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COST EFFECTIVE CURRENT CONTROL AND COMMUTATION TORQUE RIPPLE REDUCTION IN BRUSHLESS DC MOTOR DRIVES

M. Ebadpour   M.B.B. Sharifian

Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
m.ebadpour@tabrizu.ac.ir, sharifain@tabrizu.ac.ir

Abstract- The objective of this paper is to build a simple current controlled modulation technique for high performance and extensively used Brushless DC (BLDC) motors. It is based on the generation of quasi-square current waveforms, using only one current controller for three phases. Due to reducing the commutation torque ripples in proposed control system, the acoustic noise of motor is decreased. The commutation compensation technique is based on a strategy that the current slopes of the incoming and the outgoing phases during the commutation interval can be equalized by a proper duty-ratio control. In spite of conventional method, proposed method presents advantages such as very simple control scheme, balanced phase currents, and the stator currents are completely characterized by their maximum amplitude. In addition, triangular carrier modulation and PI controller for PWM generation are not needed anymore. For accessing better dynamic response characteristic for BLDC motor speed, Particle Swarm Optimization (PSO) has been used to regulate the PID parameter of speed controller. The effectiveness of the proposed control method is verified through comparative studies and simulation results.

Keywords: Commutation Torque Ripple Reduction, Brushless DC (BLDC) Motor, Particle Swarm Optimization (PSO), Simple Current Control.

I. INTRODUCTION

Brushless DC (BLDC) motors are widely used in applications which require wide range of speed and torque control because of its low inertia, fast response, high reliability and efficiency, low maintenance, and more compact construction. Moreover, basic trapezoidal BLDC motors make it possible to use a single current sensor to regulate the phase current flowing through two motor phases.

Nowadays, most of the commercial Permanent Magnet (PM) drives are based on current control strategies. There are two ways to control the phase-currents of a BLDC motor:

a. Through the measurement of the phase currents, which are compared and forced to follow a quasi-square template.
b. Through the measurement of the DC link current, which is used to get magnitude of phase-currents, I_{max}.

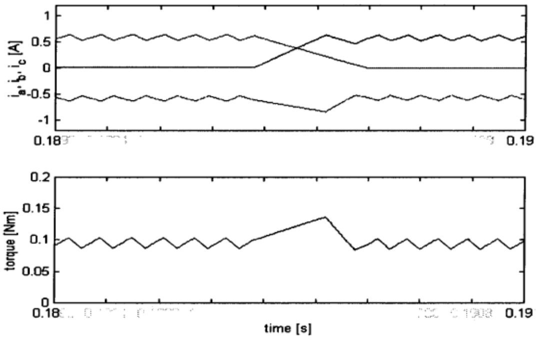
In the first case, the control is complicated, because it is required to generate three, quasi square current templates, shifted 120º for the three phases. Besides, these current templates or sensors are not easy to follow for the machine currents, because of phase-shifts and delays introduced [1]. Therefore, reduction of the number of sensors is desirable in motor drives. The most appalling current sampling method for BLDC motor is using only one current sensor. The easiest method is using a DC link current sensor.

There are some single current controls strategies have been studied on BLDC motor drives [2-5]. A modified DC-link current sensor proposed in [4]. It adds an inductance in the upper DC bus to stabilize the current flowing through the current sensor during a Pulse Width Modulation (PWM) period. Although it is helpful to evaluate the phase current with no need of any PWM strategy information, the existence of inductance tends to prevent the desired current regulation in phases. So this method is not suitable for current loop.

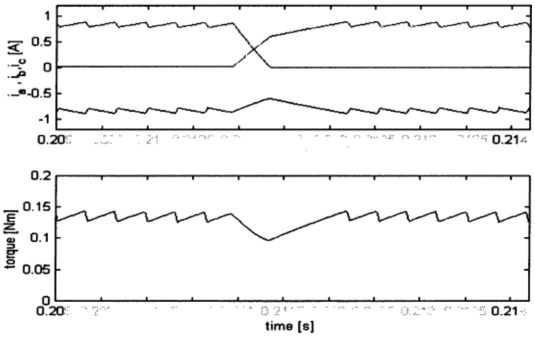
Another current sensor proposed in [5] also works well at any instant despite what PWM strategy is used. The key theory of this method is collecting both the freewheeling current through the anti-parallel freewheeling diode and the DC-link current. Therefore, it will not lose any current information during a PWM period. But, in this case the freewheeling current in the closing phase is still a torque source and produces torque ripple in commutation region.

Commutation torque ripples usually occur due to the loss of exact phase current control during the phase current commutation intervals. Figure 1, as a typical example, shows the commutation torque ripple in trapezoidal brushless dc motors, including torque spikes in the low speed range and torque dips in the high speed range.

A theoretical analysis related to these commutation torque ripples is found in literature [6, 7]. As for brushless dc motor drives with three phase current sensors, many researches regarding commutation torque ripple have been carried out [6-9].



(a)



(b)

Figure 1. Typical forms of commutation torque ripple
(a) In low speed and, (b) In high speed [6, 7]

This paper presents a cost effective current control strategy and analysis of the commutation torque ripple suppression method for brushless DC motor drives with only a single current sensor. The proposed control scheme makes the commutation current slopes of the incoming and outgoing phases balanced during the commutation interval of the phase currents. The strategy is based on a hysteresis current controller and a PSO tuned PID controller for speed regulation. Both current and torque ripples are reduced in commutation region.

II. THREE-PHASE BLDC MOTOR OPERATION PRINCIPLE

Brushless DC motor is one kind of permanent magnet synchronous motor with permanent magnets on the rotor and trapezoidal shape back-EMF. The BLDC motor employs a DC power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from the rotor position. The phase currents of BLDC motor, in typically rectangular shape, are synchronized with the back-EMFs to produce constant torque at a constant speed. The mechanical commutator of the brush DC motor is replaced by electronic switches, which supply current to the motor windings as a function of the rotor position.

This kind of AC motor is called brushless DC motor, since its performance is similar to the traditional DC motor with commutators. These brushless DC motors are generally controlled using a three-phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter.

These position sensors can be Hall sensors, resolvers, or absolute position sensors. Brushless DC motor is driven by a three-phase inverter with, what is called, six-step commutation. The conducting interval for each phase is 120° electrical degree. The commutation phase sequence is like S5-S6, S6-S1, S1-S2, S3-S4, S5-S4, and S5-S6. Each conducting stage is called one step. Therefore, only two phases conduct current at any time, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60° so that current is in phase with the back-EMF.

The commutation timing is determined by the rotor position, which can be detected by Hall sensors or estimated from motor parameters if it is sensorless system [10, 11]. For the three phases BLDC motor the back-EMF and phase current waveforms with 120° conduction mode are shown in Figure 2.

The analysis of a BLDC motor is represented in [12] as the following equations:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \\ + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where, v_a, v_b, v_c are the phase voltages, i_a, i_b, i_c are the phase currents, e_a, e_b, 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 we have:

$$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_r \quad (2)$$

where, ω_r is the mechanical speed of the rotor and T_e is the electromagnetic torque. The equation of motion is:

$$\frac{d}{dt}\omega_r = \frac{(T_e - T_L - B\omega_r)}{J} \quad (3)$$

where, B is the damping constant, J is the moment of inertia of the drive and T_L is the load torque. The electrical frequency related to the mechanical speed for a motor with P numbers of poles is:

$$\omega_e = (P/2) / \omega_r \quad (4)$$

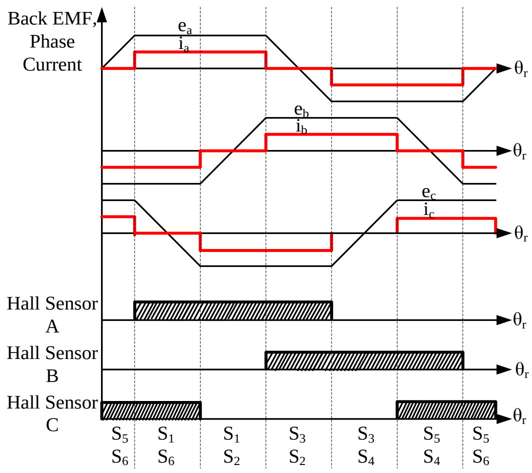


Figure 2. Signal waveforms in the BLDC motor

III. TORQUE RIPPLE REDUCTION

Figure 3 shows the switching sequence and the respective phase current waveforms during commutation intervals in the low speed region. A method to slow down the rising time of the incoming phase current i_b can be a desirable technique to equalize the mismatched commutation times of the two commutated phase currents. Solid lines show the waveforms corresponding to the case in which the PWM patterns S1, S2, and S3, which take duty ratio designed especially for the commutation interval, are applied to the inverter. The inverter output voltage driven by the PWM patterns S1, S2, S3 is modulated at duty ratio to equalize the slopes of the incoming phase current and the outgoing phase current. Referring to Figure 3, phase voltage equations during commutation intervals can be described as Equations (5) to (7) and the neutral voltage is given by

$$-\frac{V_{dc}}{2} = Ri_a + L\frac{di_a}{dt} + e_a + V_n \tag{5}$$

$$S \times \frac{V_{dc}}{2} = Ri_b + L\frac{di_b}{dt} + e_b + V_n \tag{6}$$

$$-S \times \frac{V_{dc}}{2} = Ri_c + L\frac{di_c}{dt} + e_c + V_n \tag{7}$$

$$V_n = -\frac{V_{dc}}{6} - \frac{e_a + e_b + e_c}{3} \tag{8}$$

where, S denotes 1 for switch-on and -1 for switch-off. In this commutation interval, it is assumed that the motor winding resistance is neglected, and e_a and e_b maintain the value of E and e_c holds at $-E$. The slope of the A-phase current can be described as:

$$\frac{di_a}{dt} = \frac{1}{L} \times \left(-\frac{V_{dc}}{2} - e_a - V_n \right) = -\frac{V_{dc} + 2E}{3L} \tag{9}$$

The slope of the B-phase current is calculated according to the switching function as

$$\frac{di_b}{dt} = \frac{2(V_{dc} - E)}{3L}, \quad S = 1 \tag{10}$$

$$\frac{di_b}{dt} = \frac{-V_{dc} - E}{3L}, \quad S = -1 \tag{11}$$

The slope equation corresponding to the switching state, in which S maintains 1 during $D_{\text{low}}T_s$ and -1 during $(1-D_{\text{low}})T_s$, can be arranged using a state-space averaging technique.

$$\frac{di_b}{dt} = \frac{V_{dc}(3D_{\text{low}} - 1) - 2E}{3L} \tag{12}$$

It is desired that the slope of the incoming phase current of Equation (9) is equal to that of the outgoing phase current of Equation (12) during commutation intervals. From Equations (9) and (12), therefore, the resultant duty ratio D_{low} is obtained as:

$$D_{low} = \frac{2}{3} + \frac{4E}{3V_{dc}} = \frac{1}{3} \times \left(2 + \frac{4E}{V_{dc}} \right) \tag{13}$$

Similarly, in the high speed region, as shown in Figure 4, a method to slow down the falling time of the outgoing phase current i_a becomes a desirable strategy to equalize the mismatched commutation times of the two commutated phase currents. The duty ratio D_{high} is calculated as:

$$D_{\text{high}} = \frac{4E}{V_{dc}} - 1 \tag{14}$$

Looking into Equations (13) and (14), the duty ratio applied to the inverter during commutations interval is found to have no relation with the inductance of the motor.

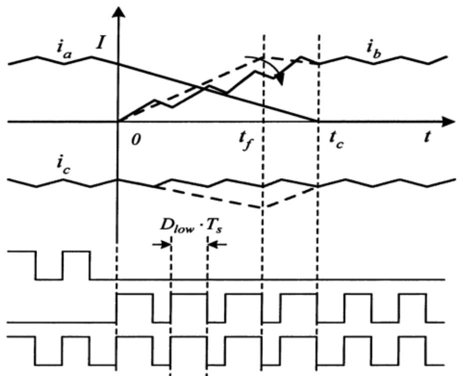


Figure 3. Switching patterns and commutation in low speed [6]

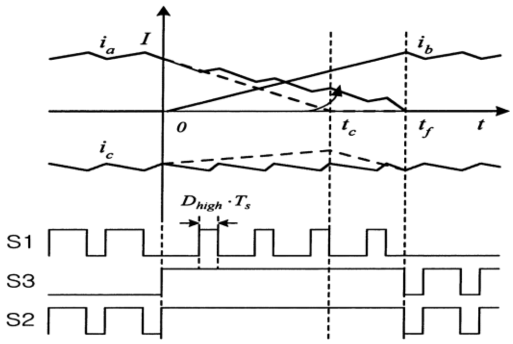


Figure 4. Switching patterns and commutation in high speed [6]

IV. PID CONTROLLER DESIGN

The PID controller is used to improve the dynamic response and reduce the steady state error. The transfer function of a PID controller is described as:

$$G_c(s) = k_p + \frac{k_i}{s} + k_d s \tag{15}$$

where, k_p, k_i and k_d are proportional, integral and derivative gains, respectively. The system response can be evaluated by overshoot (M_p), rise time (t_r), settling times (t_s), and steady-state error (E_{ss}). To improve the system performance by considering these parameters, an objective function is defined. The objective function will be minimized by an appropriate regulation of PID parameters (k_p, k_i, k_d). By minimizing the objective function, desired transient response to load disturbance is achieved [13]. The objective function can be defined as:

$$f(K) = (1 - e^{-\beta})(M_p + E_{ss}) + e^{-\beta}(t_s - t_r) \tag{16}$$

where, K is $[k_p, k_i, k_d]$ and β is the weight factor. Decreasing rise time and settling time can be achieved by using a weight factor smaller than 0.7 and increasing this parameter higher than 0.7, will lead to reduction in overshoot and steady state error.

The lower and upper limits of control variables (k_p, k_i, k_d) are chosen 0 and 30 values, respectively. Because of the system's nonlinear behavior, the objective function should be minimized by intelligent algorithms. Nowadays, the PSO algorithm is one of the fastest and most accurate methods in comparison with other intelligent algorithms. So in this paper, it is utilized to achieve optimal PID controller parameters using Matlab software. PSO results for iteration = 30 and weight factor = 0.5 are shown in the Table 1.

Table 1. Best PID controller with β=0.5 value gained by PSO algorithm

BLDC Motor				
B	Iteration	k_p	k_i	k_d
0.5	30	11	25	0.91
M_p	Ess (%)	t_r	t_s	Main Cost
0	0.22	0.007	0.02	0.0085

V. PROPOSED CURRENT CONTROL STRATEGY

In general, current control strategies for BLDC motor drives can be divided into three topologies: Hysteresis Band Control, PWM Control, and Variable DC-link Voltage Control. Hysteresis Band Control that used in this paper is one of the simplest closed-loop control schemes. In Hysteresis Band Control, the value of the controlled variable is forced to stay within certain limits (hysteresis band) around a reference value. Figure 5 shows a schematic of the proposed control strategy. The operation of the system is as follows. As the motor is a brushless DC type, the waveforms of armature currents are quasi-square. For control of speed and armature currents of motor, first, the speed of the motor is compared with its reference value. The speed error can be represented as:

$$e_{\omega}(t) = \omega_{ref} - \omega_r(t) \tag{17}$$

where, ω_{ref} is the reference speed value and $\omega_r(t)$ is the measured speed value at time t. The speed error is processed in the PID speed controller, tuned by PSO algorithm. The output of the speed PID controller is the reference torque value, but, According to this relation:

$$I_{ref} = T_{ref} / K_t \tag{18}$$

where, T_{ref} and K_t are the reference torque and torque constant respectively, the output of speed controller is considered as the reference current (I_{ref}). Then, the measured DC link current is compared with the reference current. The input of the current controller is:

$$e_i(t) = I_{ref}(t) - I_{dc}(t) \tag{19}$$

From this comparison, current error signal $e_i(t)$ is obtained. This error passing through a simple hysteresis current controller directly generates chopping for all six power switches of the inverter, which are sequentially active by the Hall-effect sensor. Ultimately the hysteresis current controller regulates the winding currents within the small band around the DC reference current. The electromagnetic torque is directly commanded by current reference. The larger the current reference, the higher torque produced. Also restriction is expelled on the PID speed controller output depending on the permissible maximum winding currents. This expelled restriction causes good compatibility with practical control systems.

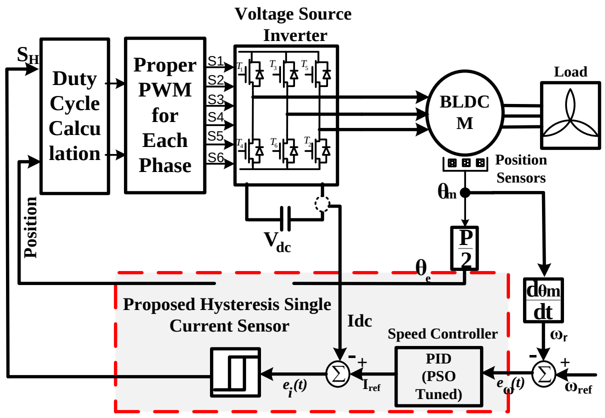


Figure 5. Overall block diagram of proposed strategies

VI. SIMULATION RESULTS AND COMPARATIVE STUDIES

To evaluate the performance of the proposed system, simulation models have been established using Matlab/Simulink. The main parameters of a BLDC motor are listed in Table 2. The sampling interval is 5 μsec, the magnitude of the current hysteresis band and switching frequency in conventional PWM control scheme are 0.2 A and 20 kHz, respectively.

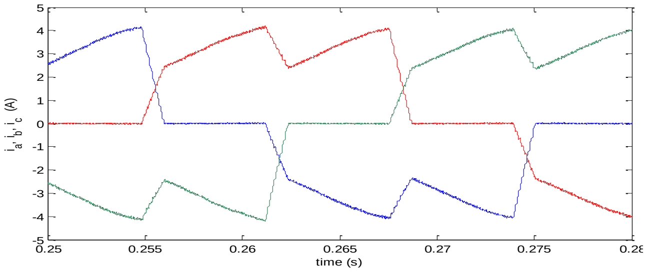
Table 2. Simulation parameters of the BLDC motor

Parameters	Value
Phase resistance	0.4Ω
Phase inductance	13 mH
Rated speed	1500 rpm
DC link voltage	300 V
Pole pairs	1
Rated torque	3 N.m
Inertia	0.004 kg.m^2
Friction factor	0.002 N.m.s
Torque constant	0.4 V/(rad/sec)

The BLDC motor phase currents are depicted in Figure 6. The square waveforms of phase currents using proposed method (Figure 6(c)) verify the well control capability of BLDC motor in comparative to two conventional current control methods. As shown in Figure 6(c), the current spikes in commutation region and current ripple in conduction region are eliminated effectively.

Figure 7 and 8 show the simulation results of the phase currents, DC-link current, and torque ripple obtained in the low speed range of 300 rpm and in the high speed range of 1500 rpm, respectively. These figures show that the proposed compensation technique is very effective at the commutation current ripple suppression over the entire motor speed range. As mentioned, the PSO has been used to regulate the PID parameter of speed controller.

As it can be seen from the Figure 9, the speed response characteristic at both low and high rates have been completely satisfied to have no overshoot, small rise and settling time.



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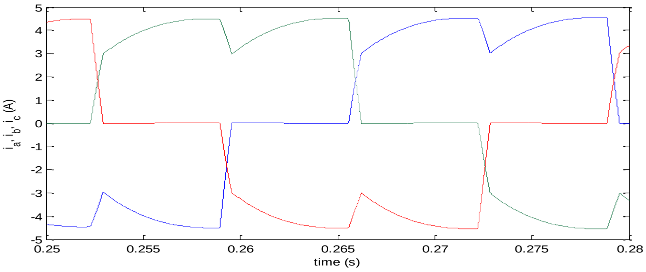

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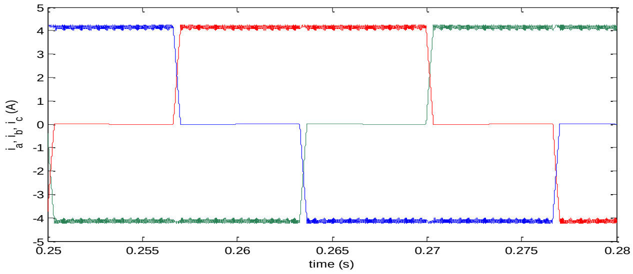
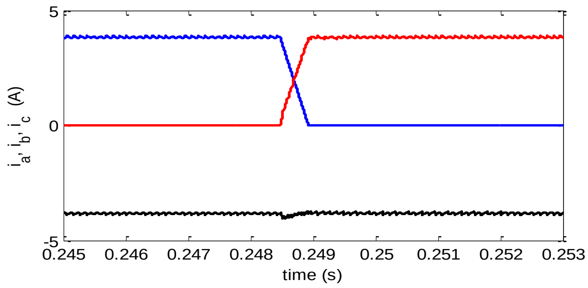


(c)

Figure 6. Motor phase currents, (a) PWM control,
(b) Variable DC link voltage control scheme, (c) Proposed method



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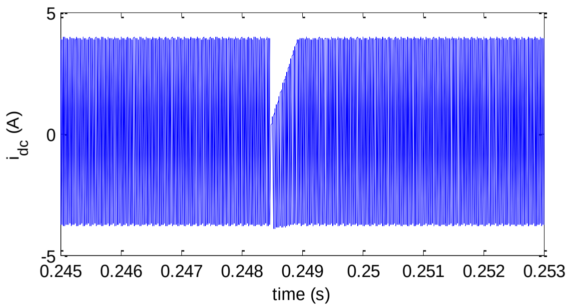

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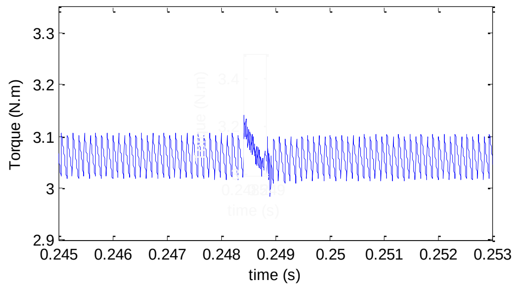
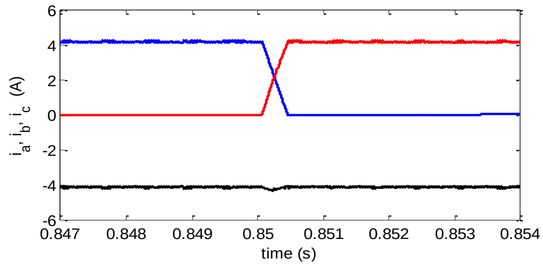


(c)

Figure 7. Simulation results in the low speed range (300 rpm),
(a) Phase currents, (b) DC-link current, (c) Commutation torque ripple



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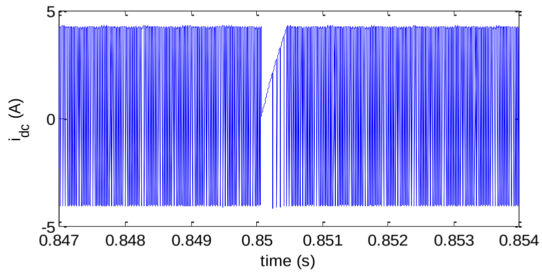

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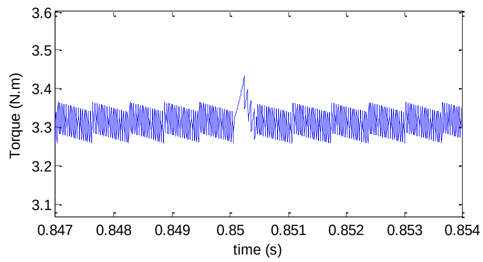

(c)

Figure 8. Simulation results in the high speed range (1500 rpm),
(a) Phase currents, (b) DC-link current, (c) Commutation torque ripple

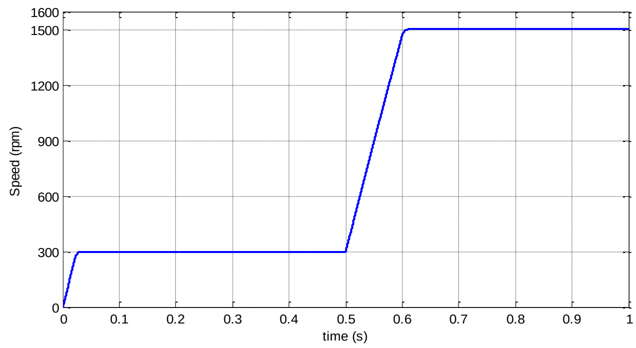

Figure 9. The speeds of rotor at low and high rate

VII. CONCLUSIONS

A cost effective, high performance drive and a commutation torque ripple reduction method for BLDC motor has been proposed. To sample the phase current at any instant, an effective single current sensor technique without the need for information of freewheeling current or current sign has been adopted. Therefore, the size of motor drives is reduced. Using the commutated phase current waveforms synthesized from the measured dc current, a duty ratio control strategy has been devised to equalize the two mismatched commutation time intervals.

The proposed control method accomplishes successful suppression of the spikes and dips superimposed on the current and torque responses during the commutation intervals. Compared to the conventional BLDC motor drive schemes, it is not complicated and eliminates the use of complex hardware. The PSO tuned PID controller is also used to improve the dynamic response and reduce the steady-state speed error. The proposed strategy makes possible low cost home appliances using BLDC motor.

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BIOGRAPHIES

Mohsen Ebadpour was born in Khodaafarin, Iran in 1987. He received the B.Sc. degree from the Azarbaijan University of Shahid Madani, Tabriz, Iran in 2009 and the M.Sc. degree from University of Tabriz, Tabriz, Iran in 2011 both in Electrical Power Engineering. He is currently pursuing the Ph.D. degree in Electrical Engineering (Electric Machine Drives). His research interests include drive and motion control of electric machines, electric vehicles (EVs), and power electronic converters. He currently focuses on the economical and optimum design of redial-flux and axial-flux permanent-magnet synchronous motor drives for electric vehicle applications.

Mohammad Bagher Bannae Sharifian was born in Tabriz, Iran, in 1965 and studied Electrical Power Engineering at the University of Tabriz, Tabriz, Iran. He received the B.Sc. and M.Sc. degrees in 1989 and 1992, respectively from University of Tabriz. In 1992 he joined the Electrical Engineering Department of the same university as a lecturer. He received the Ph.D. degree in Electrical Engineering from the same university in 2000. In 2000 he rejoined the Electrical Power Department of Faculty of Electrical and Computer Engineering of the same university as Assistant Professor. He is currently Professor of the mentioned department. His research interests are in the areas of design, modeling and analysis of electrical machines, transformers, liner electric motors, and electric and hybrid electric vehicle drives.