A Drive Strategy for Vibration Suppression in Permanent Magnet Brushless DC Motor

Tao Sun, Geun-Ho Lee, and Jung-Pyo Hong

Abstract— **This paper presents a drive strategy to suppress vibration of permanent magnet Brushless DC (BLDC) motor by reducing the torque ripple. Considering the practical Back Electromotive Force (Back-EMF) of BLDC Motor usually has unideal shape, this strategy divides the phase Back-EMF into four sections to handle respectively. In each section, the phase current is regulated by corresponding PWM duty-ratio to compensate the torque ripple caused by current commutation and unideal Back-EMF. Specially, owing to unideal Back-EMF, the conventional torque ripple estimation criterion during current commutation is valid no more. An improved criterion is proposed in this paper. A program based on this strategy has been implemented in MATLAB@Simulink. And the validity of the presented method is verified by it.**

Index Terms— **vibration suppression, torque ripple, BLDC, PWM.**

I. Introduction

PERMANENT Magnet Brushless DC (BLDC) Motors with trapezoidal shape Back Electromotive Force (Back-EMF) have been widely used in various fields such as industry robots, home appliances and medical treatments due to their high power density and high efficiency [1]. Currently, beside sensorless control to reduce drive cost, the main focus on BLDC motor drive is how to reduce the vibration to satisfy the requirement of precision manufacture and prolong motor life.

In theory, the Back-EMF of BLDC motor is 120^o (electrical angle) flat top trapezoidal shape. When a 120^o (electrical angle) wide rectangular shape current is fed during constant Back-EMF, the smooth torque can be produced. In practice, however, the commutation process may generate a current ripple in non-commutation phase. And in ideal Back-EMF case, it directly brings about a torque ripple that is the dominate source of motor vibration [2] [3]. Many solutions have been introduced to reduce this commutation current ripple. But the ideal Back-EMF usually is difficult to be designed and manufactured. In most case, the trapezoidal flat top of Back-EMF shape is shorter than 120^o as shown in fig. 1 (a).Depending on the conventional solutions, the generated torque ripple for this unideal Back-EMF is simulated and shown in fig. 1 (b). It is observed that the torque ripple may achieve about 30% of mean torque value, which means the conventional solutions are valid no more.

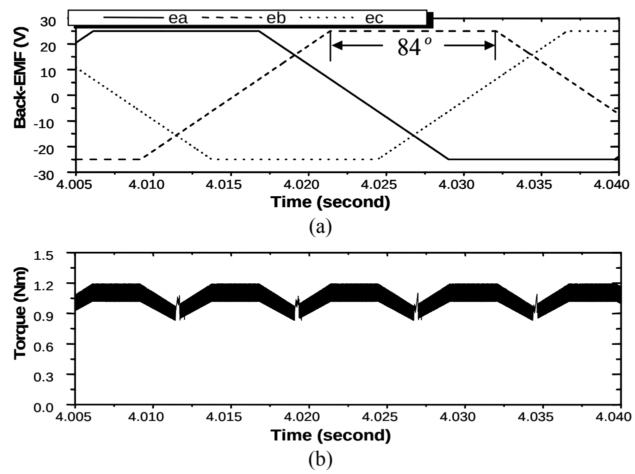


Fig. 1 (a) the unideal Back-EMF shapes with 84^o flat top; (b) the torque ripple using the conventional BLDC motor drive approach.

This paper presents a novel drive strategy to suppress vibration by reducing the torque ripple in the unideal Back-EMF BLDC motor. In this strategy, the Phase Back-EMF of every 60^o is divided into four sections: constant Back-EMF section, Back-EMF decreasing section, commutation section, and after commutation section. First, in the constant Back-EMF section, according to torque equation, a set-point constant torque value is determined. And then, in the other sections, the phase current is regulated by corresponding PWM duty-ratio to compensate the ripple of Back-EMF and maintain the set-point torque value. In commutation section, the conventional commutation torque ripple estimation equations are valid no more. An improved criterion is proposed in this section. Depending on it, the torque ripple state can be predicted easily.

As the above mentioned, the BLDC motor is driven by different duty-ratio PWM according to each Back-EMF section, which needs a simple speed controller. Due to the all drive sections are mainly determined by Back-EMF shape and rotor position, the robust performance is achieved. A program based on this drive strategy has been successfully implemented in MATLAB@Simulink. The validity of the presented method is verified by it.

Tao Sun is with the Department of Electrical Engineering, Changwon National University, Changwon, CO 641-773, Korea (e-mail: laplace_sun@hotmail.com)
Geun-Ho Lee is working in Namhea University, Namhea, Korea. (e-mail: lgh700@korea.com).
Jung-Pyo Hong is with the Department of Electrical Engineering, Changwon National University, Changwon, and CO 641-773, Korea. He is a Senior Member of IEEE. (e-mail: jphong@changwon.ac.kr).

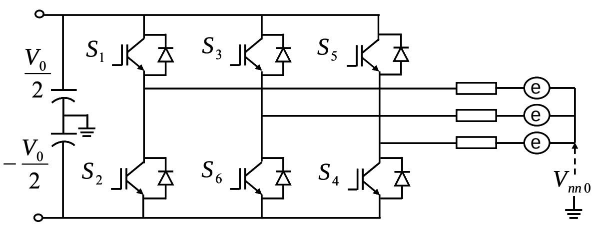


Fig. 2 the equivalent circuit of BLDC motor drive

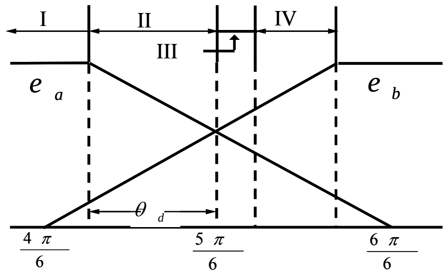


Fig. 3 the chosen part of Back-EMF and divided sections

II. The Torque Ripple Analysis and Proposed strategy

Assume 3-phase windings are "Y" connected, the permanent magnet is surface type, and the motor has a symmetrical structure. The equivalent circuit of a BLDC motor drive is shown in Fig. 2. The motor state equation is expressed as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} V_{nn_0} \\ V_{nn_0} \\ V_{nn_0} \end{bmatrix} \tag{1}$$

where the v_x is each phase voltage, i_x is each phase current, and e_x is each phase Back-EMF (where the x can means a,b or c). In addition, R, L and V_{nno} are phase resistance, phase inductance and neutral voltage, respectively. The electrical-to-mechanical energy convert equation is

$$T = \frac{1}{\omega}\left(e_a i_a + e_b i_b + e_c i_c\right) \tag{2}$$

where T and ω denote torque and angular velocity, respectively [1].

Owing to symmetry, an arbitrary section of 3-phase Back-EMF shown as Fig. 3 is chosen and analyzed. In the Fig. 3, the Back-EMF of phase c is ignored because of constant value. And the θ_d is the half short angle of Back-EMF flat top.

Where the I is constant Back-EMF section, the II is Back-EMF decreasing section, the III is commutation section, and the IV is after commutation section.

A. Constant Back-EMF Section

During this section, only two phases are excited. In steady state, the set-point current may be determined by (3). And depending on the parameter of Table 1, the PWM are set as 10k Hz and 4k Hz, respectively [4].

$$e_a i_a + e_c i_c = 2EI \tag{3}$$

B. Back-EMF Decreasing Section

As Fig. 3, the Back-EMF of phase a begins varying in this section. It is to lead the torque decreases if the phase a current is held. In order to compensate the varying of Back-EMF and hence maintain the torque, the current should be regulated properly. According to (3) and Back-EMF equation (4) and (5), the corresponding varying current may be found to be (6).

$$e_a = \frac{E(\pi - \theta)}{\pi/6 + \theta_d} \tag{4}$$

$$e_c = -E \tag{5}$$

$$\frac{di_{ar}}{dt} = \frac{2I\omega(\pi/6 + \theta_d)}{(7\pi/6 + \theta_d - \theta)^2} \tag{6}$$

Assume a complementary switching method is used to inverter operation. Owing to only two excited phases, the motor state equation is simplified as

$$\begin{aligned} \frac{V_0}{2} S_2 &= L\frac{di_a}{dt} + e_a + V_{nn_0} \\ -\frac{V_0}{2} S_2 &= L\frac{di_c}{dt} + e_c + V_{nn_0} \end{aligned} \tag{7}$$

The two states of varying current may be expressed as

$$\begin{aligned} \frac{di_a}{dt} &= \frac{V_0}{2L} - E\frac{(23\pi/6) - 4\theta - \theta_d}{3L(\pi/6 + \theta_d)} (S_2 = 1) \\ \frac{di_a}{dt} &= -\frac{V_0}{2L} - E\frac{(23\pi/6) - 4\theta - \theta_d}{3L(\pi/6 + \theta_d)} (S_2 = -1) \end{aligned} \tag{8}$$

By means of the State-Space Average Technique (SAT) [4], the PWM duty-ratio function to maintain current reference varying trend is worked out and expressed as

$$D_2 = \frac{2I\omega L(\pi/6 + \theta_d)}{V_0(7\pi/6 + \theta_d - \theta)^2} + \frac{E(23\pi/6 - 4\theta - \theta_d)}{3V_0(\pi/6 + \theta_d)} + \frac{1}{2} \tag{9}$$

C. Commutation Section

Exist of inductance makes current be not able to vanish or establish to set-point immediately. Therefore, during the commutation section, there is current in all 3 phases. At rated speed, the commutation duration is so short that the Back-EMF in this section could be regarded as constant. The Back-EMF equations are shown in

$$e_a = \frac{\pi E}{\pi + 6\theta_d} \tag{10}$$

$$e_a = \frac{\pi E}{\pi + 6\theta_d} \tag{11}$$

$$e_c = -E \tag{12}$$

The expected phase a current varying rate is expressed as

$$\frac{di_a}{dt} = -\frac{(V_0 + 2E)(\pi + 6\theta_d) + E\pi}{3L(\pi + 6\theta_d)} \quad (13)$$

In addition, if any phase is not operated by switch device during commutation, the natural establishing rate of phase b may be worked out by (14) and expressed as (15).

$$\begin{aligned} -\frac{V_0}{2} &= L\frac{di_a}{dt} + e_a + V_{nn_0} \\ \frac{V_0}{2} &= L\frac{di_b}{dt} + e_b + V_{nn_0} \\ -\frac{V_0}{2} &= L\frac{di_c}{dt} + e_c + V \end{aligned} \quad (14)$$

$$\frac{di_b}{dt} = \frac{(V_0 - E)(2\pi + 6\theta_d) + 6\theta_d V_0}{3L(\pi + 6\theta_d)} \quad (15)$$

1) Case I: If minus (13) equals to (15).

$$-\frac{di_a}{dt} = \frac{di_b}{dt} \quad (16)$$

The torque decreasing of phase a may be counteracted by the increasing of phase b and non-commutation phase, phase c, has not current ripple, i.e. the phase c torque is constant. An estimation equation is gotten by simplifying (16) and shown as

$$\frac{V_0}{E} = \frac{4\pi + 12\theta_d}{\pi + 6\theta_d} \quad (17)$$

2) Case II: If minus (13) is smaller than (15),

$$-\frac{di_a}{dt} < \frac{di_b}{dt} \quad (18)$$

This means the decreasing rate of phase a current is slower than the increasing rate of phase b current. Before phase a current vanishes, phase b current has been set-point value. According to KCL, the phase c current is increased suddenly as shown in Fig. 4 (a). An estimation equation is gotten by simplifying (18) and shown as

$$\frac{V_0}{E} > \frac{4\pi + 12\theta_d}{\pi + 6\theta_d} \quad (19)$$

In order to slow the increasing rate of phase b current, it prefers to switch it by PWM. The corresponding voltage equations are given by

$$\begin{aligned} -\frac{V_0}{2} &= L\frac{di_a}{dt} + e_a + V_{nn_0} \\ \frac{V_0}{2}S_{32} &= L\frac{di_b}{dt} + e_b + V_{nn_0} \\ -\frac{V_0}{2}S_{32} &= L\frac{di_c}{dt} + e_c + V_{nn_0} \end{aligned} \quad (20)$$

Also, by means of SAT, the PWM duty-ratio is found to be

$$D_{32} = \frac{2}{3} + \frac{4E(\pi + 3\theta_d)}{3V_0(\pi + 6\theta_d)} \quad (21)$$

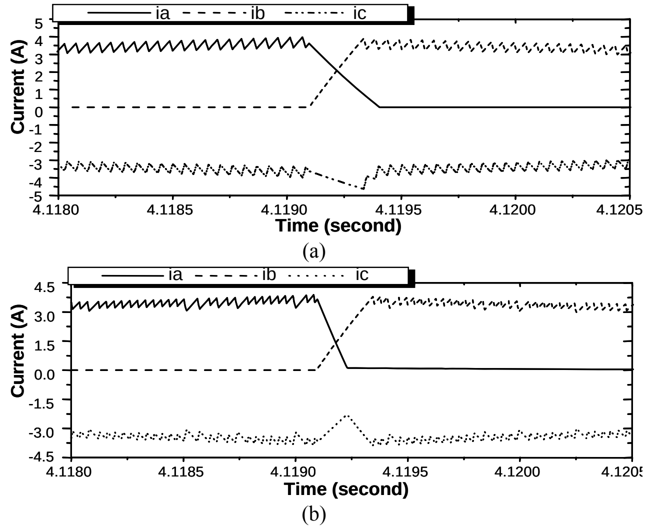


Fig. 4 (a) the current ripple of case II; (b) the current ripple of case III

3) *Case III:* If minus (13) is greater than (15),

$$-\frac{di_a}{dt} > \frac{di_b}{dt} \quad (22)$$

This means the decreasing rate of phase a current is faster than the increasing rate of phase b current. Before phase b current achieve set-point value, phase a has vanished. It leads that the phase c current is reduced as shown in Fig.4 (b). An estimation equation is gotten by simplifying (22) and shown as

$$\frac{V_0}{E} < \frac{4\pi + 12\theta_d}{\pi + 6\theta_d} \quad (23)$$

The solution is the same with case II. Nevertheless, the switching effect to neutral voltage may influence phase b current when phase a current is being regulated [5]. The neutral voltage equation in this case is

$$V_{nn_0} = -\frac{V_0 S_{33}}{6} - \frac{e_a + e_b + e_c}{3} \quad (24)$$

In different switch state, the current varying rates of phase a and b are

$$\begin{aligned} \frac{di_a}{dt} &= \frac{-V_0 - 2e_a + e_b + e_c}{3L}(S_{33} = 1) \\ \frac{di_a}{dt} &= \frac{V_0 - 2e_a + e_b + e_c}{3L}(S_{33} = -1) \end{aligned} \quad (25)$$

$$\begin{aligned} \frac{di_b}{dt} &= \frac{2V_0 - 2e_b + e_a + e_c}{3L}(S_{33} = 1) \\ \frac{di_b}{dt} &= \frac{V_0 - 2e_b + e_a + e_c}{3L}(S_{33} = -1) \end{aligned} \quad (26)$$

The PWM duty-ratio for case III is

$$D_{33} = 2 - \frac{2E(2\pi + 6\theta_d)}{V_0(\pi + 6\theta_d)} \quad (27)$$

D. *After Commutation Section*

After commutation, only phase b and phase c are excited, and the Back-EMF of phase b continues increasing. This is the similar condition with Back-EMF Decreasing Section. Hence, in the same method, the PWM duty-ratio is given by

$$D_4 = \frac{2I\omega L(\pi/6+\theta_d)}{V_0(\theta+\theta_d-\pi/2)^2} + E\frac{2\theta+\theta_d-(7\pi/6)}{3V_0(\pi/6+\theta_d)} + \frac{1}{2} \tag{28}$$

III. Simulation Results

Based on the proposed strategy, the topology of this BLDC motor simulation program is shown in Fig. 5. Specially, the PWM duty-ratio selector block is shown in Fig. 6. As the Back-EMF shape in Fig. 1 (a) and the parameters of Table I, the simulation results are shown in Fig. 7. The difference of Fig. 7 (a) and (b) is commutation section condition. The (a) is simulated for case II, while (b) is for case III.

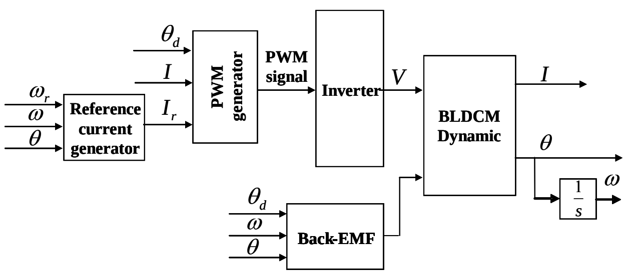


Fig. 5 the topology of simulation

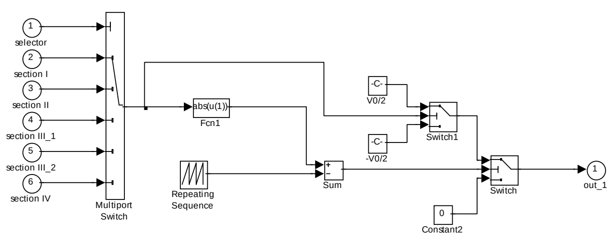
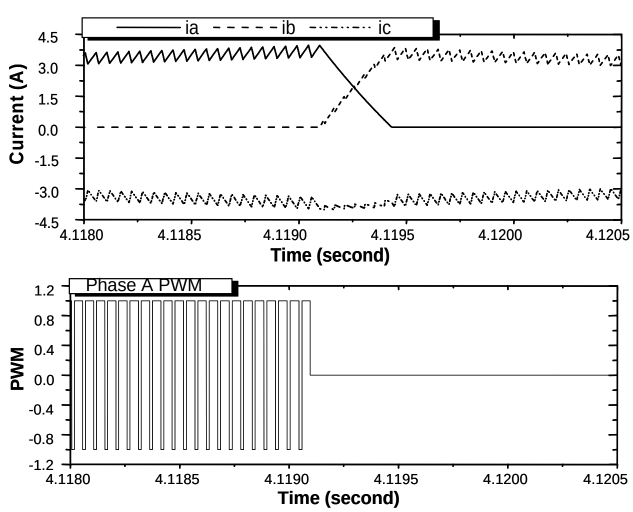
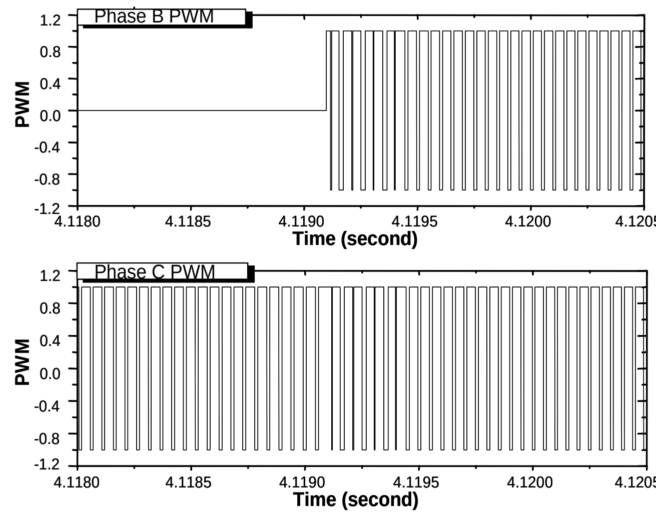
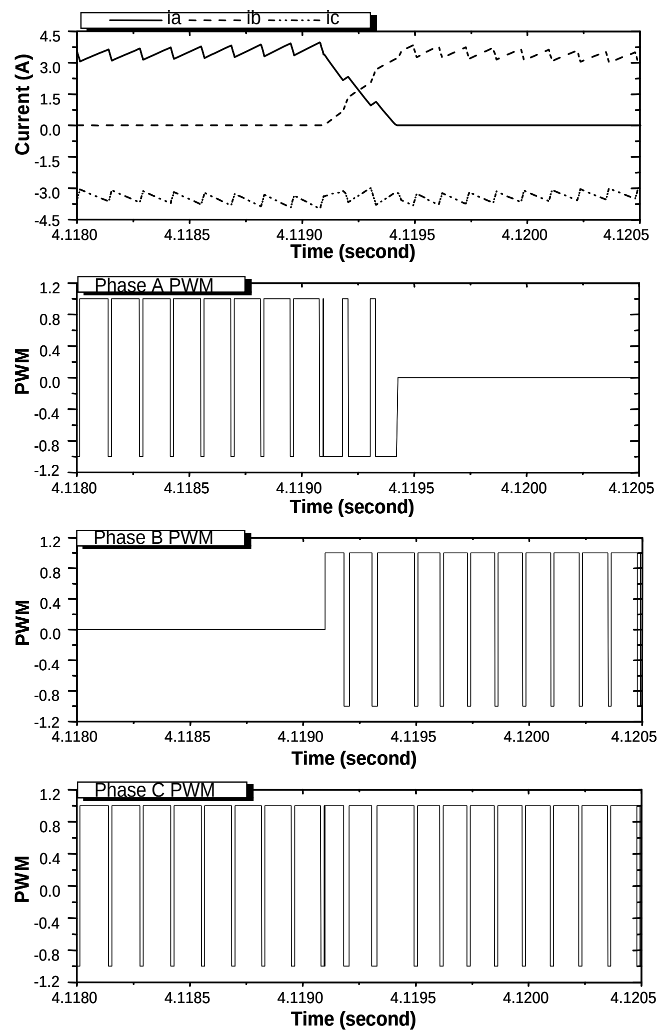


Fig. 6 the PWM duty-ratio selector block





(a)



(b)

Fig. 7 (a) the simulation results of case II; (b) the simulation results of case III

Fig. 8 (a) and (b) respectively are the current and torque results in case II.

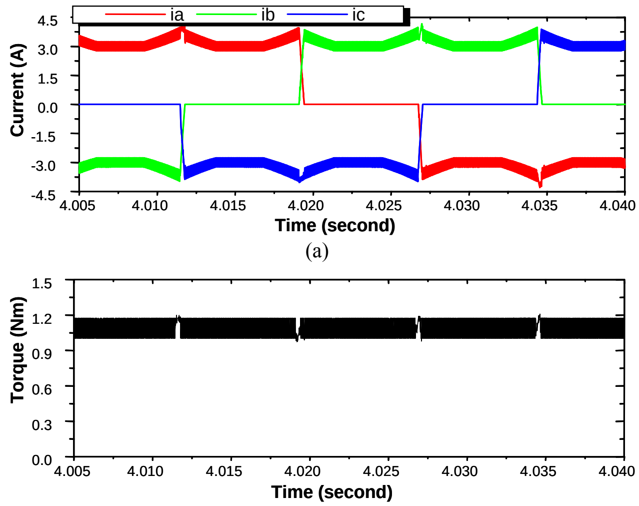


Fig.8 (a) the current shape of proposed strategy; (b) the improved torque

IV. Conclusion

In BLDC motor, both the unideal Back-EMF shape and the commutation current ripple may bring about torque ripple which is the dominate source of motor vibration. In order to suppress this vibration, many commutation current ripple reduction methods based on ideal Back-EMF shape have been presented. In practice, however, the unideal Back-EMF shape makes the conventional solutions valid no more. The torque ripple still achieves about 30% of mean torque value.

In this paper, a drive strategy which focuses on unideal Back-EMF is proposed. This strategy divides unideal Back-EMF into four sections. And according to different condition of these cases, current is regulated by varying PWM duty-ratio. Owing to the all drive sections are mainly determined by Back-EMF shape and rotor position, the robust performance is achieved. By means of this strategy, the torque ripple can be reduced to 10% of mean torque value. Subsequently upon it, the vibration of motor may be improved.

TABLE I
SPECIFICATIONS OF TSRM

Parameters	Values	
Phase Inductance	3.05	mH
Phase Resistance	0.75	Ohm
Rated Speed	1300	RPM
DC-Link Voltage in case II	80	V
DC-Link Voltage in case III	110	V
Back-EMF of case II (in rated speed)	30	V
Back-EMF of case III (in rated speed)	25	V

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