0 & 0 & -\frac{R_s}{L_s}T+1 & -\frac{p_p\psi_{rc}T}{L_s} & 0 & 0\\ -\frac{p_pT}{j_L}\psi_{ra} & -\frac{p_pT}{j_L}\psi_{rb} & -\frac{p_pT}{j_L}\psi_{rc} & -\frac{b_LT}{j_L}+1 & 0 & -\frac{T}{j_L}\\ 0 & 0 & 0 & p_pT & 1 & 0\\ 0 & 0 & 0 & 0 & 0 & 1\end{bmatrix} \qquad (26)$$

Since the derivative can be disabled from the assumption that the inductances are not saturated, if (10) is arranged;

$$\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}=\begin{bmatrix}R & 0 & 0\\ 0 & R & 0\\ 0 & 0 & R\end{bmatrix}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+\frac{d}{dt}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+\begin{bmatrix}E_a\\ E_b\\ E_c\end{bmatrix} \qquad (11)$$

formula is obtained.

E_a, E_b, and E_c are called the induced back electromagnetic force (EMF) in the motor. These voltages depend on the speed and angle of the motor, the number of turns in the stator and the magnetic flux in the rotor. The maximum rotor magnetic flux is accepted as the motor constant and is called λ_m. Depending on the motor type, they can be sinusoidal or trapezoidal [27].

If it is sinusoidal;

$$E_a = \omega_m.\lambda_m.\sin(\theta_e) \qquad (12)$$

$$E_b = \omega_m.\lambda_m.\sin(\theta_e - \tfrac{2\pi}{3}) \qquad (13)$$

$$E_c = \omega_m.\lambda_m.\sin(\theta_e + \tfrac{2\pi}{3}) \qquad (14)$$

here, ω_m, rotor mechanical angular velocity (rad/sec).

If it is trapezoidal, this voltage is;

$$E_a = \omega_m.\lambda_m.f(\theta_e) \qquad (15)$$

$$E_b = \omega_m.\lambda_m.f(\theta_e - \tfrac{2\pi}{3}) \qquad (16)$$

$$E_c = \omega_m.\lambda_m.f(\theta_e + \tfrac{2\pi}{3}) \qquad (17)$$

The rotor speed of the motor depends on the applied electrical frequency and the number of poles of the rotor. This relationship is shown in (18).

$$\omega_e = \omega_m p_p \qquad (18)$$

here p_p is the pole pair.

The instantaneous power produced by the BLDC motor is equal to the multiplication of the back EMF and the current flowing through the phase windings. This power is known as the power transferred from the stator of the motor to its rotor. This equation is given in (19).

$$P_a = E_a i_a + E_b i_b + E_c i_c \qquad (19)$$

The power-torque equation is used to calculate the electromagnetic torque produced. The generation of electromagnetic moment depends on two parameters. These are the back-EMF constant and the maximum value of the current. The moment equation is given in (20) and (21) [27].

$$T_e = \frac{P_a}{\omega_e} = \frac{E_a i_a + E_b i_b + E_c i_c}{\omega_e} \qquad (20)$$

$$T_e = \frac{E_a i_a + E_b i_b + E_c i_c}{\omega_m}.p_p \qquad (21)$$

2.2. Extended Kalman Filter for States and Parameter Estimation of BLDC Motor Model

The motor model of BLDC motor which used on EKF for the estimation of stator 3-phase currents (i_{sa}, i_{sb}, i_{sc}), rotor mechanical angular speed (ω_m), rotor electrical rotation (Θ_e), and load torque (t_L) states and parameter of BLDC motor given below in discretized form.

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\big(\boldsymbol{x}(k)\big)\boldsymbol{x}(k) + \boldsymbol{Bu}(k) + \boldsymbol{w} \qquad (22)$$

$$\boldsymbol{Z}(k+1) = \boldsymbol{Hx}(k) + \boldsymbol{v} \qquad (23)$$

where, x(k) is the extended state vector for BLDC motor model, A is the system matrix, Z(k+1) is the measurement vector, u is the control input vector, B is the input matrix, w is the process noise, H is the measurement matrix, v is the measurement noise. From here, the following equations have the matrix representation of these situations.

$$\boldsymbol{x}(k) = [i_{sa} \quad i_{sb} \quad i_{sc} \quad \omega_m \quad \theta_e \quad t_L]^T \qquad (24)$$

$$\boldsymbol{u}(k) = [v_{sa}(k)\; v_{sb}(k)\; v_{sc}(k)]^T \qquad (25)$$

here, vsa, vsb, and vsc are stator 3-phase voltages.

$$\boldsymbol{B} = \begin{bmatrix}\frac{T}{L_s} & 0 & 0 & 0 & 0 & 0\\ 0 & \frac{T}{L_s} & 0 & 0 & 0 & 0\\ 0 & 0 & \frac{T}{L_s} & 0 & 0 & 0\end{bmatrix}^T \qquad (27)$$

$$\boldsymbol{H} = \begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix} \qquad (28)$$

In (26), L_s is the stator leakage inductance, T is the sampling time, j_L is the total inertia of the BLDC motor, Rs is stator phase resistance, ψ_{ra}, ψ_{rb}, and ψ_{rc} are the rotor leakage fluxes, b_L is the coefficient of friction.

2.3. Extended Kalman Filter for State and Parameter Estimation of BLDC Motor

The equations of EKF algorithm using BLDC motor model can be given as follows.

Linearization step:

$$\boldsymbol{F}_{k+1|k} = \frac{\mathrm{d}\boldsymbol{A}\big(\hat{\boldsymbol{x}}_{k+1|k}\big)}{\mathrm{d}\hat{\boldsymbol{x}}_{k+1|k}} \qquad (29)$$

Estimation or time update step:

$$\hat{\boldsymbol{x}}_{k+1}^{-} = \boldsymbol{A}(\hat{\boldsymbol{x}}_k)\hat{\boldsymbol{x}}_k + \boldsymbol{Bu}_k \qquad (30)$$

$$\boldsymbol{P}_{k+1}^{-} = \boldsymbol{F}_{k+1|k}\boldsymbol{P}_{k}\boldsymbol{F}_{k+1|k}^{T} + \boldsymbol{Q} \tag{31}$$

Correction or measurement update steps:

$$\boldsymbol{K}_{k+1} = \boldsymbol{P}_{k+1}^{-}\boldsymbol{H}_{k}^{T}[\boldsymbol{H}_{k}\boldsymbol{P}_{k+1}^{-}\boldsymbol{H}_{k}^{T} + \boldsymbol{R}]^{-1} \tag{32}$$

$$\hat{\boldsymbol{x}}_{k+1} = \hat{\boldsymbol{x}}_{k+1}^{-} + \boldsymbol{K}_{k+1}(\boldsymbol{Z}_{k+1} - \boldsymbol{H}_{k}\hat{\boldsymbol{x}}_{k+1}^{-}) \tag{33}$$

$$\boldsymbol{P}_{k+1} = \boldsymbol{P}_{k+1}^{-} - \boldsymbol{K}_{k+1}\boldsymbol{H}_{k}\boldsymbol{P}_{k+1}^{-} \tag{34}$$

Here, $\hat{.}$ represents the estimated states and parameter. $\boldsymbol{F}_{k+1|k}$ is the function to linearize the nonlinear model by the first order Taylor series; $\boldsymbol{P}_{k+1}^{-}$ and $\boldsymbol{P}_{k+1}$ are the priori and the posteriori estimation error covariance matrices, respectively; $\boldsymbol{K}_{\boldsymbol{k+1}}$ is the Kalman gain; Q is the covariance matrix of the system noise, namely, modeling errors; R is the covariance matrix of the measurement noise.

3. Results and Discussion

3.1. Simulation Results of EKF-based Speed-Sensorless DTC of BLDC Motor

The estimation performance of the proposed EKF on i_{sa}, i_{sb}, i_{sc}, ω_m, Θ_e, and t_L states and parameter of the BLDC motor is tested with speed-sensorless DTC drive system in MATLAB Simulink simulation platform. The BLDC motor parameters is given in Table 1. The block diagram of the EKF-based closed-loop speed-sensorless DTC BLDC motor drive system is shown in Fig. 4.

In Fig.4, the velocity control is PI-type controller and two-level hysteresis flux comparator and three-level hysteresis torque comparator are used to determine the switching position of the inverter. Also three-phase rotor fluxes are calculated from the flux function given in (15)-(17) by using the estimated Θ_e. And calculated three-phase rotor fluxes is transferred into two-phase -$\alpha\beta$ stator stationary axis. Moreover, the $\alpha\beta$ axis components of the stator flux ($\psi_{s\alpha}$ and $\psi_{s\beta}$) which should be known in DTC are obtained from general magnetizing equation of three-phase motors by converting the $\hat{\psi}_{r\alpha}$ and $\hat{\psi}_{r\beta}$.

The estimation results and errors of the proposed EKF estimator are shown in Fig.5 and Fig. 6, respectively.

Table 1. BLDC motor parameters

DC power supply	*V*	72
Rated speed	*rpm*	750
Rated torque	*N.m*	21
Rated power	*kW*	1.5
Moment of inertia	$kg.m^2$	0.0073
Phase back-EMF coefficient	$V_{peak}/krpm$	96
Phase resistance	Ω	0.033
Leakage inductance	*mH*	0.16
Mutual inductance	*mH*	0.0255
Pole pairs		23

In the simulation scenario editing in order to test the estimation achievement of the proposed EKF-based estimator and the control performance of the DTC drive system of BLDC motor, the BLDC motor is forced to run in a wide speed range as rated speed (n_m*=750 rpm*), medium speed (n_m*=300 rpm*), and low speed (n_m*=150 rpm*) under different load torque conditions as rated torque (t_L*=20 N.m*), medium load torque (t_L*=10 N.m*) and low load torque (t_L*=5 N.m)*, and no-load.

During the operation of the BLDC motor, achievement of the proposed EKF-based estimator on the convergence of the estimated states and parameter to their real values is clearly shown in Fig. 5. From Fig. 5, it is understood that changes in t_L cause distortions in the ω_m estimation. In addition, errors occur in t_L estimation in the transients during acceleration and deceleration of the BLDC motor. However, the proposed EKF estimator quickly takes this error to zero quickly and provides a high estimation performance and thus the control performance of the DTC is improved.

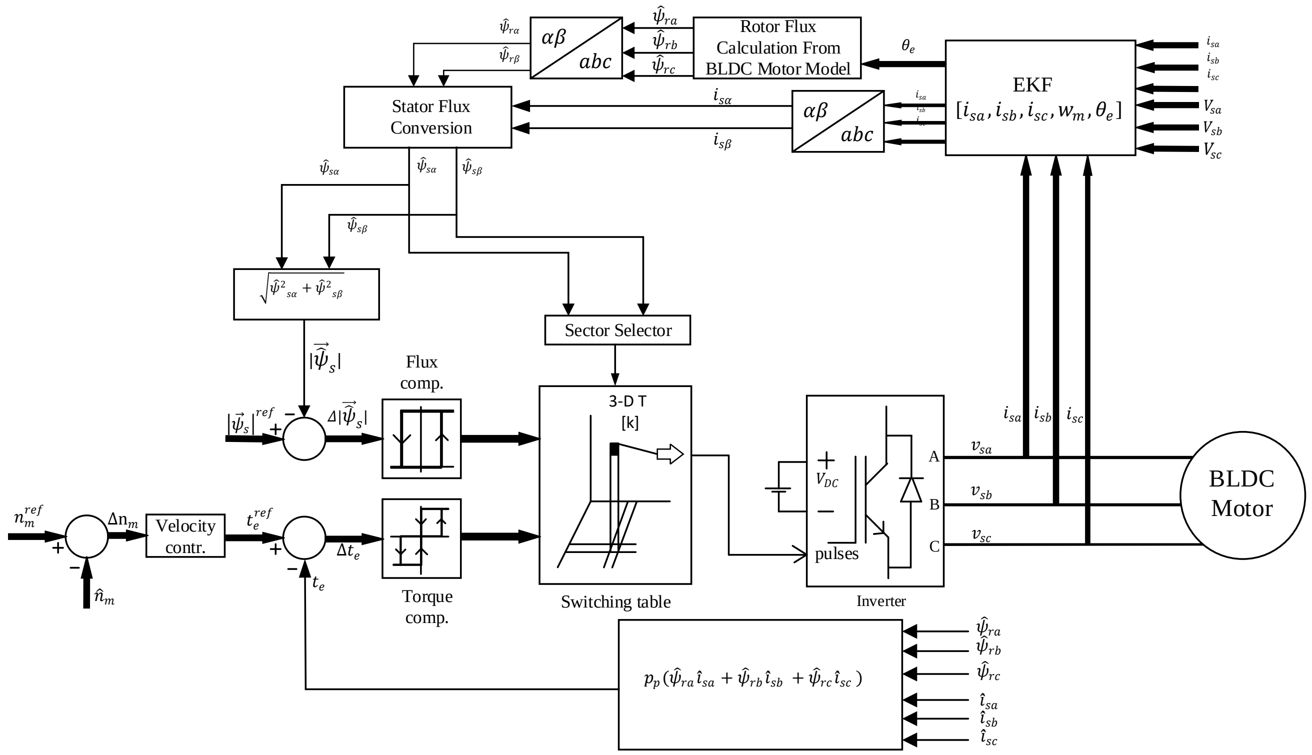

Fig. 4. EKF-based speed-sensorless DTC of BLDC motor

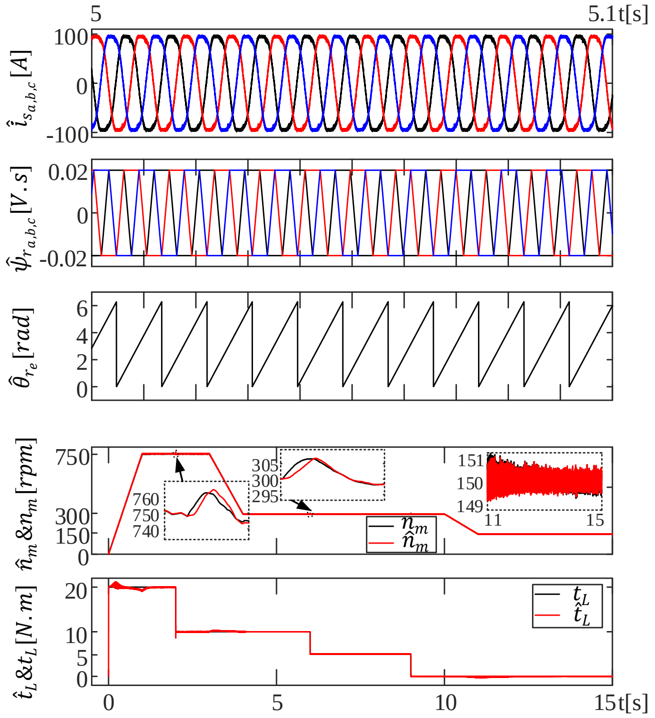

Fig. 5 Estimation results of the proposed EKF-based estimator

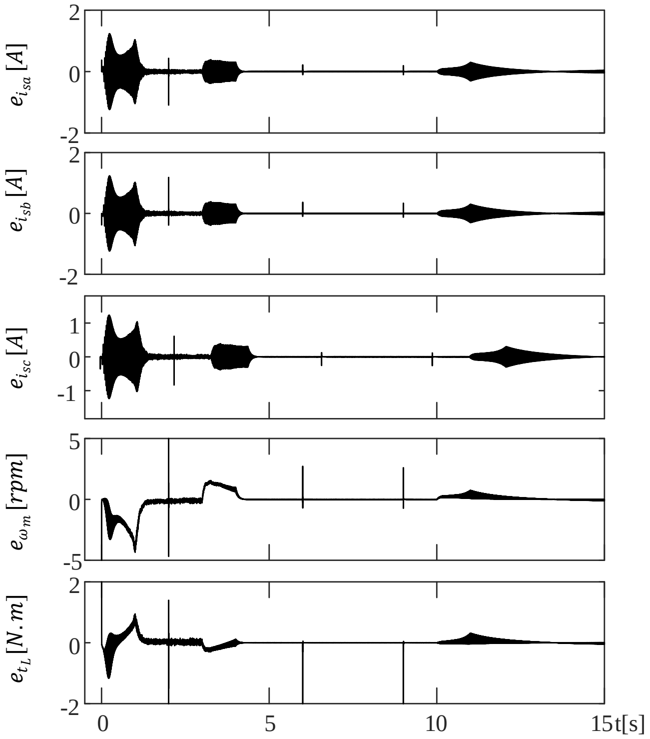

Fig. 6 Estimation errors of the proposed EKF-based estimator

4. Conclusions and Recommendations

As a result of the simulations made on the BLDC motor, it is important that this study constitutes a first in the literature, thanks to the model-based estimator of the EKF, the load torque estimation, which is not usually encountered, and the estimation of other states. This study will be a future-oriented study by using it as a control method in BLDC motors used in real-time electric vehicles planned to be made in the future.

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