International Journal of Engineering

Journal Homepage: www.ije.ir

Influence of DC-Link Voltage on Commutation Torque Ripple of Brushless DC Motors with Two-Segment Pulse-width Modulation Control Method

S. Gol*, G. Ardeshir, M. Zahabi, A. Ale Ahmad

Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran

PAPER INFO

Paper history:
Received 07November2017
Received in revised form 26November2017
Accepted 30November2017

Keywords:
Brushless DC Motors
Motor Drive System
Commutation Torque Ripple
Pulse-width Modulation
DC-link Voltage

ABSTRACT

The commutation process causes current ripple to be generated in the drive system of brushless DC (BLDC) motor. This, in turn, leads to torque ripple that causes mechanical vibration and acoustic noise which are undesirable phenomenon in some applications. A new method is presented in this paper which reduces torque ripple and commutation period in the entire range of motor speed. This method is designed and implemented using two-segment pulse-width modulation (PWM) and DC-link voltage doubling during commutation. Based on the presented theory and given the influence of DC-link voltage on ripple magnitude, some experiments were carried out in which simultaneous contribution of the above mentioned factors in reducing current ripple and commutation time in the entire speed range of rotor are shown. The experimental results showed that the current ripple magnitude in high speed range is almost 20 times less than conventional method based on H-PWM_L-ON technique.

***doi**: 10.5829/ije.2018.31.02b.15*

1. INTRODUCTION

Brushless DC motors are extensively used in industrial applications such as electrical tools, compressor, and electrical vehicle system. This is due to high power density, reliable structure, low maintenance, and diversity of control methods from simple to advanced ones. On the other hand, the torque ripple in the output of brushless DC motors can prevent obtaining high performance. Therefore, some methods are required for its reduction or elimination.

The elimination of commutation torque ripple in the brushless DC motors with conduction angle of 120 electrical degrees could be possible by keeping current slope of outgoing and incoming phase in commutation period identical. This was shown mathematically and also demonstrated by simulation reported in literature [1]. One of the possible methods is using a proper mode of PWM. Some methods are proposed by research scientists [2, 3] in which in commutation period, incoming phase is turned on, and outgoing and non-commutation phases with the same duty cycle are turned on-off by PWM. Though, these methods cause equality of current slope of outgoing and incoming phases, their commutation period increases. It has been reported in literature [4, 5], an adjustable DC-DC converter is applied to DC-link for producing a voltage equal to four times of back-electromotive force (BEMF) in commutation period. This leads to make balancing of current slope of outgoing and incoming phases, and as a result, the commutation torque ripple is removed. Other sources reported [2, 6], three-phase PWM technique is used for elimination of commutation torque ripple. For eliminating commutation torque ripple, a method is presented by Shi and Li [7] in which each PWM period in commutation period is divided into three segments. By appropriate selection of the period of each segment, the current slopes of the outgoing and incoming phases in each PWM period become identical in average. On the other hand, the commutation period terminates in the shortest time. However, by changing duty cycle from 50 to 100%, commutation period and torque ripple increase. In[8], by applying C-dump converter to freewheeling diode, commutation time, and as a result, commutation torque ripple decreases; however, in this method, in addition to C-dump converter, three-phase

*Corresponding Author's Email:*gol@nit.ac.ir*(S. Gol)

Please cite this article as: S. Gol, G. Ardeshir, M. Zahabi, A. Ale Ahmad, The Influence of DC-Link Voltage on the Commutation Torque Ripple of the Brushless DC Motors with Two-Segment Pulse-width Modulation Control Method,International Journal of Engineering (IJE),IJE TRANSACTIONS B: Applications Vol. 31, No. 2, (February 2018) 307-314

inverter topology must be changed. Also, some factors such as PWM signal makes motor phases currents non-square and cause torque ripple to be appeared. Therefore in applications that mechanical vibration and acoustic noise are undesirable, this ripple must be eliminated.

In this paper, a method is proposed that in commutation interval, while dividing each PWM period into two segments, a voltage which is two times as that of phases conduction period, is applied to DC-link of three-phase inverter. The appropriate period for each of two segments can adjust the current slope of the outgoing and incoming phases in commutation period effectively and leads to elimination of the commutation torque ripple. Based on the equations resulted from the proposed method, the commutation process is controlled in such a way that the commutation period is minimized and the torque ripple is eliminated. The experimental results based on the proposed method using drive system of AK-ST7FMC showed that changing DC-link voltage in the commutation period reduces the torque ripple and the commutation period.

This paper's structure is as follows: section 2 describes the origins of commutation torque ripple and provides some effective solutions for its elimination. Section 3, while describing the proposed method for ripple elimination, presents the mathematical analysis of the mentioned method. Section 4 is allocated to the experimental results based on conventional method [2, 4], and the proposed method as well. In addition, the deviation by changing DC-link voltage is investigated.

2. THE COMMUTATION TORQUE RIPPLE AND ITS ELIMINATION METHOD

Figures 1 and 2 show brushless DC motor drive system model in conventional and proposed methods, respectively. In the proposed model, in addition to main power supply, another power supply with twice voltage and power far less than the main one is supplied. This power supply is connected to DC-link in commutation interval. Like the conventional model, each motor phase includes inductance, resistance, and back-electromotive force (BEMF) related to the winding of each phase. The wave form of BEMF of each phase is trapezoidal and the magnitude of its smooth section is equal to E_m. If we consider transition from *ab* to *ac* section in motor commutation period with six-step control method [9], in which non-commutation phase, outgoing phase, and incoming phase are *a*, *b* and *c*, respectively. The electromagnetic torque of motor is achieved by the following equation [1]:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} = \frac{2E_m . i_a}{\omega_r} \quad (1)$$

In which ω_r, T_e, e_i, and i_i (i=a, b, c) are angular velocity of the rotor, electromagnetic torque, BEMF, and phase current, respectively. Equation (1) states that electromagnetic torque waveform in commutation period is similar to the non-commutation phase current wave form. Therefore, by keeping non-commutation phase current constant, torque ripple would be eliminated. Figure 3 (a) and (b) show the reason for creation of commutation torque ripple. If brushless DC motor is considered in commutation time, the average absolute amount of the reduction slope of the outgoing current ($|\overline{s_b}|$), is not equal with the average absolute amount of increasing slope of the incoming current ($|\overline{s_c}|$), i.e., in Figure 3(a), $|\overline{s_b}| < |\overline{s_c}|$, and in Figure 3(b), $|\overline{s_b}| > |\overline{s_c}|$. The inequality of the reduction slope of the outgoing phase current and increasing slope of the incoming phase current is the reason of creation of non-commutation phase current ripple, which in turn, is the reason of the existence of torque ripple in motor. For eliminating this ripple, an effective solution is to set the average slope of the non-commutation phase current to zero ($\overline{s_a} = 0$) or equalizing the average slope of the outgoing and incoming phase currents ($\overline{s_b} = -\overline{s_c}$).

A more effective solution for eliminating torque ripple is to increase the slope which is slower between two slopes of outgoing and incoming phases (Figures 3(c) and 3(d)). Since commutation time is minimized by this method, which in turn, leads to smoother performance of the motor. Therefore, the idea of this work is the above mentioned solution, in which a method based on a two-segment PWM modulation along with doubling DC-link voltage of the three-phase inverter in the commutation interval is presented.

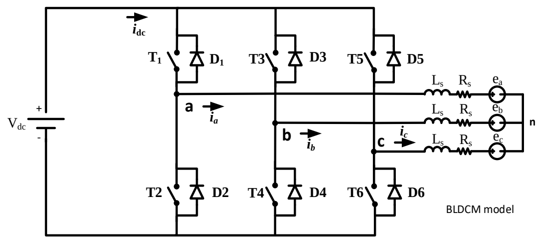


Figure 1. Brushless DC motor drive model in the conventional method

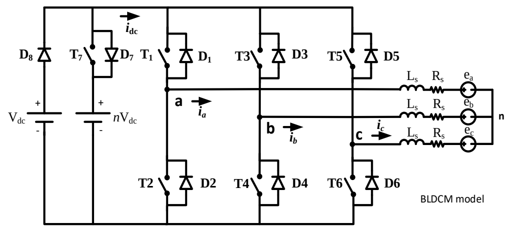


Figure 2. Brushless DC motor drive model in the proposed method

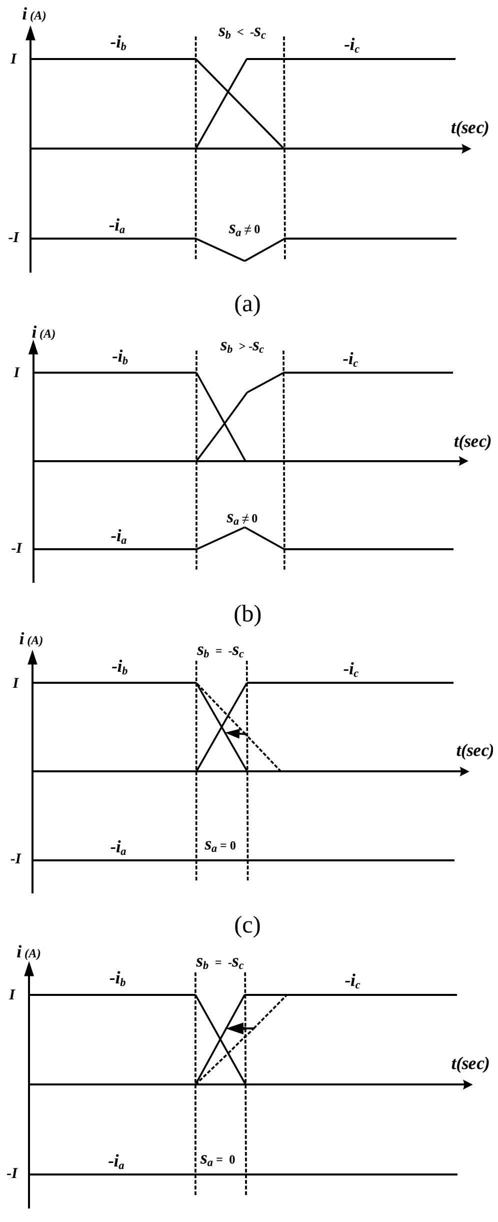


Figure 3. (a) and (b) The reason of creation of commutation torque ripple (c) and (d) ripple elimination method.

3. The Fundamental of Two-Segment PWM Modulation Method

The proposed two-segment PWM modulation method is shown in Figure 4. In the conduction period of phases, the upper switches of the three-phase inverter in the brushless DC motor drive system with PWM signal and duty cycle (*d*) are modulated while in the commutation period, the non-commutation phase voltage is modulated with variable duty cycle. For example in transition from *ab* to *ac* section, the applied

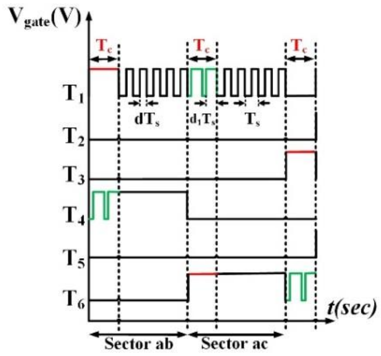


Figure 4. PWM signal in the proposed method

PWM signal to T_1 switch in a non-commutation phase with d_1 duty cycle, T_4 switch in outgoing phase with 0% duty cycle and T_6 switch in incoming phase with 100% duty cycles are adjusted.

Figure 5 shows the proposed two-segment modulation method in a PWM period. In addition, in commutation time, the applied voltage to DC-link is twice that of main power supply. Hence, T_7 switch in the proposed drive system (see Figure2) is turned on based on detection of the commutation time. Two segments of S_1 and S_2 in Figure 5 act as following. S_1 segment period is selected as equal to [(1-d_1).T_s], so that enough space is provided for commutation period regulation, in such a way that more commutation slope, the shorter (1-d_1). The amount of S_2 segment period is selected equal to (d_1T_s). This segment increases incoming phase current slope. Higher rotor speed reuslted in bigger d_1.

In fact, balancing current slopes of the outgoing and incoming phases, appropriate period should be selected for two segments of S_1 and S_2. Under this condition, commutation torque ripple is eliminated. The two-segment proposed method can be used for entire range of rotor speed. Table 1 summarizes the involved switches and PWM signal duty cycles of them for six-step control method.

3.1. Period of Each Segment in a PWM Interval

In this section, by considering brushless DC motor model and applied symbols in Figure 2, the proposed method is analyzed.

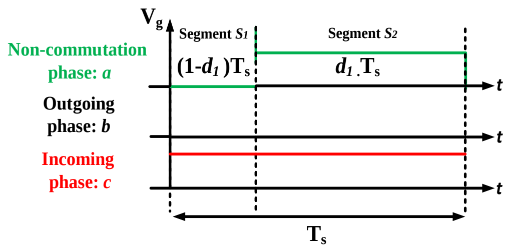


Figure 5. Two-segment modulation in a PWM interval

TABLE 1. Involved switches and their PWM signal duty cycle in the proposed method

Duty Ratio \ Sector	ab / ac	ac / bc	bc / ba	ba / ca	ca / cb	cb / ab
d_1	T_1	T_6	T_3	T_2	T_5	T_4
0	T_4	T_1	T_6	T_3	T_2	T_5
1	T_6	T_3	T_2	T_5	T_4	T_1

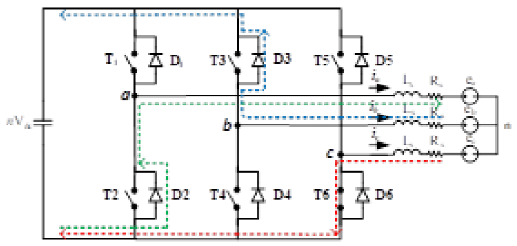
The terminal voltages of the windings of statorare obtained from the following equation:

$$v_j = L_s \frac{di_j}{dt} + R_s i_j + e_j + v_n \, ; \;\; j = a, b, c \tag{2}$$

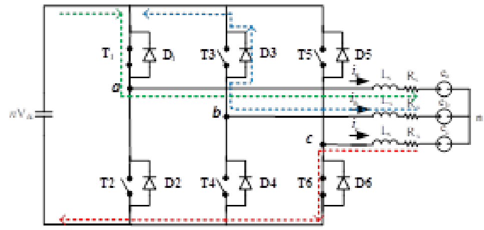
If, for example, we consider transition from *ab* to *ac* section in S_1 segment from PWM interval in Table 1, the circuit and current path of motor phases are according to Figure 6(a). In this segment, PWM signal is in off-state; hence, the upper and lower switches of the non-commutation phase, *a*, would be turned off; therefore, the stored energy in (L_a=L_s) inductance would return to power supply through lower free wheeling diode, in such a way that i_a current decreases. Also, upper and lower switches of outgoing phase, *b*, are off; therefore, the stored energy in (L_b=L_s) inductance return to power supply through upper free wheeling diode, hence, i_b current decreases.

The lower switch of the incoming phase, *c*, is turned on; therefore, i_c current increases slowly. Now, if we consider S_2 segment from PWM interval, the circuit and current path of motor phases are according to Figure 6(b). In this segment, PWM signal is on-state and upper switch of the non-commutation phase, *a*, is turned on; therefore, phase *a* is connected to the positive terminal of second power supply, hence, i_a current increases. The upper and lower switches of the outgoing phase, *b*, are turned off, hence, i_b current decreases. The lower switch of the incoming phase, *c*, is turned on, thus, *a* and *c* phases form a loop along with second power supply which leads to i_c current increase.

To analyze the proposed method, based on Figure 6 the equivalent motor circuit and its drive system model are shown in Figure 7. The current slope of phases in the two segments of S_1 and S_2 can be obtained from Kirchhoff law stated as follows:

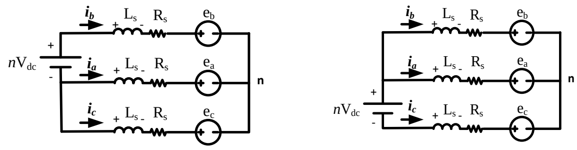


(a)



(b)

Figure 6. Circuit and currents' path in a PWM interval in transition from *ab* to *ac* section a) for S_1 segment. b) for S_2 segment



(a) (b)

Figure 7. The equivalent circuit based on drive system modeling in Figure 6 a) for S_1 segment. b) for S_2 segment

The current slope of the phases in S_1 segment are:

$$\begin{aligned} s_a|_{S1} &= \left[\frac{di_a}{dt}\right]_{Seg-S1} = -n\frac{V_{dc}}{3L_s} + \frac{e_b+e_c-2e_a}{3L_s} - \frac{i_a.R_s}{L_s} \\ s_b|_{S1} &= \left[\frac{di_b}{dt}\right]_{Seg-S1} = 2n\frac{V_{dc}}{3L_s} + \frac{e_a+e_c-2e_b}{3L_s} - \frac{i_b.R_s}{L_s} \\ s_c|_{S1} &= \left[\frac{di_c}{dt}\right]_{Seg-S1} = -n\frac{V_{dc}}{3L_s} + \frac{e_a+e_b-2e_c}{3L_s} - \frac{i_c.R_s}{L_s} \end{aligned} \tag{3}$$

Also, the current slopes in S_2 segment are:

$$\begin{aligned} s_a|_{S2} &= \left[\frac{di_a}{dt}\right]_{Seg-S2} = n\frac{V_{dc}}{3L_s} + \frac{e_b+e_c-2e_a}{3L_s} - \frac{i_a.R_s}{L_s} \\ s_b|_{S2} &= \left[\frac{di_b}{dt}\right]_{Seg-S2} = n\frac{V_{dc}}{3L_s} + \frac{e_a+e_c-2e_b}{3L_s} - \frac{i_b.R_s}{L_s} \\ s_c|_{S2} &= \left[\frac{di_c}{dt}\right]_{Seg-S2} = -2n\frac{V_{dc}}{3L_s} + \frac{e_a+e_b-2e_c}{3L_s} - \frac{i_c.R_s}{L_s} \end{aligned} \tag{4}$$

Based on the above equations, current slopes in two segment of S_1 and S_2 are unequal. To make equal the slope of outgoing and incoming currents, we need to allocate an appropriate portion to each of them in each segment. For this purpose, the slopes of currents are calculated as follows.

S_1 and S_2 segments in an interval are considered by the (1-d_1) and d_1 cooperation level, respectively. Hence we have:

$$\begin{aligned} \bar{s_a} &= \overline{\left[\frac{di_a}{dt}\right]} = (1-d_1)\left[\frac{di_a}{dt}\right]_{Seg-S1} + d_1\left[\frac{di_a}{dt}\right]_{Seg-S2} \\ \bar{s_a} &= \overline{\left[\frac{di_a}{dt}\right]} = (1-d_1)\left(-n\frac{V_{dc}}{3L_s}\right) + d_1\left(n\frac{V_{dc}}{3L_s}\right) + \frac{e_b+e_c-2e_a}{3L_s} - \frac{I.R_s}{L_s} \end{aligned} \tag{5}$$

On the other hand, regarding 3-phase brushless DC motors, we can write:

$$e_a = -e_b = -e_c = E_m \tag{6}$$

Therefore, Equation (5) can be written as:

$$\bar{s_a} = \overline{\left[\frac{di_a}{dt}\right]} = 2d_1\left(n\frac{V_{dc}}{3L_s}\right) - \left(n\frac{V_{dc}}{3L_s}\right) - \frac{4E_m}{3L_s} - \frac{I.R_s}{L_s} \tag{7}$$

Similarly for $\overline{\left[\frac{di_b}{dt}\right]}$ and $\overline{\left[\frac{di_c}{dt}\right]}$ we have:

$$\begin{aligned} \bar{s_b} &= \overline{\left[\frac{di_b}{dt}\right]} = (1-d_1)\left[\frac{di_b}{dt}\right]_{Seg-S1} + d_1\left[\frac{di_b}{dt}\right]_{Seg-S2} \\ \bar{s_b} &= \overline{\left[\frac{di_b}{dt}\right]} = (1-d_1)\left(2n\frac{V_{dc}}{3L_s}\right) + d_1\left(n\frac{V_{dc}}{3L_s}\right) + \frac{e_a+e_c-2e_b}{3L_s} + \frac{I.R_s}{2L_s} \\ \bar{s_b} &= \overline{\left[\frac{di_b}{dt}\right]} = 2\left(n\frac{V_{dc}}{3L_s}\right) - \left(n\frac{V_{dc}}{3L_s}\right)d_1 + \frac{2E_m}{3L_s} + \frac{I.R_s}{2L_s} \end{aligned} \tag{8}$$

and

$$\begin{aligned} \bar{s_c} &= \overline{\left[\frac{di_c}{dt}\right]} = (1-d_1)\left[\frac{di_c}{dt}\right]_{Seg-S1} + d_1\left[\frac{di_c}{dt}\right]_{Seg-S2} \\ \bar{s_c} &= \overline{\left[\frac{di_c}{dt}\right]} = (1-d_1)\left(-n\frac{V_{dc}}{3L_s}\right) + d_1\left(-2n\frac{V_{dc}}{3L_s}\right) + \frac{e_a+e_b-2e_c}{3L_s} + \frac{I.R_s}{2L_s} \\ \bar{s_c} &= \overline{\left[\frac{di_c}{dt}\right]} = -\left(n\frac{V_{dc}}{3L_s}\right) - \left(n\frac{V_{dc}}{3L_s}\right)d_1 + \frac{2E_m}{3L_s} + \frac{I.R_s}{2L_s} \end{aligned} \tag{9}$$

Based on the above equations, for eliminating commutation torque ripple, it is necessary to have:

$$\bar{s_a} = 0 \quad or \quad \bar{s_b} = -\bar{s_c} \tag{10}$$

Therefore:

$$2n.d_1 = n + \frac{4E_m}{V_{dc}} + \frac{3I.R_s}{V_{dc}} \tag{11}$$

On one hand, at steady state, according to PWM technique, we have:

$$d.V_{dc} = 2(I.R_s + E_m) \tag{12}$$

where*d* is PWM's duty cycle.
Using Equations (11) and (12) we obtain:

$$d_1 = \frac{1}{2} + \frac{d}{n} - \frac{I.R_s}{2nV_{dc}} \tag{13}$$

Therefore, commutation torque ripple is eliminated if Equation (13) is satisfied. In practical situations, the last term of Equation (13) is ignored due to low resistance (R_s) of windings. On the other hand, for duty cycle we have 0≤d≤1. Also, according to Equation (13) n=2 is the best value to avoid the issues regarding maximum insulation voltage of the motor and electric break down of IGBT switches. Since 0≤d≤1 and *n*=2, we obtain 0.5≤d_1≤1 by ignoring the last term in Equation (13).

4. EXPERIMENTAL RESULTS

For evaluating the proposed method, some experiments were carried out for investigating the influence of DC-link voltage on commutation torque ripple. The experiment set-up specifications are summarized in Table 2. In the experimental set-up, DC generator acts as a load. In commutation interval, the outgoing and incoming phase current obtained by the proposed method are shown in Figure 8. As it can be seen in this figure, the slopes of the currents were defined as equal.

Given the fact that ripple magnitude of phase current and also, torque has an inverse relationship with PWM frequency, increasing of this frequency is desired. On the other hand, since PWM maximum frequency in AK-ST7FMC control board is 20 KHz, this frequency was selected in all experiments. Also, coefficient of current probe is set to 100 mv/A condition. Figure 9(b) shows voltage and current signals of motor phase and DC-link for the proposed method with *d*=0.3, d_1=0.65. Main power supply voltage is V_{dc}=24V. Therefore, the second power supply is 48V. In this figure, phase *a* voltage, phase *a* current, DC-link current and voltage are shown from top to bottom, respectively. As it can be seen, current ripple is small. For demonstrating the influence of the second source voltage oncommutation current ripple, its value was deviated as ±12V (±25%) compared to twice of phases voltages during conduction time.

Illustrations in Figures 9(a) and (c), current ripple increases in these situations compared to Figure 9(b). Figure 10 shows the above mentioned wave forms for *d*=0.6 and d_1=0.8 for three supply voltages in commutation period (36V, 48V, and 60V). As it can be seen, current ripple increases when DC-link voltage is not twice.

TABLE 2. Drive and motor specifications

Main source	24 V	Rated power	100 W
Second source	48 V	Rated torque	0.5 Nm
PWM freq.	20 kHz	Poles no.	8
Switch	IGBT	R_s	0.3 Ω
Rated speed	2200 rpm	L_s	0.7 mH

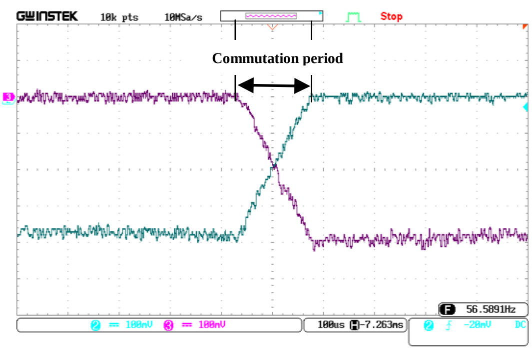


Figure 8. Outgoing and incoming phases current in commutation for *d*=0.9, d_1=0.95 and 4A phase current

Figure 11 shows waveforms for d=0.9 and d_1=0.95. According to this figure, it can be observed that the results are the same as for other values of d. We can conclude that the proposed method acts for entire range of rotor speed very well.

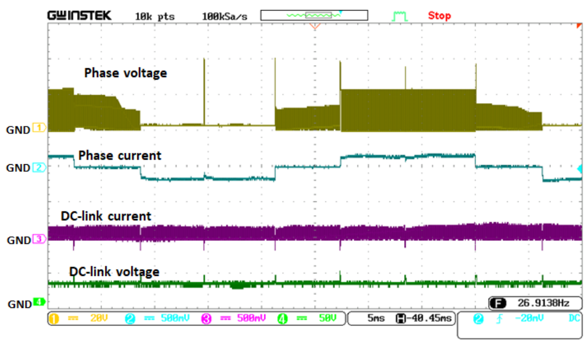
For investigating the reduction of current ripple and commutation period, some experiments were carried out with conventional method based on common technique of H-PWM_L-ON. Figure 12 shows experimental results where the PWM duty cycle is 0.3, 0.6, and 0.9, respectively. Tables 3 and 4 summarize extracted numerical information from Figures 9-12 for comparing the conventional method with the proposed method.

TABLE 3. Current ripple in conventional and proposed methods

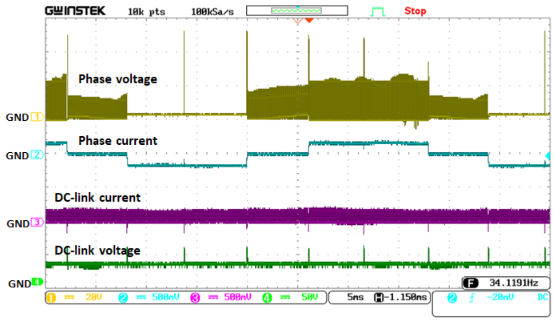
Duty Cycle (*d*) / Measured Current Ripple		30%	60%	90%
Proposed method	36V	≃20%	≃20%	≃20%
	48V	≃2%	≃2%	≃2%
	60V	≃30%	≃30%	≃30%
H-PWM_L-ON method		≃50%	≃50%	≃50%

TABLE 4. Commutation period in the proposed and conventional methods

Duty Cycle (*d*) / Measured Commutation Period	30%	60%	90%
Proposed method	≃60µs	≃90µs	≃120µs
H-PWM_L-ON method	≃300µs	≃300µs	≃300µs



(a)



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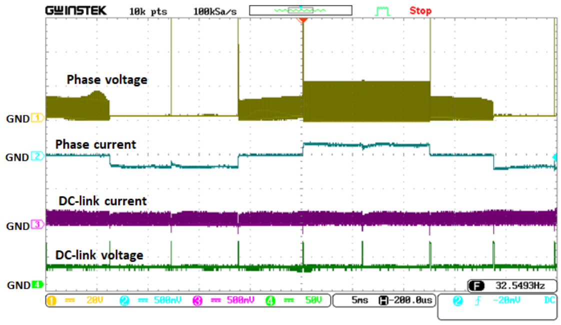
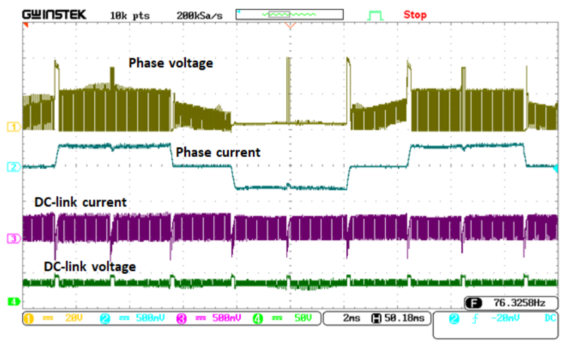


(c)

Figure 9. Experimental signals in the proposed method for 24V, d=0.3, and d_1=0.65, supply voltage source regulation in a) 36 volts, b) 48V, and c) 60V states. Each segment's signals from top to bottom, phase voltage, phase current, DC-link current and voltage, respectively



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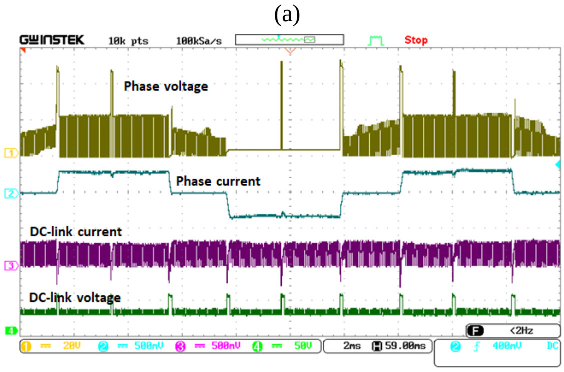

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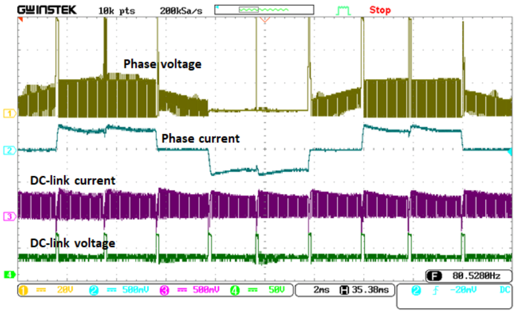
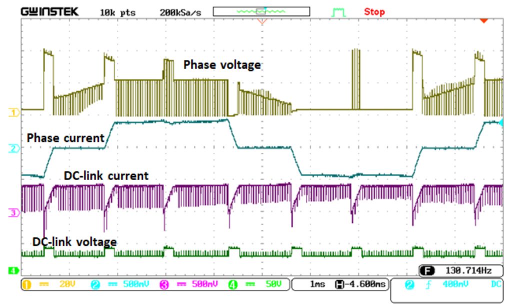
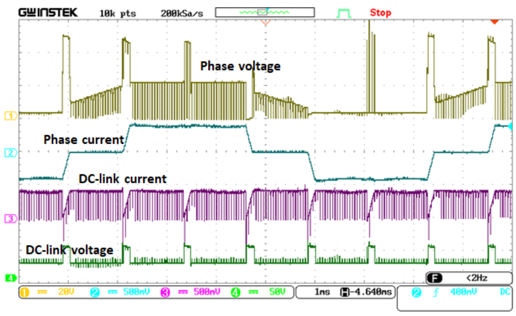


(c)

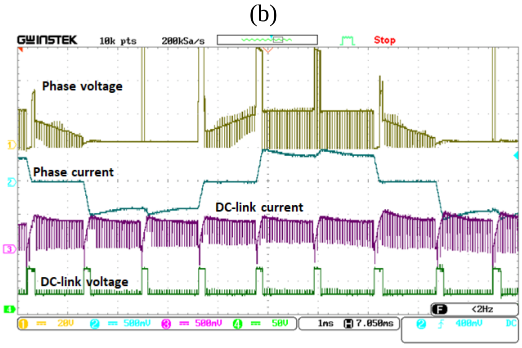
Figure 10. Experimental signals in the proposed method for 24V, *d*=0.6, and d_1=0.8, supply voltage source regulation in a) 36 volts, b) 48V, and c) 60V states. Each segment's signals from top to bottom, phase voltage, phase current, DC-link current and voltage, respectively



(a)



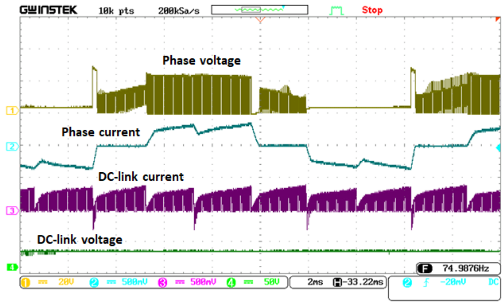
(b)



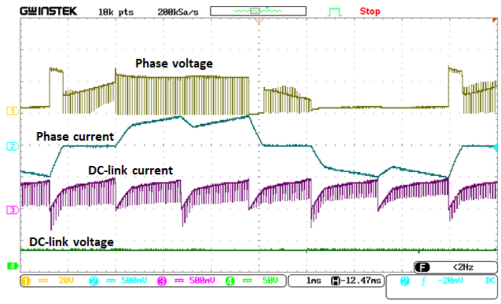
(c)

Figure 11. Experimental signals in the proposed method for 24 volts, *d*=0.9, and d_1=0.95, supply voltage source regulation in a) 36V, b) 48V, and c) 60V states. Each segment's signals from top to bottom, phase voltage, phase current, DC-link current and voltage, respectively

(a)



(b)



(c)

Figure 12. Experimental signals in the conventional method based on H-PWM_L-ON technique for 24V supply voltage in a) *d*=0.3, b) *d*=0.6 and c) *d*=0.9 states. Each segment's signals from top to bottom, phase voltage, phase current, DC-link current and voltage, respectively

5. CONCLUSION

Since mechanical vibration resulting from motor torque ripple in applications with high performance is undesirable, a new method for reduction of torque ripple is presented in this paper. The proposed method reduces commutation period. In addition to a two-segment PWM modulation, a voltage equal to twice of the voltage of main power supply in commutation time is applied to DC-link of drive system. Results of the experiments, showed that by deviation of DC-link voltage compared to the appropriate state (twice), the commutation current ripple magnitude increases. According to the theory and the results obtaining from the experiments, the method performs very well in entire range of rotor speed from the least amount to almost 100% rated speed of the motor.

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The Influence of DC-Link Voltage on Commutation Torque Ripple of Brushless DC Motors with Two-Segment Pulse-width Modulation Control Method

S. Gol, G. Ardeshir, M. Zahabi, A. Ale Ahmad

Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran

P A P E R I N F O

Paper history:
Received 07November 2017
Received in revised form 26November 2017
Accepted 30November 2017

Keywords:
Brushless DC Motors
Motor Drive System
Commutation Torque Ripple
Pulse-width Modulation
DC-link Voltage

چکیده

فرآیند کموتاسیون سبب پیدایش ضربان جریان در سامانه راه‌انداز موتور DC بدون جاروبک می‌شود. این به نوبه خود منجر به نوسان گشتاور خروجی می‌گردد. لرزش مکانیکی و نویز صوتی از آثار آن بوده که در برخی از کاربردها پدیده‌ای نامطلوب است. در این مقاله روش جدیدی ارائه می‌شود که ضربان گشتاور و مدّت‌زمان کموتاسیون را در کل محدوده سرعت موتور کاهش می‌دهد. این روش بر اساس مدولاسیون پهنای پالس دو قسمتی و دو برابر نمودن ولتاژ لینک DC در بازه کموتاسیون طراحی و پیاده‌سازی شده است. بر مبنای تئوری ارائه شده و با توجه به تاثیر ولتاژ تغذیه بر دامنه ضربان، آزمایشاتی انجام شد که مشارکت دو عامل مذکور بطور همزمان در کاهش ضربان جریان و مدّت‌زمان کموتاسیون در محدوده وسیع سرعت روتور اثبات شد. نتایج آزمایشات نشان داده است که دامنه ضربان جریان در محدوده سرعت زیاد تقریباً ۲۰ برابر کمتر از روش متداول مبتنی بر تکنیکH-PWM_L-ON می‌باشد.

***doi**: 10.5829/ije.2018.31.02b.15*