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Speed and Torque Estimation of BLDC using DTC and Sliding Mode Observer

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Abstract

This paper presents speed and torque estimation for Brushless DC (BLDC) motors with non-sinusoidal back electromotive force using six switch inverter and DTC technique. The 180 conduction mode is the more popular method used for three-phase drives but here we use two-phase conduction mode. A simple approach is discussed n how to reduce ripples in the estimated torque at low frequency operation. A simple look-up table at a pre-defined sampling time is used to select the inverter voltage space vectors and the quasi-wave current is obtained. Estimation of electromagnetic torque for BLDC drives is the key issue and so sensor-less control method are used. The sliding mode observer estimates the back-EMF and generates torque, as under sliding mode observer error equation is reduced and it makes stability easier. Only the measurements of the stator currents is used in the estimation of back-EMF waveform. The electromagnetic torque and the rotor speed is estimated using values from Sliding Mode Observer. Fuzzy Gain Scheduling method is used to tune the parameters because this scheme uses human expertise on PID gain scheduling can be represented in fuzzy rules. Furthermore, better control performance can be expected in the proposed method than that of the PID controllers with fixed parameters and the gains of the sliding mode observer are tuned manually. The effectiveness of the proposed scheme is verified by using simulation results.

Keywords: BLDC, DTC, Sliding Mode Observer(SMO), PID Controller, Fuzzy Gain Scheduling, Estimated Rotor speed, Estimated Torque, Estimated Back-EMF.

1. INTRODUCTION

The fastest growing markets for BLDCs are common household appliances such as air-conditioners, refrigerators, washers, dryers use electric motors, but now-a-days consumers demand better performance, reduced noise and higher efficient motor for their appliances. Hence, BLDC have been introduced to fulfill these requirements [1]. BLDC are usually small horsepower control motors that provide various advantages such as higher efficiency, quiet operation, high reliability, compact form and lower maintenance [9]. Variable speed drives are used to overcome the drawbacks of BLDC.

BLDC electric motor have been used in inconstant speed drives for many years for the reason that of their better speed torque characteristics, high dynamic response, noiseless operation, higher speed ranges, high efficiency, high power factor, high torque, simple control and lower maintenance [2]. Because of above reasons BLDC has many extensive range of applications such as information technology apparatus, aerospace and defense equipment, sound equipment and research laboratory medical apparatus.

The conventional DTC method recommended in [3] and [4] has been used to drive the BLDC motors, it has features like reduced torque oscillations, robust design. Here we use Clark's transformation which forms 2x2 matrix instead of 2x3 matrix. Six discrete rotor positions per electrical cycle is required to feed the rectangular current which has to be in phase with the back-EMF for the BLDC to operate. Hall Effect sensors are used at precise rotor positions to carry out commutation. However they have serious drawbacks such as; they need special mechanical arrangements to be mounted which in turn increases the cost of the whole setup, they are temperature sensitive [8]. Keen interest has been there on sensor less techniques which detect rotor position precisely. There have been variety of strategies, including Direct back-EMF sensing, Phase current sensing, detection of freewheeling diode current, flux calculation methods and observer based methods such as Kalman filter and sliding mode observer. Mechanical equations were hard to solve as suggested by Luenberger Techniques [5] and [13] and the estimated load torque could not be used in the DTC scheme directly

In this paper, a sliding mode observer for position sensor less control of BLDC is used. Furthermore when the sliding mode occurs the observer order is reduced and the pole assignment problem is easier to solve. In addition the observer is robust to any parameter deviations and finite time convergence of all the observable states is possible [6] and [14].

To estimate the trapezoidal back-EMF of BLDC motor, SMO is used, which in turn estimates the torque and the speed of BLDC and SMO gains are tuned manually. Fuzzy gain Scheduling technique [17] is used to tune the gains of PID controller.

2. BLDC MOTOR OPERATION PRINCIPLE

In BLDC motor there exists electronic switching converter as compared to brushed DC motor which has mechanical commutaotr. [3]. Stator is energized by 3-phase supply which generates magnetic field to make the rotor rotate. The stator and rotor has same frequency so that's why they fall under the category of synchronous machine. In the armature permanent magnets are used so there is no need brushes [2]-[4]. The following assumptions are made for the modelling of BLDC motor:

- The three-phase stator windings are star connected.
- The mutual torque produced by the motor varies linearly to the phase current.
- The cogging torque does not exist.
- The mutual inductance among phases is negligible.
- DC voltage source is capable of delivering infinite di/dt.
- The motor is not saturated.
- The resistance and inductance are equal for all phases.
- Back-EMF shape is identical for all three phases.
- Power semiconductor devices in the inverter are ideal.
- Iron losses are negligible.

The mathematical modelling of BLDC motor is as follows [3]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

(1)

where v_a, v_b and v_c are the phase voltages, i_a, i_b and i_c are the phase currents, e_a, e_b and e_c are the phase back-EMF waveforms, R is the phase resistance, L is the self-inductance of each phase and M is the mutual inductance between any two phases.

So the electromagnetic torque can be obtained as:

$$T_e = \frac{1}{\omega_r}(e_a i_a + e_b i_b + e_c i_c)$$

(2)

where ω_r is the mechanical speed of the rotor.

The dynamic equation is:

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e + T_L + B\omega_r) \tag{3}$$

where B is the damping constant, J is the moment of inertia of the drive and T_L is mechanical torque.

3. ANALYSIS IN TWO-PHASE CONDUCTION MODE OF BLDC MOTOR USING DTC

The estimation of the electromagnetic torque is the main issue with the DTC of a BLDC and the below equation gives electromagnetic torque in stationary reference frame.

$$T_e = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_e}(e_{sq} i_{sq} + e_{sd} i_{sd}) \tag{4}$$

where ω_e is the electrical rotor speed and e_{sq}, e_{sd} and i_{sq}, i_{sd} are stationary frame (d-q) axis motor back-EMFs and stator currents respectively [5] and [10].

In torque comparator, the reference torque is compared with the actual value using a hysteresis control block. The actual speed is compared to the reference speed and an error is generated and then from the speed regulator torque command is formed. In conventional DTC, both torque and flux are considered in the overall control system but there are three reasons to exclude the flux control [3]-[12]. First, if the magnitude of the back-EMF is less than 50 percent of the dc link voltage in the constant torque region, there is no need to control the flux amplitude. Second, in 120 degree conduction sudden sharp dips occur in the stator flux linkage that complicate the control scheme. Third, whatever may be the stator flux linkage magnitude if the phase currents match the flat portion of the trapezoidal wave of stator voltage then under these conditions we can neglect flux control.

The operation of BLDC is always done in 120 degree conduction mode. Here only two phases are conducting at any given point of time and the third phase remains off. For every 60 degree commutation occurs and the next two phases conduct. Since the upper and lower switches in a phase leg may be simultaneously off, six digits are required for each switch [15].

Thus the voltage space vectors V1, V2…….V6 are represented as switching signals (100001), (001001), (011000), (010010), (000110), (100100) respectively, where from left to right the logical values are states of the upper and lower switch signals of phases A, B and C respectively [5] and [7]. The switching table for DTC of

BLDC motor in 120 degree conduction mode is shown in Table I.

TABLE I. SWITCHING STATE SELECTOR

F_{st}	T_{st}	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
F	T1	V2	V3	V4	V5	V6	V1
F	T2	V5	V6	V1	V2	V3	V4

In the DTC of a BLDC motor drive the flux error F_{st} is always considered zero only torque error T_{st} is considered depending upon the error level in the voltage vector selection look up table. If the reference torque is higher than the actual torque, within the hysteresis bandwidth, the torque error T_{st} is defined as "T1", otherwise it will be defined as "T2", as shown in Table I. By means of this method BLDC motor will be successfully driven [3]. The idea of DTC is that, we control the electromagnetic torque developed by the machine directly and independently by the help of voltage source inverter switching table. The DTC include a hysteresis controller for torque error correction. The hysteresis torque controller makes the motor torque stay in a predefined hysteresis band [11]. The two signals required for the generation of voltage space vectors are electromagnetic torque error and the sector of rotor speed.

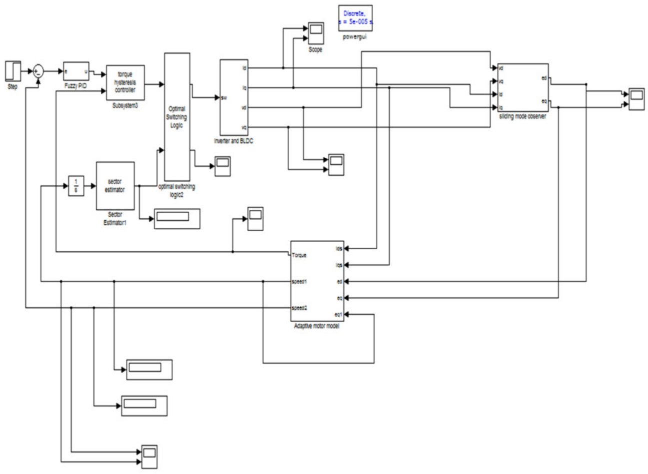

Figure 1. Simulation block of BLDC drive.

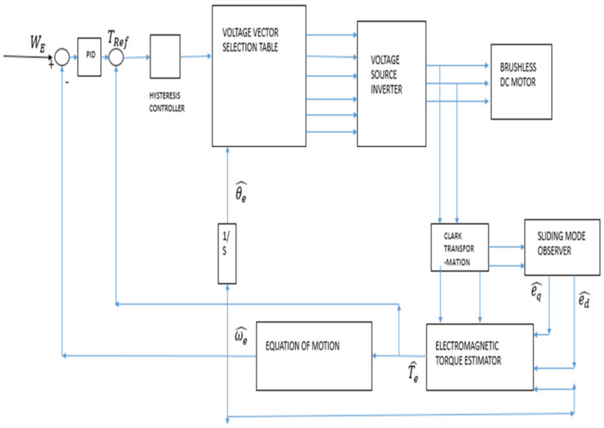

Figure 2. Block Diagram of BLDC drive

4. SLIDING MODE OBSERVER DESIGN

Sliding mode observer has the unique capability to generate a sliding motion on the error between the measured plant and the output of the observer. Sliding mode observer generates state estimates that are precise with the actual output of the plant. The BLDC motor equations are presented in [3], [6] and [16]:

$$\frac{di_{sq}}{dt} = -\frac{R}{L}i_{sq} - \frac{1}{L}e_{sq} + \frac{1}{L}v_{sq}$$
$$\frac{di_{sd}}{dt} = -\frac{R}{L}i_{sd} - \frac{1}{L}e_{sd} + \frac{1}{L}v_{sd}$$
$$\frac{de_{sq}}{dt} = 0 \tag{5}$$

$$\frac{de_{sd}}{dt} = 0$$

The back-EMF value can be assumed to be constant during each sampling period if the sampling period is much less than the electrical and mechanical time constants [5].

Saturation function is used instead for sign function to reduce the effect of chattering as represented in [10] and [16].

Therefore the sliding mode observer is as proposed as:

$$\frac{d\widehat{\iota_{sq}}}{dt} = -\frac{R}{L} i_{sq} + \frac{1}{L}\left(-e_{sq} + v_{sq}\right) + k_{s1} sat\left(i_{sq} - \widehat{\iota_{sq}}\right)$$

$$\frac{d\widehat{\iota_{sd}}}{dt} = -\frac{R}{L} i_{sd} + \frac{1}{L}(-e_{sd} + v_{sd}) + k_{s2} sat(i_{sd} - \widehat{\iota_{sd}})$$

$$\frac{d\widehat{e_{sq}}}{dt} = k_{s3} sat(i_{sq} - \widehat{\iota_{sq}})$$

(6)

$$\frac{\widehat{de_{sd}}}{dt} = k_{s4} sat(i_{sd} - \widehat{\iota_{sd}})$$

By finding $e = x - \hat{x}$, the error dynamics are calculated the sliding mode observer is designed.

5. FUZZY GAIN SCHEDULING

PID controllers are the most efficient controllers used in engineering control process as they have simple structures and have robust performance in a varied range of operating conditions. The design PID controller requires knowledge of three parameters terms: proportional gain, integral time constant and derivative time constant. So far, countless effort has been devoted to develop methods to reduce the time spent on optimizing the choice of controller parameters, some of them are intelligent controllers, predictive methods, genetic algorithms etc. One such method is fuzzy gain scheduling of PID controllers and it can be divided into two main groups. First, the control process are fixed during control after they have been tuned or chosen in a certain optimum way. The Ziegler-Nicolas tuning formula is conceivably the most well-known tuning method. The method is simple but cannot always efficiently control, systems with changing parameters, and may need frequent on-line returning. The controllers of the second category have a configuration similar to PID controllers, but their parameters are adopted on-line base on parameter estimation, which requires certain information of the process.

In fuzzy control, linguistic descriptions of human expertise is represented as fuzzy rules or relations and it is used to control a plant. The inference mechanism in combination with some knowledge of the states of the plant uses the knowledge base. Although they do not have an apparent structure of PID controllers whose parameters can be determined on-line based on the error signal and their time derivatives or difference.

Here fuzzy rules are utilized and reasoned to govern the controller parameters, and the PID controller generates the control signal. It is demonstrated here that human expertise on PID gain scheduling can be represented in fuzzy rules [17].

The transfer function of a PID controller has the following form:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{7}$$

where K_p, K_i and K_d are proportional, integral and derivative gains, respectively. Another useful equivalent form of PID controller is

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right)$$

(8)

where $T_i = \frac{K_p}{K_i}$ and $T_d = \frac{K_d}{K_p}$. T_i and $T_d$are known as the integral and derivative time constants, respectively.

The parameters of the PID controller K_p, T_i and T_d can be manipulated to produce various response curves from a given process. Finding optimum adjustments of a controller for a given process is not trivial. In the following section, an on-line gain scheduling scheme of the PID controller based on fuzzy rules is introduced.

It is assumed that K_p, K_d are in the prescribed ranges $[K_{pmin}, K_{pmax}]$ and $[K_{dmin}, K_{dmax}]$ respectively. The appropriate ranges are determined experimentally. For convenience K_p and K_d are normalized into the range between zero and one by the following linear transformation:

$$K'_p = (K_p - K_{pmin})/(K_{pmax} - K_{pmin})$$

(9)

$$K'_d = (K_d - K_{dmin})/(K_{dmax} - K_{dmin})$$

(10)

The PID parameters are determined based on the current error $e(k)$ and its first difference $\Delta e(k)$. The integral time constant is determined with reference to the derivative time constant, i.e.

$$T_i = \propto T_d \tag{11}$$

And the integral gain is thus obtained by

$$K_i = \frac{K_p}{\propto T_d} = \frac{K_p^2}{\propto K_d} \tag{12}$$

The parameters K_p', K_d' and $\propto$ are determined by a set of fuzzy rules of the form.
If $e(k)$ is A_i and $\Delta e(k)$ is B_i, then K_p' is C_i, K_d' is D_i and $\propto = \propto_i$.

$$i = 1, 2, 3, \dots \dots \dots . n$$

Here A_i, B_i, C_i and D_i are fuzzy set on the corresponding supporting sets; $\propto_i$ is a constant. The membership function (MF) of these fuzzy sets for $e(k)$ and Δe(k) are shown in Figure 5.1 and Figure 5.2.

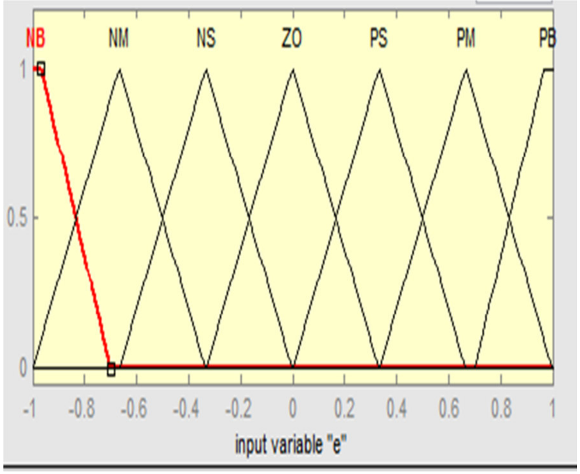

Figure 3. Membership Function $e(k)$

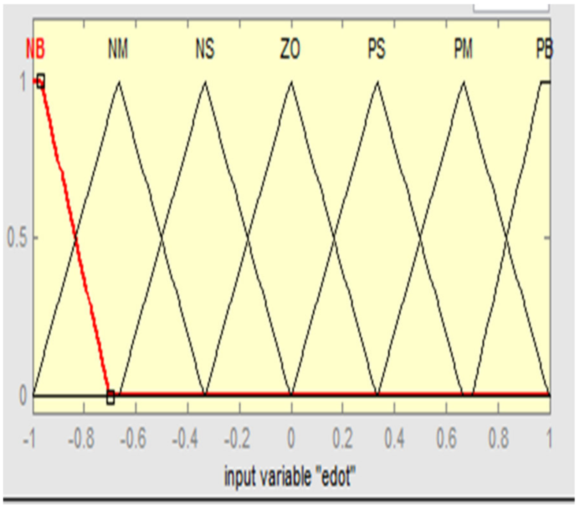

Figure 4. Membership Function $\Delta e(k)$

In this figure, N represents negative, P positive, ZO approximately zero, S small, M medium, B big. Thus NM stands for negative-medium, PB for positive-big, and so on. The fuzzy sets C_i and D_i may be either Big or Small and are characterized by the membership functions shown in Figure 5.3, where the grade of the membership functions μ and the variable x(= K_p' or K_d') have the following relation:

$$\mu_{SMALL}(x) = -\frac{1}{4}\ln x \ \ or \ x_{SMALL}(\mu) = e^{-4\mu}$$

(13)

$$\mu_{BIG}(x) = -\frac{1}{4}\ln(1-x) \ \ or \ x_{BIG}(\mu) = 1 - e^{-4\mu}$$

(14)

The rule around a_1 reads, If $e(k)$ is PB and $\Delta e(k)$ is ZO, the K_p' is Big, K_d' is Small, and $\propto = 2$.
If $e(k)$ is ZO and $\Delta e(k)$ is NB, the K_p' is Small, K_d' is Big, and $\propto = 5$

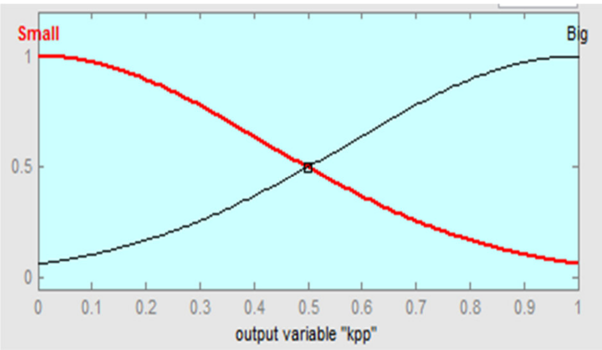

Figure 5. Membership Function of kpp

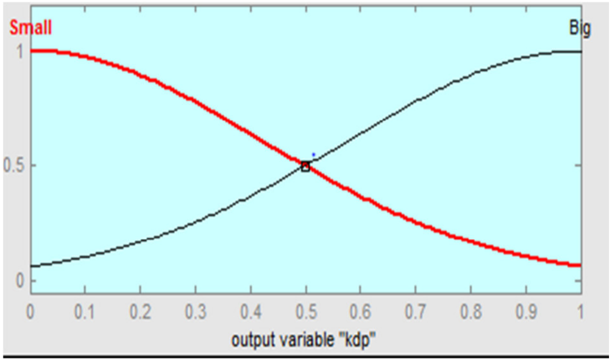

Figure 6. Membership Function of kdp

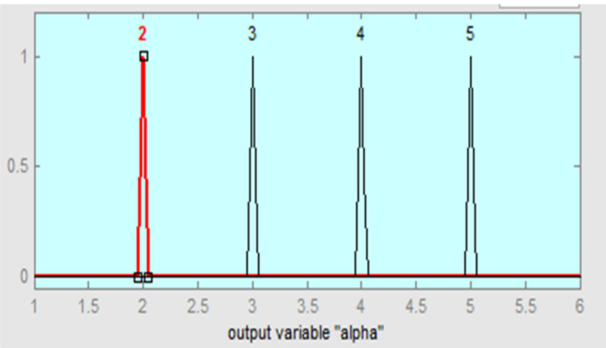

Figure 7. Membership Function of alpha

The truth table of ith rule is obtained by the product of the membership function values in the antecedent part of the rule:

$$\mu_i = \mu_{Ai}[e(k)].\mu_{Bi}[\Delta e(k)] \tag{15}$$

where μ_{Ai} is the membership function value of the fuzzy set A_i given a value of $e(k)$, μ_{Bi} is the membership function value of the fuzzy set B_i given a value of $\Delta e(k)$

The implication of a fuzzy rule is shown in Figure 8.

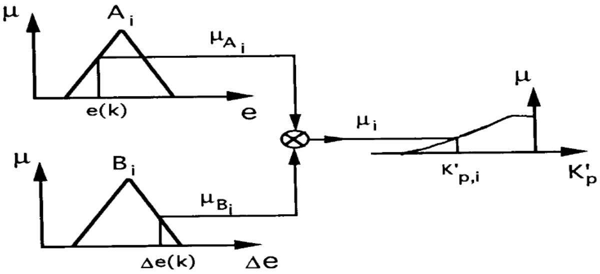

Figure 8. Implication of a Fuzzy Rule.

By using membership function we have the following condition,

$$\sum_{i=1}^{m} \mu_i = 1 \tag{16}$$

Then, the defuzzification yields the following:

$$K_p' = \sum_{i=1}^{m} \mu_i K_p' ;$$
$$K_d' = \sum_{i=1}^{m} \mu_i K_d' ; \qquad (17)$$
$$\propto = \sum_{i=1}^{m} \mu_i \propto_i ;$$

6. SIMULATION RESULTS

In order to evaluate the proposed system, the block shown in Fig. 1 was simulated by MATLAB/Simulink. Motor parameters used for simulation are given in table II

TABLE II. BLDC MOTOR PARAMETERS USED FOR SIMULATION

Parameters	Value
Number of Poles	2
DC Link Voltage	300 V
Phase Resistance	0.4 ohms
Self-Inductance	13 mH
Load Torque	20 N.m
Rated Speed	1500 r.p.m
Moment of Inertia	0.004 kg.m^2

The estimated d-q back-EMFs are shown in Figs. 9 and 10 which are estimated from the sliding mode observer. And a sliding mode observer is a good option for back-EMF estimation without demanding look up table and position sensors. The estimated speed is shown in Fig. 11, the speed increases from standstill and reaches the steady state without any serious distortion. The estimated load torque is calculated according to the Appendix and is shown in Fig. 12 and the stator phase currents are depicted in Fig. 13, the waveforms of the phase currents are appropriate despite the elimination of position sensors.

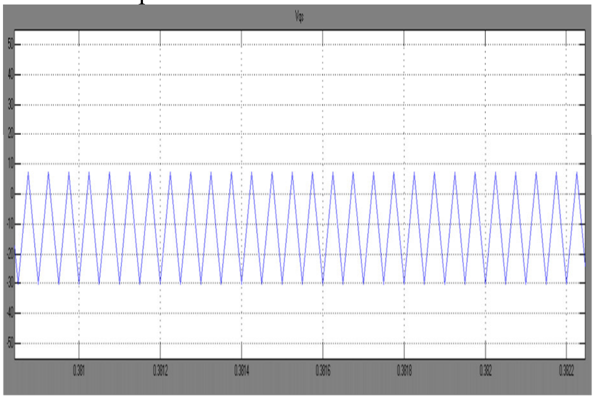

Figure 9. Back EMF (e_q)

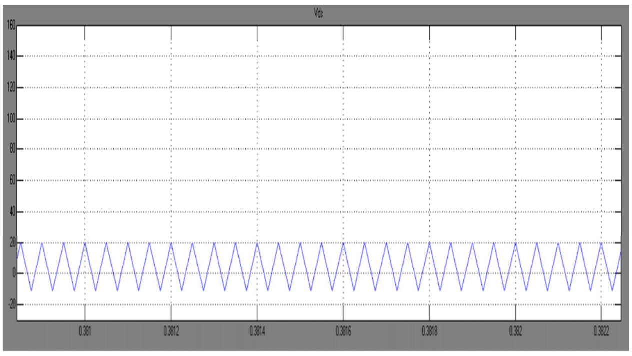

Figure 10. Back EMF (e_d)

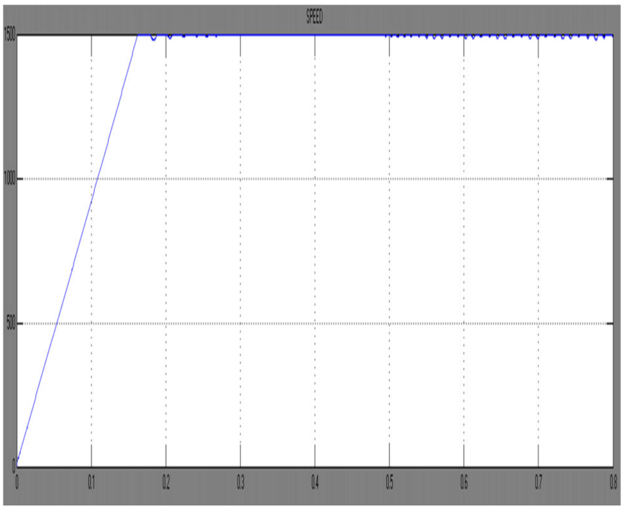

Figure 11. Rotor Speed

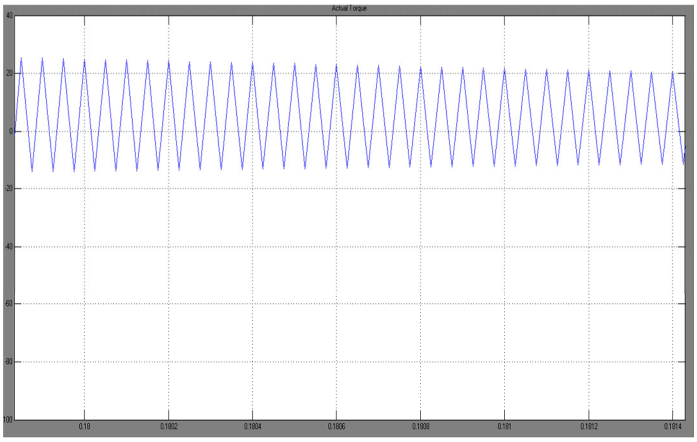

Figure 12. Torque of the BLDC

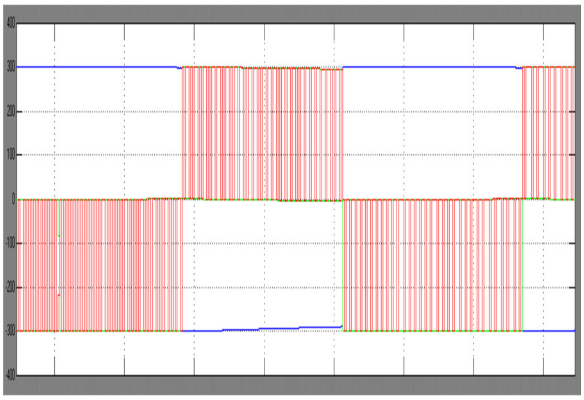

Figure 13. Stator Currents (I_{abc})

7. CONCLUSION

The primary contribution of thesis work is the development, analysis and simulation verification of DTC of BLDC using sliding mode observer that is based on stator reference frame topology. Sliding Mode Observer is used to estimate the trapezoidal back EMFs of BLDC, which in turn is used to estimate the torque and speed of the motor. DTC offers some advantages such as simple algorithm, simplicity of implementation, faster torque response, reduced torque ripple and less sensitivity to the variation of parameters, so the proposed system has utilized DTC method in order to benefit from the mentioned advantages. The effectiveness of the proposed sensor less method depends on proper selection of sliding mode observer and PID controller parameters. Therefore Fuzzy Gain Scheduling method is applied to tune the PID controller's values and sliding mode observer gains were tuned manually. The proposed method has been verified by simulation and the results were presented.

APPENDIX

Consider the back-EMFs that are estimated in section IV, the torque, electrical rotor speed, and position can be calculated. From the estimated back-EMF and measured stator currents, the estimated torque is calculated as follows:

$$\widehat{T_e} = \frac{3}{2}\frac{P}{2}\frac{1}{\widehat{\omega_e}}(\widehat{e_q} i_{sq} + \widehat{e_d} i_{sd})$$

(18)

where $\widehat{e_q}$ and $\widehat{e_d}$ are the estimated d-q frame back-EMFs, $\widehat{\omega_e}$ is the estimated electrical rotor speed.

Estimated electrical rotor speed and subsequently electrical position of the rotor are calculated as follow:

$$\frac{d}{dt}\widehat{\omega_e} = \frac{1}{J}[\frac{P}{2}(\widehat{T_e} + T_L) + B\widehat{\omega_e}]$$

(19)

$$\widehat{\omega_e} = \frac{d}{dt}\widehat{\theta_e}$$

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