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A torque ripple minimization method for brushless DC motor in high speed applications using buck boost topology

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ABSTRACT

The torque ripple occurs due to commutation time of phase currents in the brushless direct current (BLDC) motors. In this paper, an effective method is developed to reduce torque ripple with wide speed control range for the high speed BLDC motor applications. A boost-buck converter topology has been used in this work. The boost-buck converter is placed between DC power supply and DC-link of the inverter. The DC-link voltage is adjusted depending on motor speed. Pulse Width Modulation (PWM) is used in order to control the phase currents of high speed BLDC motor. The PWM duty cycle is adjusted to reduce the ripple of the phase currents at the commutation time. The current control of the high speed BLDC motor is analyzed for three different methods. Firstly, the conventional method with constant DC-link voltage has been performed. Secondly, a variable DC-link voltage by using a boost-buck DC-DC converter has been performed. Thirdly, both variable DC-link voltage via boost-buck converter and current control method by using PWM have been performed. The waveforms of current and torque are given for different speed conditions in the steady state and during commutation. The conventional current controls and proposed current control strategies are presented by comparing performance.

Keywords: brushless DC motors; pwm; boost-buck converter; torque ripple; current commutation.

INTRODUCTION

In the recent years, the BLDC motors are widely used in electric vehicles, space crafts, medical fields, and industrial automation systems (Al-Othman et al., 2016; Arashloo et al., 2015; Baszynski & Pirog, 2014; Chenjun et al., 2015; Dixon et al., 2011; Hwang et al., 2012). The interest of using high speed BLDC motor, especially, is increased in the mechanical energy storage system with flywheel and torque control gyroscope of space craft (Aydın & Aydemir, 2013; Bharaktar et al., 2009; Briat et al., 2007; Çelikel et al., 2017; Gurumurthy et al., 2013; Kenny et al., 2005). The BLDC motors are preferred in these applications due to the low weight, high power density, high stability, and high efficiency. Having a simple switching technique is the most important reason for using BLDC motors in high speed applications. The six-step switching method is performed by using hall effect sensors placed inside stator windings. The current commutation is has occurred in every 60 degrees when the drive is with conventional six-step control strategy. Direction of the phase currents changes during commutation and the current ripple occurs in non-commutation current. The current ripples cause torque ripple, which is the most important disadvantage for high-speed applications. The motor performance is reduced because these ripples cause vibration and noise (Xia et al., 2014).

Recently, the sensorless control and reduced torque ripple methods have been used to increase the performance of the motor (Chen et al., 2017; Jiang et al., 2017; Nam et al., 2006; Shi et al., 2017; Viswanathan & Jeevananthan, 2016). A method has been developed to control ripple at the commutation time by using only one current sensor (Song & Choy, 2004). Some works have been focused on adjusted voltage level of the inverter to reduce torque ripple. A new circuit topology has been obtained by using Single-Ended Primary Inductor Converter (SEPIC). The experimental results have shown that the torque ripple is reduced (Shi et al., 2010). However, the cost of the motor driver increases due to additional DC-DC converter. Therefore, a novel method has been developed to reduce torque ripple with low cost motor drive. A PWM algorithm has been experimentally performed for torque ripple reduction (Salah et al., 2011; Salah et al., 2015; Ransara & Madawala, 2015). In addition, more efficient motor driver and drive methods has been developed to smooth torque ripple (Im et al., 2010; Kim et al., 2010; Mozaffari Niapour et al., 2014; Pan et al., 2015).

Recently, using the high speed BLDC motor increases in industrial applications. High speed BLDC motor can be operated in a wide speed range for energy storage system with flywheel. Therefore, the control methods can provide torque ripple reduction in a wide speed range. High speed BLDC motors have low commutation time due to low inductance of the motors and high speed. Therefore, the torque ripple reduction of high speed BLDC motors is not obtained by using conventional methods.

In this work, a torque ripple reduction method is proposed for high speed BLDC motors. The simulation results are performed by using MATLAB. The DC-link of the inverter is controlled via boost-buck converter. The current control of the BLDC motor is also obtained with speed control. The current and torque data are obtained by using three different methods for various speed references. The results obtained are also compared with each other in order to verify the efficiency of the proposed method.

THE MATHEMATICAL MODEL OF THE BLDC MOTOR

BLDC motors have three phase stator windings on the stator like the other AC motors. The permanent magnets can mount on the rotor with different formations. The information of the rotor position is obtained by hall-effect sensors mounted inside motor. The sensors give digital information in every 60 degrees of the rotor rotation. The information determines the place of the phase current commutation (Bist & Singh, 2014). The mathematical model of the BLDC is given in Equation (1).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - L_m & 0 & 0 \\ 0 & L_s - L_m & 0 \\ 0 & 0 & L_s - L_m \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} U_N \\ U_N \\ U_N \end{bmatrix} \tag{1}$$

where R_a , R_b , R_c are resistance of the motor phase windings, L_s is the self-inductance of each phase of BLDC, L_m is the mutual inductance between two phases, i_a , i_b , i_c are current of the motor phase. e_a , e_b , e_c are motor back-electromotive force (EMF). U_N represents the star point of the phase windings. Assuming that the motor operates with balance load, the sum of the motor phase currents is zero at any torque as shown Equation (2). e_a , e_b and e_c can be shown as Equation (3) in the commutation time.

$$i_a + i_b + i_c = 0 \quad and \quad i_a = I_0 \ , \ i_b = 0 \ , \ i_c = -I_0 \tag{2}$$

$$e_a + e_c = 0 \quad and \quad e_a = E_m \ , \ e_c = -E_m \tag{3}$$

Generated electrical torque can be obtained by Equation (4) and Equation (5).

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \tag{4}$$

$$T_e = \frac{2E_m \times I_0}{\omega_m} \tag{5}$$

where T_e is the torque generated by motor, I_0 is maximum value of the phase current, E_m is the back EMF of the motor, and ω_m is the angular speed of the motor. The six-step drive technique based on the information is obtained from hall-effect sensors. The two-phase windings are always energized at every moment. This method is widely used for high-speed BLDC applications because the six-step drive technique is easy to implement.

ANALYSIS OF COMMUTATION INTERVAL AND TORQUE RIPPLE

The torque ripple is an important problem for the BLDC motor driven with six-step switching technique. Calculation of commutation time is necessary to eliminate torque ripple. Therefore, voltage equations must be determined during commutation. Assuming that the commutation takes place between phase A and phase B. The phase to phase voltage can be calculated as seen between Equation (6) and Equation (10).

$$V_{ac} = R_{ac}(i_a - i_c) + L_{ac}\frac{d(i_a - i_c)}{dt} + (e_a - e_c) = 0 \; and \; (e_a - e_c) = 2E_m \tag{6}$$

$$V_{bc} = R_{bc}(i_b - i_c) + L_{bc}\frac{d(i_b - i_c)}{dt} + (e_b - e_c) = V_{dc} \; and \; (e_b - e_c) = 2E_m \tag{7}$$

$$i_b = -i_c - i_a \tag{8}$$

$$V_{bc} = R_{bc}(i_a + 2i_c) + L_{bc}\left(\frac{di_a}{dt} + 2\frac{di_c}{dt}\right) - 2E_m = -V_{dc} \tag{9}$$

$$V_{ab} = -3R_{ab}i_c - 3L_{bc}\frac{di_c}{dt} + 4E_m - V_{dc} = 0 \tag{10}$$

where L_a=L_b=L_c=L_s-L_m is the inductance of each phase of BLDC. The value of expression $3R_{ab}i_c$ seen in Equation (10) is very low and it can be negligible. The current commutation of BLDC motor can be obtained by using three-phase inverter structure. In the literature, PWM strategy and DC-DC converter connected input of the inverter can be also used for current commutation in six-step switching. In this work, a hybrid method including two techniques is proposed to improve the torque ripple of the high speed BLDC motor. The control of inverter's DC-link is obtained by using boost-buck converter. The PWM is used in order to control the motor current. The winding inductance and resistance of the high speed BLDC motor have too low values. Therefore, the stator currents have high ripple. The switching frequency must be taken as high as possible due to the high fundamental frequency of the motor current. The dv/dt stresses in the windings occur due to the high switching frequency. The L_f filter inductance is used to reduce the dv/dt stresses and adjust commutation time of high speed BLDC. The drive system of the high speed BLDC motor is shown in Figure 1.

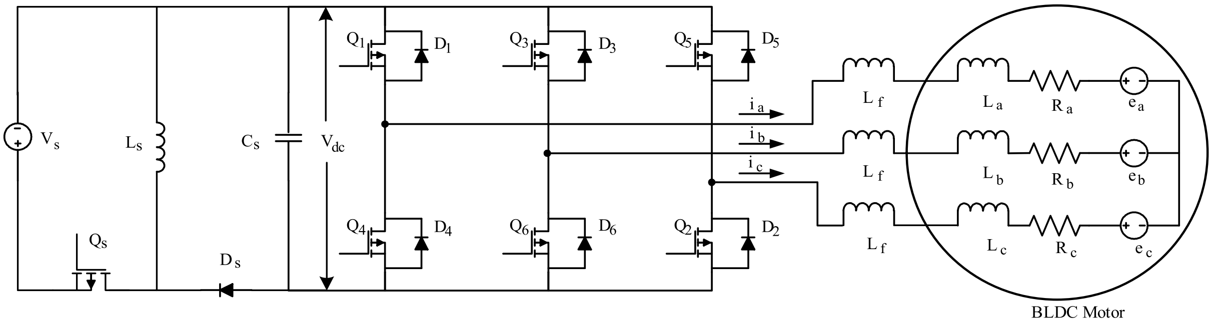

Fig. 1. The high speed BLDC motor drive.

where L_f is the inductance of the filter. V_s is supply voltage. V_{dc} is DC link voltage of inverter. L_s, C_s, D_s *are* inductance, capacitance, and diode of boost-buck converter, respectively. The drive system inductance is determined by the sum of motor inductance. The filter inductance is given in Equation (11). Thus, the currents of the three phase winding are obtained as shown from Equation (12) to Equation (14).

$$L = L_{ab} = L_{bc} = L_{ca} = (L_a + L_b + 2L_f) \tag{11}$$

$$\frac{di_c}{dt} = \frac{4E_m - V_{dc}}{3L} \tag{12}$$

$$\frac{di_a}{dt} = -\frac{2E_m + V_{dc}}{3L} \tag{13}$$

$$\frac{di_b}{dt} = \frac{2(V_{dc} - E_m)}{3L} \tag{14}$$

There are three different cases during the commutation time as shown in Figure 2. The current waveforms are given in Figures 2(a) and 2(b) for operation in low/high speed ranges. It can be shown that there is not any ripple on the no-commutation current. The waveform must be obtained as shown in Figure 2(c). Equation (15) must be provided in order to obtain this case. Equation (16) is the rise time of the turn-on current. Equation (17) is the fall time of the turn-off current.

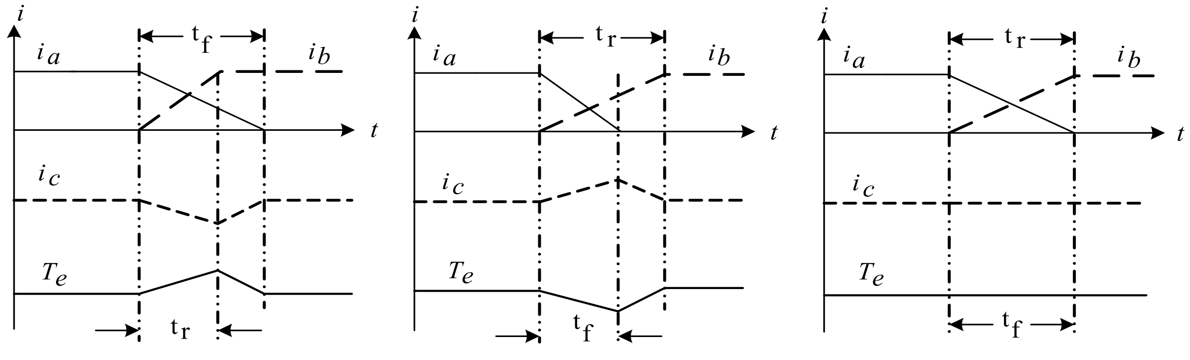

Fig. 2. The current waveforms at the commutation; a) $t_f > t_r$ and $V_{dc} > 4E_m$ ow-speed operation b) $t_f < t_r$ and $V_{dc} < 4E_m$ high-speed operation c) $t_f = t_r$ and $V_{dc} = 4E_m$ constant torque operation.

$$\frac{di_a}{dt} = \frac{di_b}{dt} \tag{15}$$

$$t_f = \frac{3LI_0}{2(V_{dc} - E_m)} \tag{16}$$

$$t_r = \frac{3LI_0}{2E_m + V_{dc}} \tag{17}$$

$$I_0 = \frac{|I_a|+|I_b|+|I_c|}{2} \tag{18}$$

$$V_{dc} = 4E_m \quad , \quad E_m = k\omega_m \tag{19}$$

where, k is the speed constant of motor, t_f and t_r are the fall time and rise time, respectively. I_0 is DC-link current as shown in Equation (18). It is equal to the maximum motor phase current. In this case, $t_f = t_r$ can be obtained by using Equation (19).

PROPOSED METHOD FOR TORQUE RIPPLE REDUCTION

The boost-buck converter adjusts the inverter DC-link voltage to reduce the torque ripples. Inverter DC link voltage is calculated as shown in Equation (20) and where D_b is duty ratio of boost-buck converter. The commutation time is determined to obtain current waveform shown in Figure 2(c) as given in Equation (21).

$$V_{dc} = \frac{D_b}{1-D_b} V_s \tag{20}$$

$$t_f = t_r = \frac{LI_0}{2E_m} \tag{21}$$

The commutation time is too small to be controlled due to low inductance of the high speed BLDC motor. Minimum value of the commutation time must be equal to switching period in the proposed control method. It can be shown that, in Equation (22),

$$t_{fmin} = t_{rmin} = \frac{1}{f_c} \tag{22}$$

where f_c is inverter switching frequency. The value of minimum filter inductance is calculated by using Equation (21) and Equation (22) for half load and 6213 rad/s speed.

$I_0 = 3.35A,\quad f_c = 50kHz,\quad \omega_m = 6213r/s,\quad L_{min} = 402\mu H$

The filter inductance is added to the system as 200 µH. The flowchart of the proposed method is given in Figure 3, where firstly, ω_m and phase currents of the BLDC motor are measurements to the calculated E_m, t_f, t_r and I_0. Secondly, the duty rate of boost-buck converter is calculated to adjust the DC link voltage of inverter. Thirdly, the current controller duty rate is taken as 1 during the commutation as shown below. Thus, the calculated DC-link voltage drops on the windings at that moment. The current controller duty rate is obtained by using PI controller in other situations.

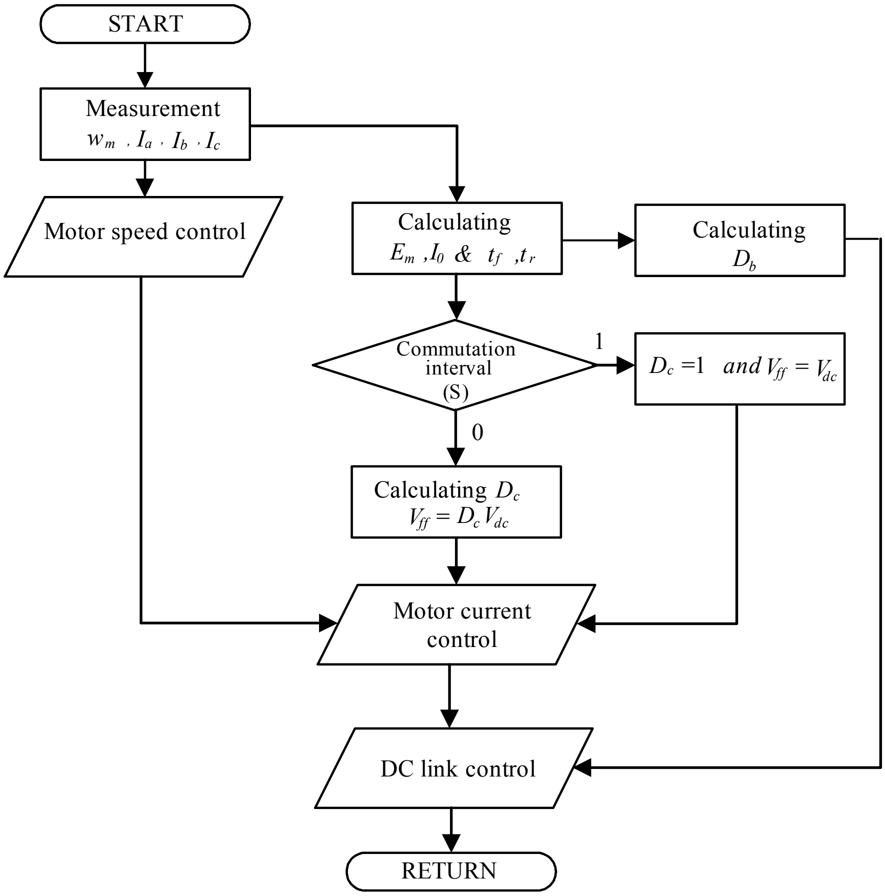

Fig. 3. Flowchart of the proposed method.

$S = 0 \;\; or \; S = 1$

$if \; S = 1 \; then \;\; V_{ff} = V_{dc}$

$Else$

$V_{ff} = D_c \, V_{dc}$

End

where

S= Commutation region detector

S=1 Commutation region

D_c= Current control duty ratio

D_b= Duty ratio of boost-buck converter

V_{ff}= The phase to phase voltage of the high speed BLDC motor.

The general control diagram of the proposed method is shown in Figure 4. The DC-link voltage value is determined depending on the instant speed value. Current reference is produced by using speed controller. Thus, not only speed control but also torque ripple reduction is performed by using proposed method.

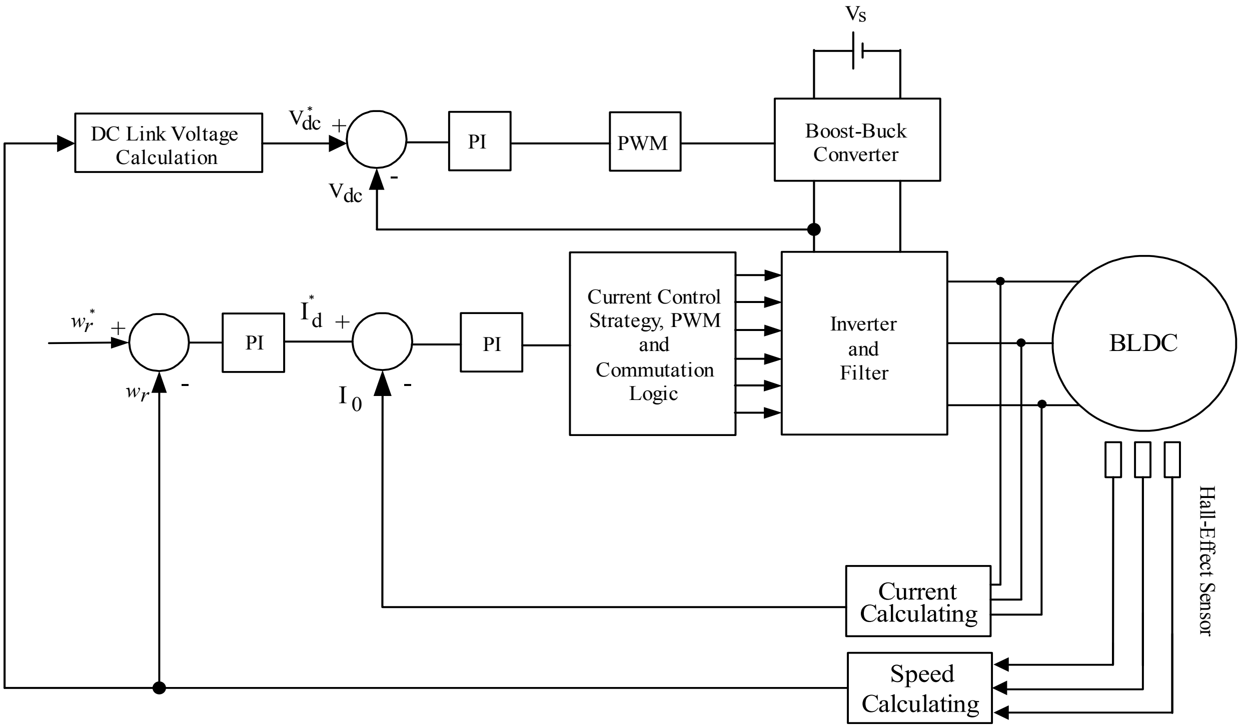

Fig. 4. The diagram of the proposed control method.

SIMULATION RESULTS

The simulation of the BLDC motor control is performed by using MATLAB/SimPowerSystem blocks as shown in Figure 5. The parameters of the Maxon EC-25 high speed BLDC, which is used for simulation, are given in Table 1. The simulation sample time is taken as 100 ns. The sample time of motor current controller is 20 µs and the sample time of DC-link voltage controller is 10 µs. The control signal block of commutation time, which is generated demand on hall-effect sensors, is given in Figure 6. Logic 1 signal is generated as long as each commutation time. This signal and current control PWM signal are applied to the windings by using proposed method. The microcontroller process capability is important in high speed applications. The proposed system is more suitable for high speed applications since it does not contain complex control methods. The BLDC motor is driven by ON-PWM method in the simulation. High-side switches of the inverter are turn-on with hall-effect sensor information and low-side switches are switched with PWM signal in this method. The simulation results are performed under the rated load condition with three different reference speeds. Current and torque of the high speed BLDC motor are analyzed in simulation environment.

Table 1. Maxon EC-25 motor parameters

Symbol	Unit	Parameter	Value
V	V	Nominal voltage	36
R	Ω	Terminal resistance phase to phase	0.122
L	mH	Terminal inductance phase to phase	0.014
I_0	A	Nominal current	6.74
K_t	mNm/A	Torque constant	5.36
K_e	rpm/V	Speed constant	1780
n	rpm	Nominal speed	62200
T_m	mNm	Nominal torque	35.1
J	kgm^2	Torque of inertia	5.45x10^{-7}
B	Nms/rad	Friction constant	~0

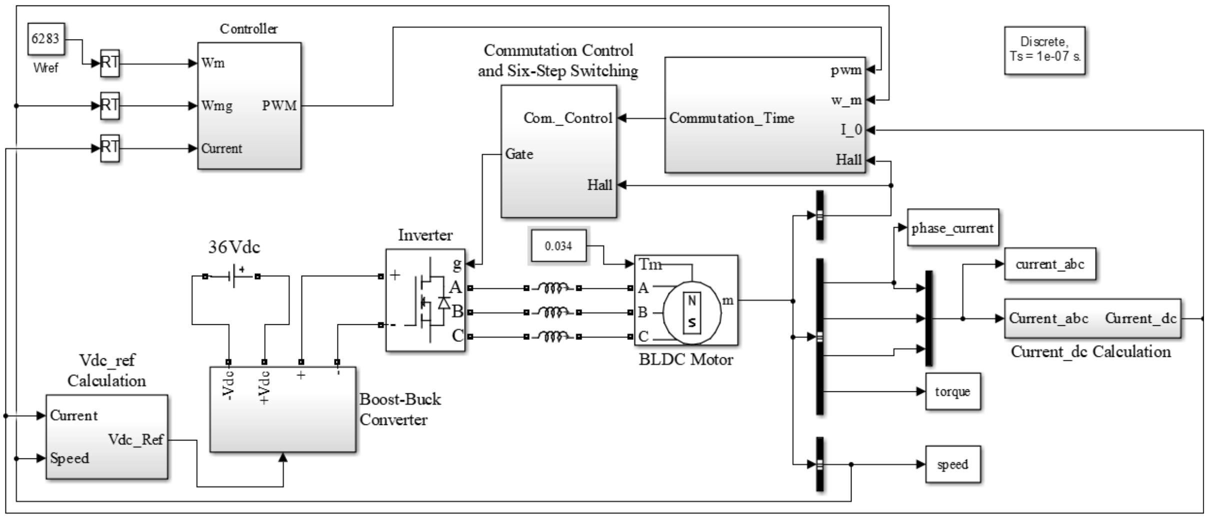

Fig. 5. The proposed torque ripple reduction method via using MATLAB/SimPowerSystem.

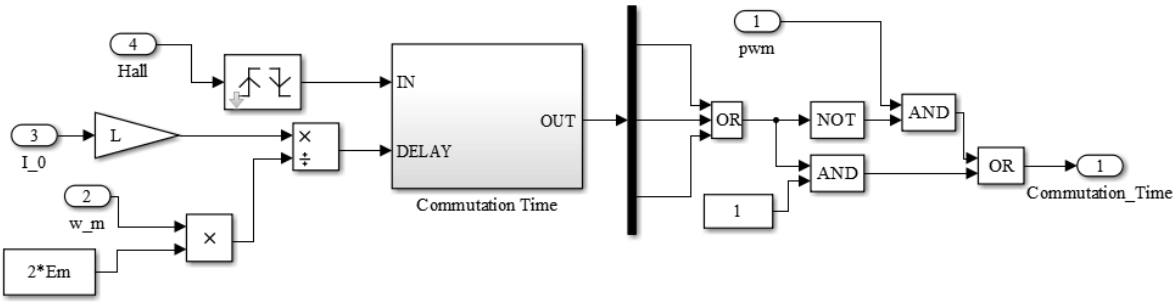

Fig. 6. Generating commutation time and control signal.

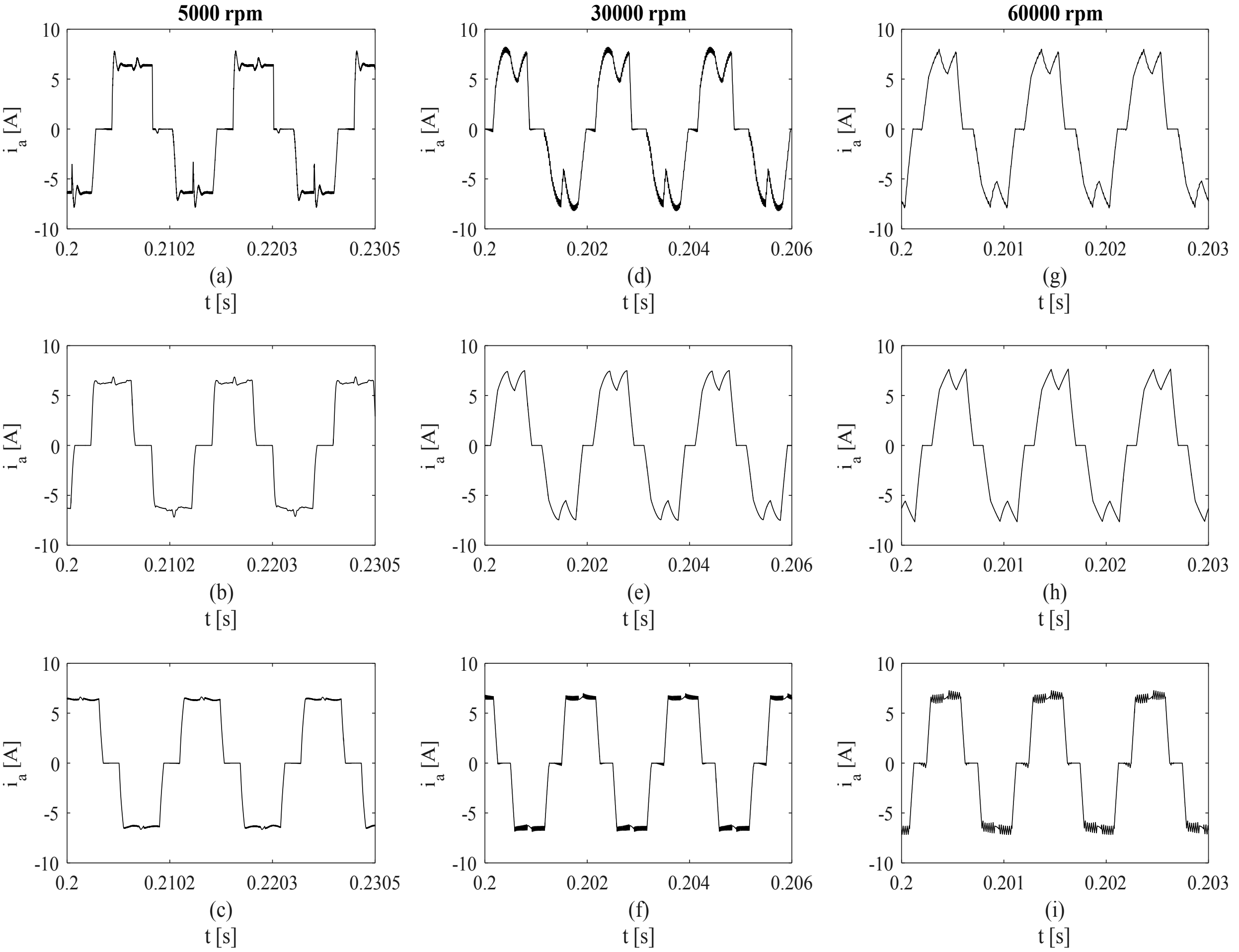

Fig. 7. The phase current of the high speed BLDC: Conventional method a) 5000 rpm, d) 30000 rpm, g) 60000 rpm. Boost-buck converter used method b) 5000 rpm, e) 30000 rpm, h) 60000 rpm. Proposed method c) 5000 rpm, f) 30000 rpm, i) 60000 rpm.

The phase current of the BLDC under the rated load condition is obtained by using three different methods for three different speed values as given in Figure 7. The phase current obtained by using conventional control method is shown in Figures 7(a), 7(d), and 7(g) for speeds 5000rpm, 30000rpm, and 60000rpm, respectively. The motor phase current obtained only using boost-buck converter is given in Figures 7(b), 7(e), and 7(h) for the same speeds. The last line of Figure 7 is given for the proposed method. The proposed method gives an effective result for wide-speed range as shown in the current waveforms. The motor torque waveforms obtained with different speed values and control methods are shown in Figure 8. The motor torque waveform obtained by using conventional control method is shown in Figures 8(a), 8(d), and 8(g) for speeds 5000rpm, 30000rpm, and 60000rpm, respectively. The motor torque waveform obtained only using boost-buck converter is given in Figures 8(b), 8(e), and 8(h) for the same speeds. The last line of Figure 8 is given for the proposed method. The torque ripples of the high speed BLDC motor are significantly reduced by using the proposed method.

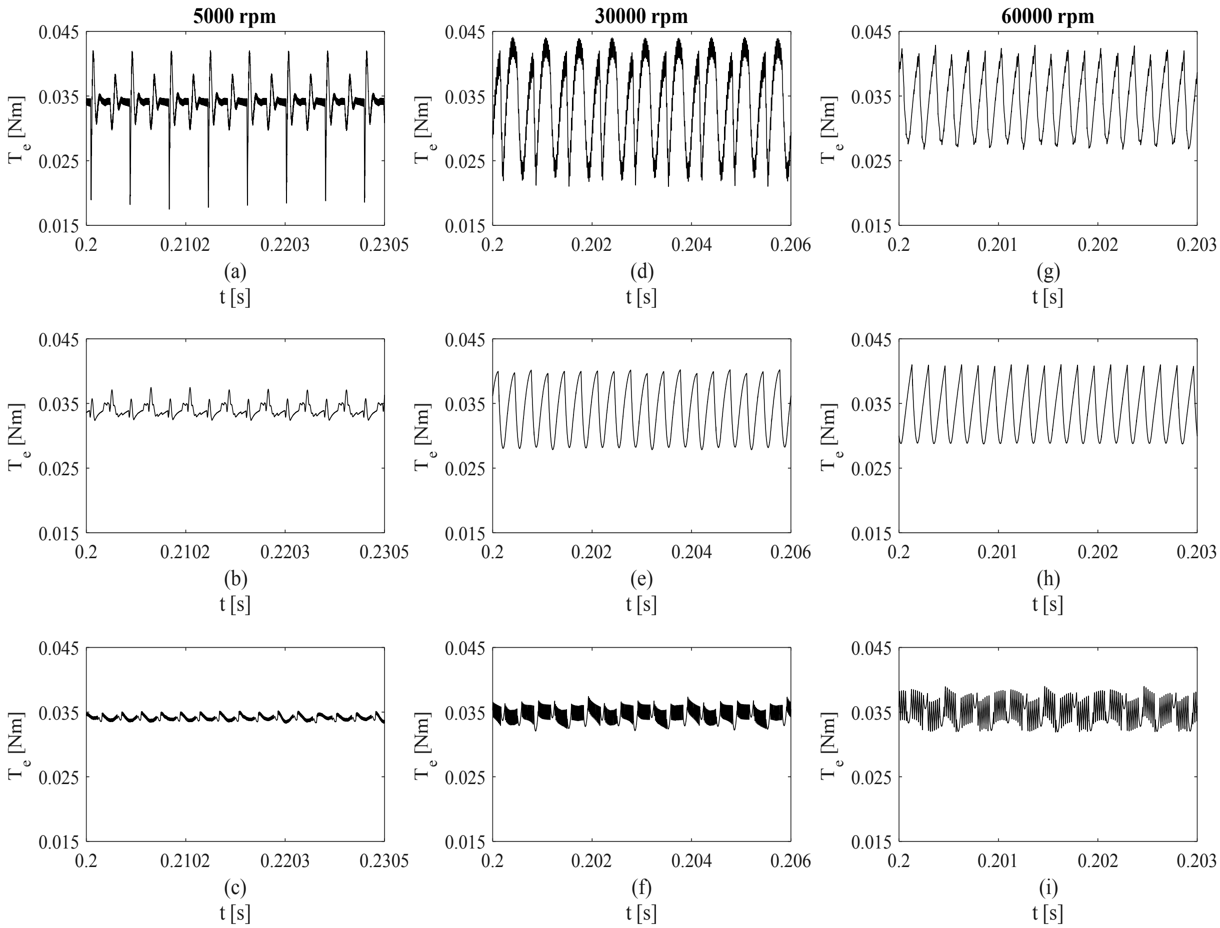

Fig. 8. The torque waveform of the high speed BLDC: Conventional method a) 5000 rpm, d) 30000 rpm, g) 60000 rpm. Boost-buck converter used method b) 5000 rpm, e) 30000 rpm, h) 60000 rpm. Proposed method c) 5000 rpm, f) 30000 rpm, i) 60000 rpm.

In Table 2, the torque ripple is given as percentage under the full-load. The proposed method provides more low torque ripple in the wide speed range than the conventional method.

Table 2. Comparison between conventional method and proposed method for torque ripple.

%Torque Ripple	**5000rpm**	**30000rpm**	**60000rpm**
Conventional Method	70.5	58.8	44.4
Boost-Buck Method	14.7	35.2	36.7
Proposed Method	5.8	17.6	23,5

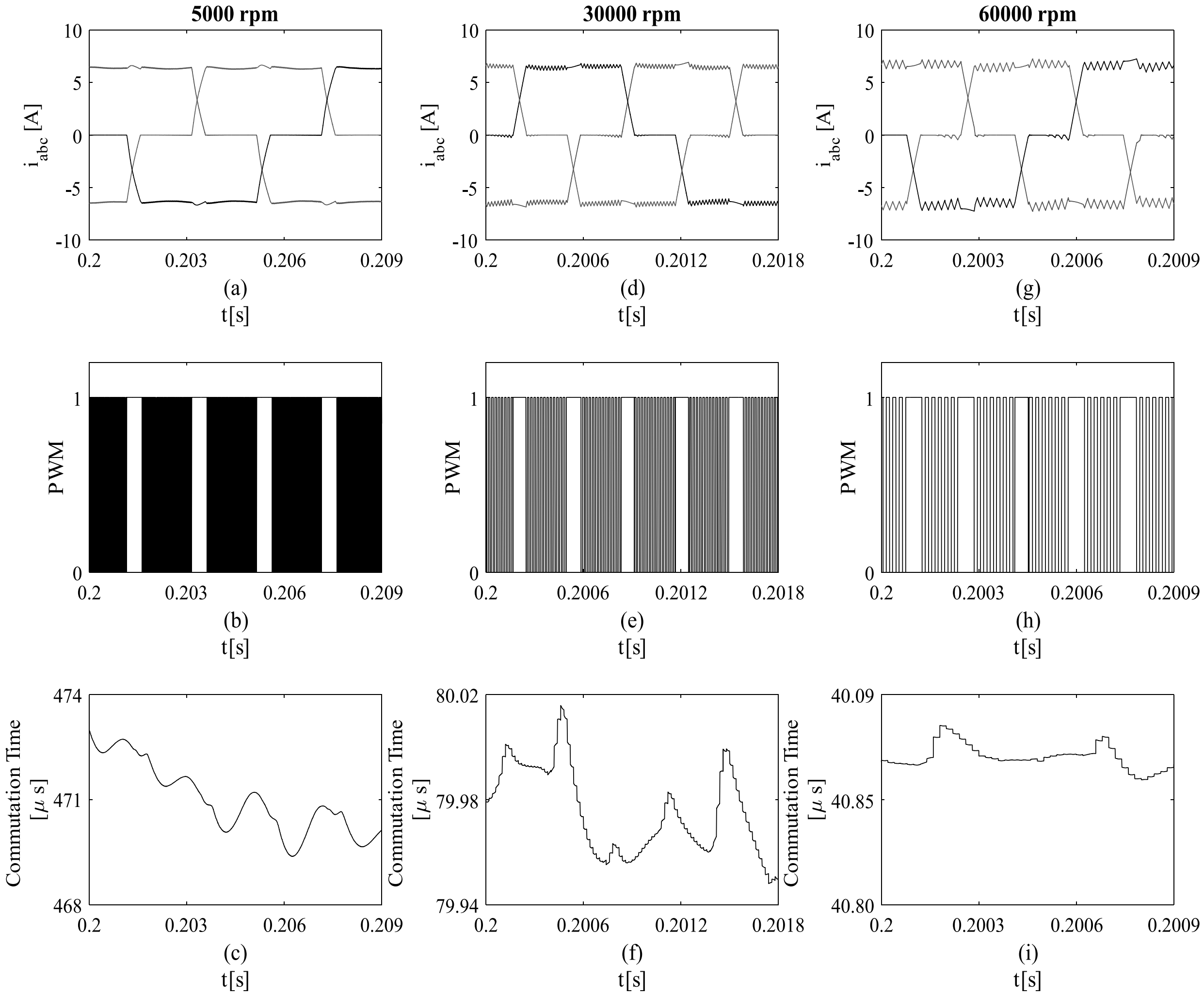

Fig. 9. Phase currents of the high speed BLDC, PWM waveform and commutation time: 5000 rpm a) phase currents b) PWM c) commutation time. 30000 rpm d) phase currents e) PWM f) commutation time. 60000 rpm g) phase currents h) PWM i) commutation time.

Three-phase current and PWM signals with commutation time are given in Figure 9 for 5000rpm, 30000rpm, and 60000rpm, respectively. The applied PWM duty period has been 1 at each commutation. Thus, the DC-link voltage is applied to windings at that moment. Besides, inverter DC-link voltage is adjusted without ripple by using DC converter in commutation time.

The inverter DC link voltage and motor speed are shown in Figure 10 for acceleration to 60000rpm speed at rated load. The boost-buck converter output voltage is determined by motor speed and motor current.

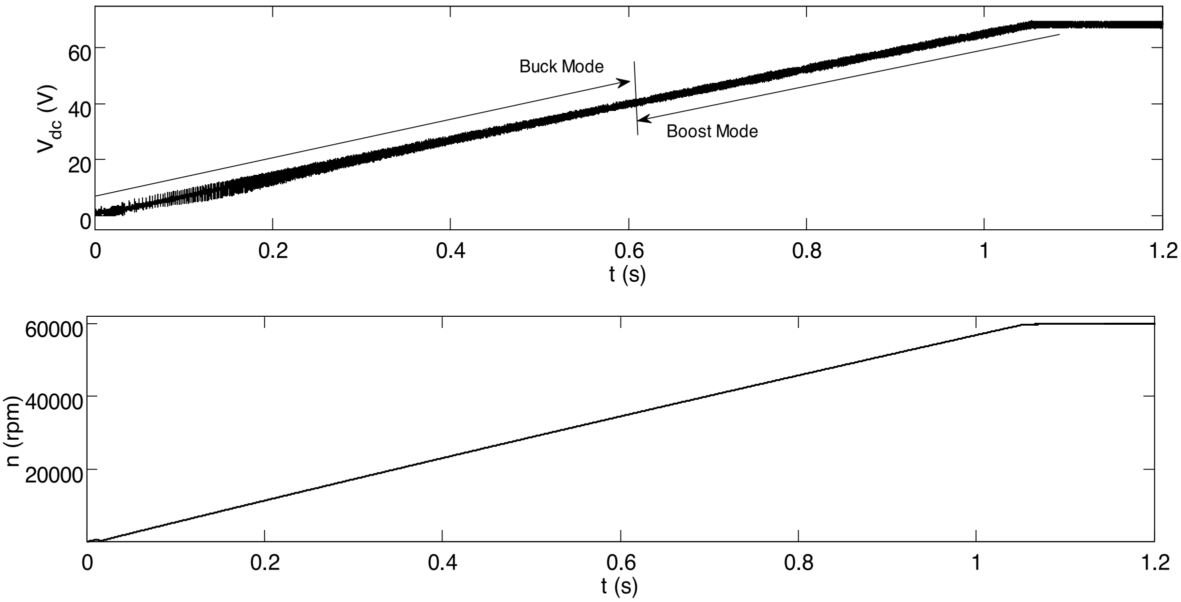

Fig. 10. Between 0 and 60000 rpm Top: Inverter DC link voltage. Bottom: Motor speed.

CONCLUSION

The most important disadvantage of the BLDC motor is torque ripple for high-speed applications. Eliminating torque ripple can reduce the motor vibration and noise. In this study, a boost-buck converter is proposed to reduce the torque ripple of the high speed BLDC motor. The boost-buck converter generates a voltage to avoid torque ripple. The commutation times of the phase currents are calculated in order to use in current control strategy. A new PWM method is used for switching inverter. It is shown to be suitable for use at high speed applications due to the simple structure of this PWM technique. The simulation results are performed by using MATLAB/SimPowerSystem blocks. The simulation results are taken for 5000rpm, 30000rpm, and 60000rpm speed values. The conventional method and the proposed method are compared for torque ripple and current waveforms. The results obtained using the proposed method are shown to be superior to those of the conventional methods. Besides, the current waveforms showed the accuracy of the calculated commutation time. Consequently, the superior performance is obtained by improving the torque ripple of the high speed BLDC motors. The motor can be used in the wide speed range by using the proposed method.

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طريقة لتقليل تموج عزم الدوران لمحرك التيار المستمر بدون فرش في التطبيقات عالية السرعة باستخدام المحول العكسي لفرق الجهد

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الخلاصة

يحدث تموج عزم الدوران بسبب وقت تبديل تيارات الطور في محركات التيار المستمر بدون فرش (BLDC). في هذا البحث، تم تطوير طريقة فعالة لتقليل تموج عزم الدوران مع نطاق تحكم واسع في السرعة لتطبيقات محرك BLDC عالي السرعة. تم استخدام المحول العكسي لفرق الجهد (مغير الإضعاف والتعزيز) في هذا العمل حيث تم وضعه بين مصدر طاقة ووصلة التيار المستمر للعاكس. تم ضبط وصلة نظام التيار المستمر عالي الجهد اعتماداً على سرعة المحرك، كما تم استخدام تضمين عرض النبضة (PWM) للتحكم في تيارات الطور لمحرك BLDC عالي السرعة. تم ضبط دورة تشغيل PWM لتقليل تموج تيارات الطور في وقت تبديل التيار. تم تحليل التحكم في تيار محرك BLDC عالي السرعة بثلاث طرق مختلفة. أولاً، تم تنفيذ الطريقة التقليدية مع جهد التيار المستمر للوصلة. ثانياً، تم تنفيذ جهد متغير لوصلة التيار المستمر عن طريق استخدام المحول العكسي لفرق الجهد dc-dc. ثالثاً، تم تنفيذ كل من جهد متغير لوصلة التيار المستمر عبر المحول العكسي لفرق الجهد وطريقة التحكم في التيار باستخدام PWM. تم تقديم الطول الموجي للتيار وعزم الدوران في ظل ظروف سرعات مختلفة في الحالة المستقرة وأثناء تبديل التيار. وتم عرض ضوابط التيار التقليدي والاستراتيجيات المقترحة للتحكم في التيار عن طريق المقارنة مع الأداء.