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Novel PWM Method with Low Ripple Current for Position Control Applications of BLDC Motors

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Abstract

BLDC Motors are widely used in various speed control applications due to their ease of control and low cost. Generally, the unipolar PWM method is used for speed control applications. However, the unipolar PWM method has a current spike problem in the braking operation which can be a problem in speed reversal which generally happens in position control applications. However, the current spike problem can be solved by the conventional bipolar PWM method. Although the current spike problem can be solved, the conventional bipolar PWM method has the problem of a large current ripple. In this paper, a novel bipolar PWM method is proposed to solve this problem. The current ripple and the current spike problems are analyzed in this paper for the unipolar and bipolar PWM methods. At last, the merits of the proposed bipolar PWM method are proven by experiment.

Key Words: Bipolar PWM, Brushless DC motor (BLDC motor), PWM method, Unipolar PWM

I. INTRODUCTION

Recently, the brushless DC (BLDC) motor and the permanent magnet synchronous motor (PMSM) have been receiving a great deal of attention because of their inherent advantages of high power density, high efficiency, a large torque to inertia ratio, high starting torque, free maintenance, and ease of control [1]. Generally, a BLDC motor has a trapezoidal electro motive force (EMF) waveform, so the current waveform of a BLDC motor has a square waveform to reduce torque ripple [2]. Therefore, a BLDC motor controller requires a low resolution position sensor and only one current sensor. On the other hand, since a permanent magnet synchronous motor (PMSM) has a sinusoidal EMF waveform, the current waveform of a PMSM must be sinusoidal. As a result, a PMSM requires an expensive high resolution position sensor such as an absolutely encoder and resolver. Therefore, a BLDC motor is generally used for low-cost applications due to its ease of control, and its low cost position and current sensors [3].

On the other hand, a BLDC motor's electrical attribute is similar to a DC motor, so a BLDC motor's pulse width modulation (PWM) method is similar to the PWM method of a DC Motor. The only difference is the commutation. The commutation of a BLDC motor is electrically achieved by a 3 phase inverter, while the commutation of a DC motor is carried out by a mechanical brush and commutator. There have been several studies on PWM methods for BLDC motors [2], [4]–[7]. In the PWM control of a BLDC motor, generally, the unipolar PWM method is used as a DC motor uses the unipolar PWM method for the chopping control in which only one switch is On and Off controlled by PWM among the selected two switches, while the other switch is in the On-state continuously. In general, four unipolar PWM methods are used for controlling a BLDC motor, and the unipolar PWM methods are distinguished by the selection of the PWM switch among the 2 On-state switches [2], [4]–[7]. Most of the studies on PWM methods are related to commutation torque ripple minimization under the freewheeling interval. On the other hand, there is an interesting report on a PWM method for electromechanical actuators [8]. In that paper, it has been reported that there is a current spike problem in the period of speed reversal of the unipolar PWM method. It has also been reported that this bipolar PWM method, in which the active selected two switches by commutation are on and off controlled by the PWM at the same time, can control the motor current effectively during the period of speed reversal. However, an analysis of the current spike of the unipolar PWM method was not reported in that paper. Also, the reason why the bipolar PWM method does not have a current spike problem was not reported. However, although the current spike problem has been solved by the bipolar PWM, the symptoms of a large current ripple can be made by the bipolar PWM. Therefore, the torque ripple and the acoustic noise are remarkably increased, and the motor efficiency is reduced by the increased motor core loss of the bipolar PWM method.

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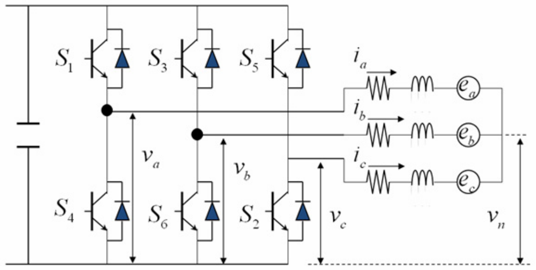


Fig. 1. Equivalent circuit of BLDC motor.

In this paper, the reason why the current spike problem of unipolar PWM happens in the braking operation, in which the direction of the motor speed command and the direction of the real speed are opposite, is analyzed. In addition, a novel bipolar PWM method is proposed so that the motor current can be controlled in the braking operation and the current ripple in the motoring mode can be reduced as much as the current of the unipolar PWM. To analyze the current spike problem, the unipolar PWM method is explained and a mathematical model of the unipolar PWM is described in section 2. In section 3, the proposed new bipolar PWM method is explained. In section 4, experimental results are shown for the unipolar PWM method, the conventional bipolar PWM method, and the proposed bipolar PWM method. From the experimental results, the merits of small current ripples without the current spike problem of the proposed bipolar PWM method are proven.

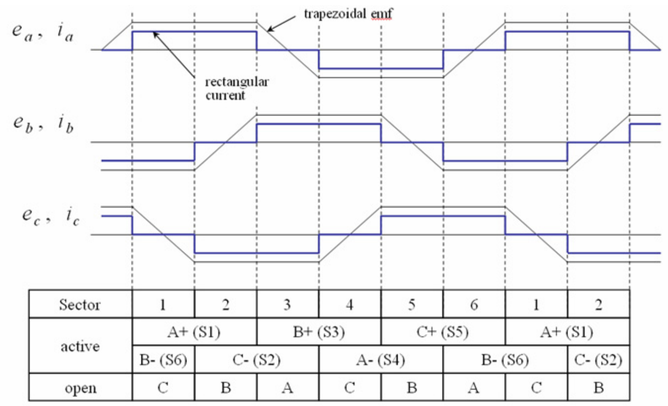
II. MATHEMATICAL MODEL OF PWM METHODS FOR BLDC MOTOR

Generally, a BLDC Motor has 3 phase stator windings. These windings can be modeled as stator resistance, inductance, and electromotive force (EMF). An equivalent circuit of a BLDC motor is shown in Fig. 1 and the phase current and EMF shapes for a BLDC motor are shown in Fig. 2. As shown in Fig. 2, the EMF of a BLDC motor has a trapezoidal waveform and the current has a rectangular waveform. In every moment, 2 phases of the motor are active phases which means that the gate drive signals are applied to these phases, and the other phase is an inactive phase which means that the gate drive signal is not applied to this phase. The freewheeling current by electrical commutation appears for this inactive phase after the turn-off commutation.

A. Mathematical model of unipolar PWM

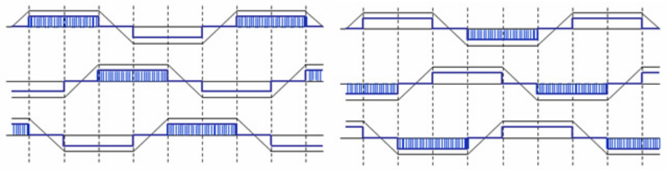
To control of the voltage of the active phases, a PWM signal is applied to a BLDC motor. In general, unipolar PWM methods are used for the motoring operation of a BLDC motor [5], [6]. Unipolar PWM means that one switch of the active phase is in the PWM mode, while the other switch of the other active phase is turned on continuously. Generally there are 4 types of PWM modes as shown in Fig. 3 [6]. In general, the current dynamics of a commutation period can be changed by the selection of PWM methods [5], [6].

In Fig. 4, the switching states for sector 1 are shown for the PWM on and off periods, respectively. In this figure, sector 1

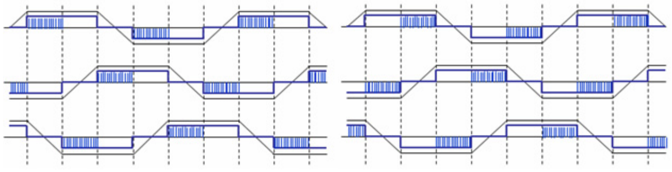


Sector	1	2	3	4	5	6	1	2
active	A+ (S1)		B+ (S3)		C+ (S5)		A+ (S1)	
	B- (S6)	C- (S2)		A- (S4)		B- (S6)		C- (S2)
open	C	B	A	C	B	A	C	B

Fig. 2. EMF and Phase Current of BLDC motor of motoring.

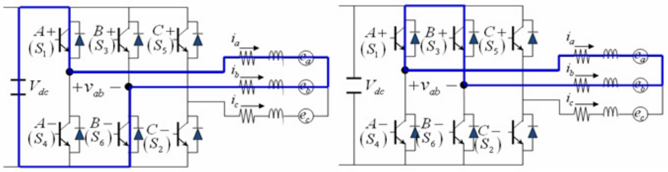


(a) H_PWM-L_On. (b) H_On-L_PWM.



(c) PWM-On. (d) On-PWM.

Fig. 3. Unipolar PWM patterns for BLDC motor operation[5], [6].



(a) PWM on state. (b) PWM off state.

Fig. 4. Switching states of motoring operation for PWM On and off cases on sector 1.

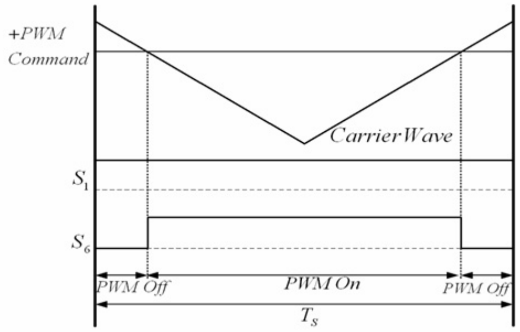


Fig. 5. Implementation for Unipolar PWM using Carrier Comparison.

means that the A+ and B- switches are the active switches of the active phases, as can be shown in Fig. 2. In the case of Fig. 4, it is assumed that the A+ switch is turned on continuously and that the B- switch is in the PWM mode. Therefore, the B- switch is in the off state during the PWM off period. The implementation of the unipolar PWM method using the carrier comparison method is shown in Fig. 5. In this method, the PWM command is compared with the PWM carrier signal, and the switching function S_1 of the A+ switch and the switching function S_6 of the B- switch are determined. Since the A+ switch is in the on state continuously, the positive line to line voltage, v_{ab}, can be applied to the motor for any value of the PWM command.

The current dynamics of unipolar PWM can be calculated from the equivalent circuit of Fig. 1. In the operation shown in Fig. 4, if it is assumed that the current of the inactive C phase is zero after electrical commutation, then the voltage equation can be written as:

$$\begin{bmatrix} V_{dc} \\ (1-S_6)V_{dc} \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \end{bmatrix} + \begin{bmatrix} v_n \\ v_n \end{bmatrix}. \tag{1}$$

In this equation, S_6 is the switching function for the B- switch. S_6 = 1 means that the B- switch is in the on-state and the B+ switch is in the off-state. S_6 = 0 means that the B- switch is in the off-state and the B+ switch is in the on-state by the freewheeling diode. In this equation, the saturation voltage of switch is assumed to be zero.

In sector 1 of the motoring mode of the BLDC motor, which is shown in Fig. 2, the phase currents and the EMF can be expressed as:

$$i_a \geq 0, e_a \geq 0, i_b \leq 0, e_b \leq 0. \tag{2}$$

The phase currents in this sector can be written as:

$$i_a + i_b = 0, i_c = 0. \tag{3}$$

The current dynamics of the A phase can be calculated from equation (1) by subtraction of the second row from the first row and $i_b = -i_a$. The current dynamics can be expressed as:

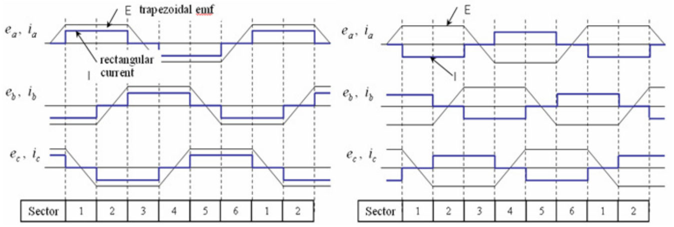
$$S_6 V_{dc} = 2Ri_a + 2L\frac{di_a}{dt} + e_a - e_b. \tag{4}$$

In sector 1, the EMF is constant as can be seen in Fig. 2. As a result, $e_a = E$, $e_b = -E$. Therefore, the current dynamics of the PWM On period and the PWM Off period can be written as follows:

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

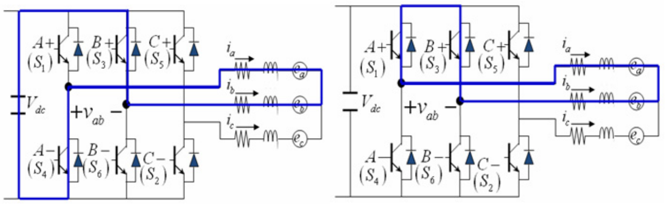
$$L\frac{di_a}{dt} = -Ri_a - E. \tag{6}$$

In the PWM On period, the a phase current is increased because right side of equation (5) is positive. In the PWM off period, the a phase current is decreased because right side of equation (6) is negative. Therefore, the current can be controlled by the unipolar PWM method in the motoring operation.



(a) Motoring operation. (b) Braking operation.

Fig. 6. Motor current and EMF at motoring and braking operation.



(a) PWM on state. (b) PWM off state.

Fig. 7. Switching states of braking operation for PWM On and off cases on sector 1.

Although unipolar PWM can control a BLDC motor in the motoring mode, the current cannot be easily controlled in the braking operation mode [8]. Fig. 6 presents the ideal current and the EMF in the motoring operation and in the braking operation modes, respectively. The difference between the two modes is the current phase angle difference between the current and the EMF, as shown in Fig. 6.

In Fig. 7, the switching states of the unipolar PWM for the braking operation of sector 1 are shown for the PWM on and off periods, respectively. The line to line voltage, v_{ab}, for sector 1 is a negative value for the braking operation. Implementation of the unipolar PWM using the carrier comparison method for a negative voltage is shown in Fig. 8. To generate a negative voltage for the braking operation, the switching devices B+ and A- are selected. It is assumed that the switch A- is in the PWM mode and that B+ is turned on continuously for calculation of the current dynamics.

In section 1 of the braking mode, the voltage equation can be written as follows if it is assumed that the inactive phase current is zero:

$$\begin{bmatrix} (1-S_4)V_{dc} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \end{bmatrix} + \begin{bmatrix} v_n \\ v_n \end{bmatrix}. \tag{7}$$

In equation (7), S_4 is the switching function for the A- switch. In the braking mode, the phase currents and the EMF, as shown in Fig. 6, can be expressed as follows:

$$i_b \geq 0, e_b \leq 0, i_a \leq 0, e_a \geq 0. \tag{8}$$

To calculate the a phase current dynamics, the current derivative equation can be calculated from equation (7) by subtracting the second row from the first row. The current dynamics can be expressed as follows in the braking mode:

$$-S_4 V_{dc} = 2Ri_a + 2L\frac{di_a}{dt} + e_a - e_b. \tag{9}$$

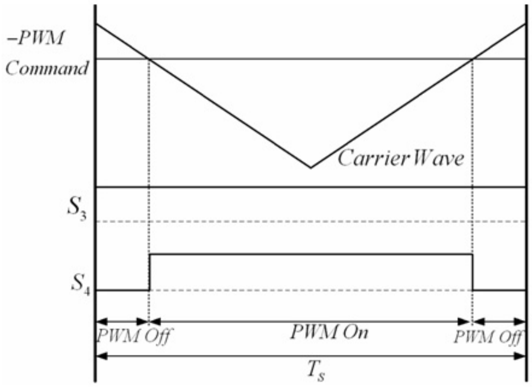
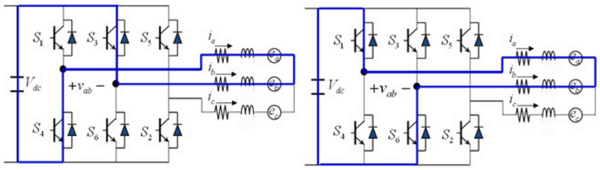


Fig. 8. Implementation for unipolar PWM for braking operation.



(a) –PWM. (b) +PWM.

Fig. 9. Switching states of braking operation. for bipolar PWM On sector 1.

Because $e_a = E$, $e_b = -E$ in sector 1, the current dynamics of the PWM on period and off period can be written as follows:

$$L\frac{di_a}{dt} = -\frac{V_{dc}}{2} - Ri_a - E \tag{10}$$

$$L\frac{di_a}{dt} = -Ri_a - E, \tag{11}$$

where S_4 = 1 in the PWM on period and S_4 = 0 in the PWM off period. Since right side of equation (10) is a large negative value and the phase a current is also negative, the absolute value of the phase a current is increased to a large negative value rapidly in the PWM on period. Furthermore, in the PWM Off period the absolute value of the phase absolute value of the a phase current is also increased to a negative value because the right side of equation (11) is negative. Therefore, the current cannot be controlled by the unipolar PWM method in the braking operation and can cause a current spike. This current spike is not good for the system reliability [8]. To control the current, the PWM mode must be changed from the braking mode (in which the current dynamics are shown in equation (10) and (11)) to the motoring mode (in which the current dynamics are shown in equation (5) and (6)) in a very short period. However, this method complicates the implementation of the PWM method. To overcome this problem, the bipolar PWM method has been proposed [8].

B. Mathematical model of bipolar PWM

In bipolar PWM operation, the two active switches are simultaneously on and off. In the braking operation of bipolar PWM, the switching states of sector 1 are represented in Fig. 9 and the voltage equations are written as follows, if it is assumed that the inactive phase current is zero:

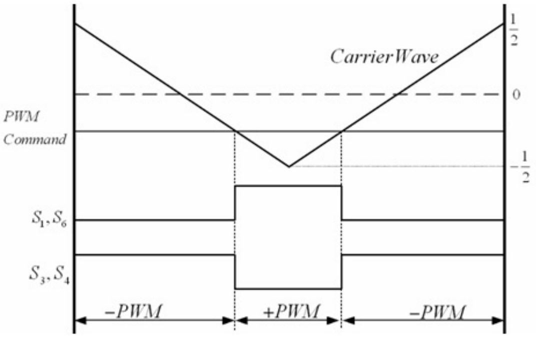


Fig. 10. Implementation for bipolar PWM using carrier comparison.

$$\begin{bmatrix}(1-S_4)V_{dc}\\ S_3V_{dc}\end{bmatrix} = \begin{bmatrix}R & 0\\ 0 & R\end{bmatrix}\begin{bmatrix}i_a\\ i_b\end{bmatrix} + \begin{bmatrix}L & 0\\ 0 & L\end{bmatrix}\frac{d}{dt}\begin{bmatrix}i_a\\ i_b\end{bmatrix} + \begin{bmatrix}e_a\\ e_b\end{bmatrix} + \begin{bmatrix}v_n\\ v_n\end{bmatrix}. \tag{12}$$

In Fig. 10, the implementation of the bipolar PWM method using the carrier comparison method is shown. When the PWM command is less than the carrier wave, the PWM state becomes the –PWM mode and the switching functions are S_3 = S_4 = 1. In this situation, the line to line voltage, v_{ab}, becomes $-V_{dc}$. When the PWM command is larger than the carrier wave, the PWM state becomes the +PWM mode and the switching functions are S_1 = S_6 = 1. In this situation, the line to line voltage, v_{ab}, becomes V_{dc}. When the PWM command is larger than zero, the average line to line voltage in the PWM period, $< v_{ab} >$, is positive which means the motoring mode. If the PWM command is less than zero, the average line to line voltage in the PWM period, $<v_{ab}>$, becomes a negative value which means the braking mode. Unlike unipolar PWM, the bipolar PWM method can easily produce a negative voltage or a positive voltage without a change of the selective switching device. Therefore, this PWM method is proposed for the position control of a BLDC motor as an actuator in which the direction of the speed command can be changed from positive to negative or vice versa [8].

The current dynamics in the braking mode in sector 1 can be expressed as:

$$(1 - S_3 - S_4)V_{dc} = 2Ri_a + 2L\frac{di_a}{dt} + e_a - e_b. \tag{13}$$

Because $e_a = E$, $e_b = -E$ in sector 1, the current dynamics of the PWM on period and the PWM off period can be represented as follows:

$$L\frac{di_a}{dt} = -\frac{V_{dc}}{2} - Ri_a - E \tag{14}$$

$$L\frac{di_a}{dt} = \frac{V_{dc}}{2} - Ri_a - E. \tag{15}$$

The current dynamics of the -PWM period are same as those of the PWM On period of the braking control by the unipolar PWM in equation (10). However, the current dynamics of the +PWM period differ from equation (11), which is the PWM off period of the braking control. The right side of equation (15) is positive and the A phase current is negative, so that the absolute value of the current during the + PWM

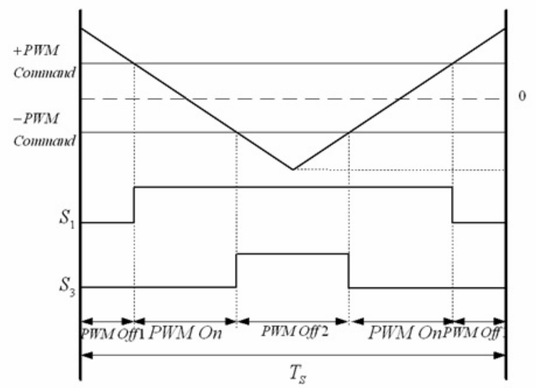
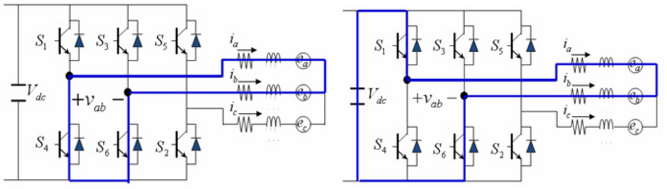
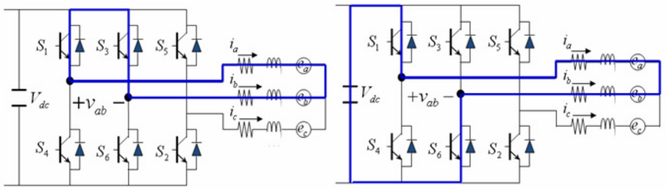


Fig. 11. Proposed new unified bipolar PWM method for BLDC motoring drive in motoring operation.



(a) PWM off 1. (b) PWM on.



(c) PWM off 2. (d) PWM on.

Fig. 12. switching states of proposed bipolar PWM on sector 1 of positive PWM command in motoring operation.

period can be decreased to zero. Therefore, the current can be controlled in the braking operation by the bipolar PWM method. Furthermore, when the control mode is changed to the motoring mode, the PWM command becomes a positive value and a positive voltage can be easily produced without changing the selected switching device. For this reason, the bipolar PWM method must be used for the position control operation.

Even though the bipolar PWM method has the merits of easily producing a positive and negative voltage and easy control of the current dynamics in the braking operation, the current ripple of bipolar PWM in the motoring mode is larger than that of the unipolar PWM method. The voltage equation for bipolar PWM in the motoring mode can be written as:

$$\begin{bmatrix} S_1V_{dc} \\ (1-S_6)V_{dc} \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \end{bmatrix} + \begin{bmatrix} v_n \\ v_n \end{bmatrix}. \tag{16}$$

The current dynamics can be calculated by subtracting the second row from the first row. The current dynamics can be expressed as:

$$(S_1+S_6-1)V_{dc} = 2Ri_a + 2L\frac{di_a}{dt} + e_a - e_b. \tag{17}$$

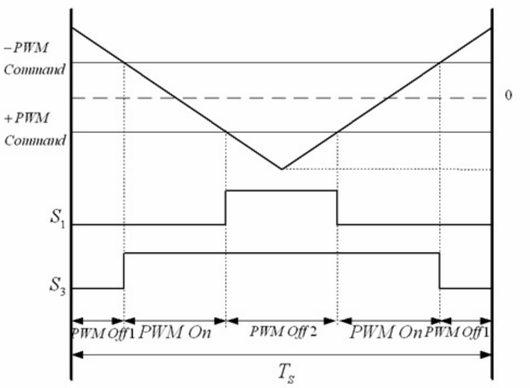
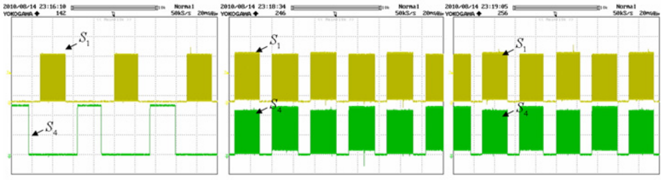


Fig. 13. Proposed new unified bipolar PWM method for BLDC braking drive.



(a) Unipolar PWM. (b) Bipolar PWM. (c) Proposed PWM.

Fig. 14. Switching functions S_1 and S_4 by the different PWM method.

The current dynamics of the +PWM period where $S_1 = S_6 = 1$ and the –PWM period where $S_1 = S_6 = 0$ can be written as follows:

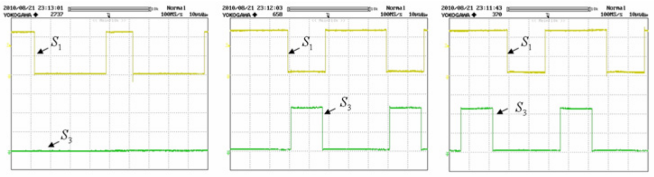
$$L\frac{di_a}{dt} = \frac{V_{dc}}{2} - Ri_a - E \tag{18}$$

$$L\frac{di_a}{dt} = -\frac{V_{dc}}{2} - Ri_a - E. \tag{19}$$

Comparing current dynamics of the PWM Off period of bipolar PWM to that of unipolar PWM, the right hand side of equation (19) for bipolar PWM has a larger negative value than that of equation (6) for unipolar PWM. For this reason, a higher current ripple can be predicted for the bipolar PWM method than for the unipolar PWM method in the motoring operation..

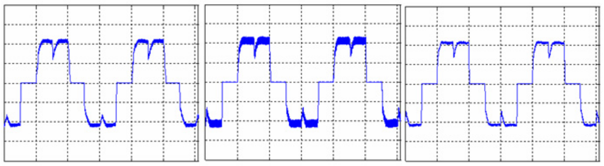
III. PROPOSED LOW RIPPLE BIPOLAR PWM

To overcome this large current ripple problem of bipolar PWM in the motoring operation, a new bipolar PWM method is proposed for BLDC motor control. The proposed method is shown in Fig. 11. When the PWM command is given by the current or speed controller in sector 1, the +PWM command is imposed on the A phase pole voltage and the –PWM command is imposed on the B phase pole voltage. The +PWM command is equal to the PWM command and the –PWM command is calculated from the –PWM with the same absolute value but negative. The +PWM value can be a positive value or a negative value depending on the state of the current or speed controller. When the +PWM command is larger than the carrier wave in sector 1, the switching functions are $S_1 = 1$, $S_4 = 0$. If the +PWM command is less than the carrier wave, the switching functions are $S_1 = 0$, $S_4 = 1$. When the –PWM command is larger than the carrier wave in sector 1, the switching functions are $S_3 = 1$, $S_6 = 0$. If the –PWM command is less than the carrier wave, the switching functions are $S_3 = 0$, $S_6 = 1$. The switching states for the new bipolar PWM



(a) Unipolar PWM. (b) Bipolar PWM. (c) Proposed PWM.

Fig. 15. Enlarged switching functions S_1 and S_4 by the different PWM method.



(a) Unipolar PWM. (b) Bipolar PWM. (c) Proposed PWM.

Fig. 16. Current waveform comparison by PWM methods by simulation.

method when the PWM command is positive are shown in Fig. 12.

The voltage equation for the proposed bipolar PWM can be written as:

$$\begin{bmatrix} S_1V_{dc} \\ S_3V_{dc} \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \end{bmatrix} + \begin{bmatrix} v_n \\ v_n \end{bmatrix}. \tag{20}$$

The current dynamics can be calculated by subtraction the second row from the first row. The current dynamics can be expressed as:

$$(S_1 - S_3)V_{dc} = 2Ri_a + 2L\frac{di_a}{dt} + e_a - e_b. \tag{21}$$

In the PWM on mode of sector 1 of Fig. 12, $S_1 = 1$, $S_3 = 0$. Therefore, the current dynamics can be written as:

$$L\frac{di_a}{dt} = \frac{V_{dc}}{2} - Ri_a - E. \tag{22}$$

During the PWM off 1 mode, $S_1 = 0$, $S_3 = 0$, and during the PWM off 2 mode, $S_1 = 1$, $S_3 = 1$. In both cases, the current dynamics can be written as:

$$L\frac{di_a}{dt} = -Ri_a - E. \tag{23}$$

Although, both switches carry out the PWM operation of the proposed PWM method, the current dynamics of equations (22) and (23) are equal to equations (10) and (11) which are the current dynamics of the unipolar PWM method. The only difference with the unipolar PWM is that the PWM On event and the PWM Off event happen twice in one PWM frequency, T_S. Therefore, the effective switching period becomes doubled in the proposed method.

When the *a* phase PWM command is negative, the PWM operation is as shown in Fig. 13. Since the *a* phase PWM command is a negative value, the BLDC motor operation mode is the braking mode. As can be seen in Fig. 13, the switching function of the PWM On mode is $S_1 = 0$, $S_3 = 1$. Therefore, the current dynamics can be written from (21) as follows:

$$L\frac{di_a}{dt} = -\frac{V_{dc}}{2} - Ri_a - E \tag{24}$$

TABLE I
SPECIFICATIONS OF BLDC MOTOR

Parameters	Value
Number of Poles	6
Stator resistance @ 70°C	0.023Ω
Inductance	68μH
Back EMF constant	0.0109Vsec

During the PWM Off mode 1, $S_1 = 0$, $S_3 = 0$, and during the PWM Off mode 2, $S_1 = 1$, $S_3 = 1$. As a result, the current dynamics can be written as:

$$L\frac{di_a}{dt} = -Ri_a - E. \tag{25}$$

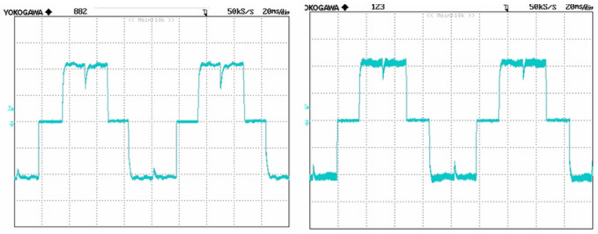
Therefore, the current cannot be controlled by the proposed bipolar PWM method in the braking operation mode only. However, the current can be controlled by the combined braking and motoring operations, because a positive and negative voltage can be easily produced by the proposed method. When the current error between the current command and the real current becomes a negative value, the current controller for the BLDC motor produces a positive voltage command. When the current error becomes a positive value, the current controller produces a negative voltage command. In this application, a proportional controller must be used instead of a proportional-integral (PI) current controller.

IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the merits of the proposed bipolar PWM method, simulations and experiments for the three different PWM methods are carried out. The PWM methods compared are the unipolar PWM, the bipolar PWM, and the proposed bipolar PWM. Fig. 14 shows the switching functions of the compared PWM methods. Figure (a) in Fig. 14 shows the switching function for S_1 and S_4 of the upper switch PWM in Fig. 14. In this figure, the switching function S_1 for A+ is in the PWM mode, but the switching function S_4 is continuously on when the switch is selected by commutation logic. The figures (b) and (c) in Fig. 14 show the switching functions of the bipolar PWM and the proposed bipolar PWM, respectively. The switching functions S_1 and S_4 are both in the PWM mode, simultaneously. In Fig. 15, the switching function of A+, S_1, and the switching function of B+, S_3, by the various PWM methods are shown, respectively. As can be seen from Fig. 15, the switching function of S_3 of the unipolar PWM is continuously in the off state regardless of the state of the switching function of S_1. The switching function of S_3 of the conventional bipolar PWM is a logical inverting of S_1 including dead time because S_4 is equal to S_1. However, the switching function S_3 becomes either a high or low value by the PWM command and the period of the high state is equal to the period of the low state of the switching function of S_1, as can be seen in Fig. 11.

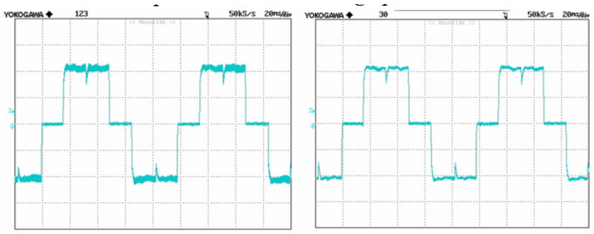
The current ripple is compared depending on the PWM mode by simulations and experiments. For these simulations and experiments, the parameters of the BLDC motor used are listed in Table I.

Fig. 16 shows the simulation current waveforms of the BLDC motor with the different PWM methods. As can be seen in this figure, the current ripple of the conventional PWM



(a) Unipolar PWM. (b) Bipolar PWM.

Fig. 17. Current ripple comparison between the unipolar and bipolar PWM in motoring operation.



(a) Bipolar PWM. (b) Proposed PWM.

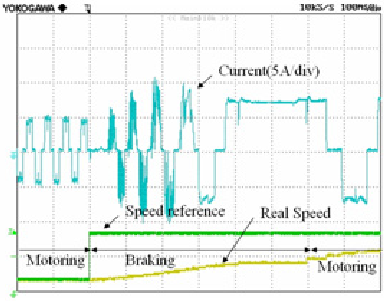
Fig. 18. Current ripple comparison between the bipolar PWM in motoring operation.

method is larger than that that of the unipolar PWM method. However, the proposed bipolar PWM method has low ripples, as much as compared with the conventional bipolar PWM method.

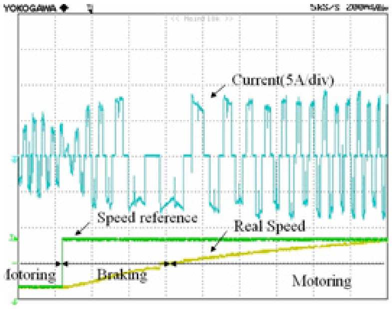
Fig. 17 shows the current of the BLDC motor for each of the different PWM methods. The left side figure shows the current waveform of the unipolar PWM and the right side figure shows the current waveform of the conventional bipolar PWM in the motoring operation. As can be seen in this figure, the current ripple of the unipolar PWM method is smaller than that of the bipolar PWM method.

To compare the current ripples of the conventional bipolar and the propose bipolar PWM methods, Fig. 18 shows the current ripple of the BLDC motor for the bipolar PWM and the proposed bipolar PWM methods. The left side figure shows the current waveform of the conventional bipolar PWM and the right side figure shows the current waveform of the proposed bipolar PWM. In this figure, it can be seen that the proposed method has a very small current ripple. Generally, acoustic noise is proportional to the current ripple. Therefore, acoustic noise can be reduced by the proposed PWM method. Also, the motor eddy current and hysteresis losses can be reduced by the proposed PWM method.

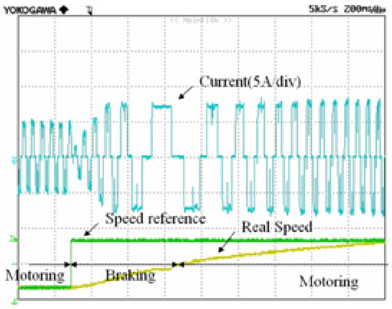
To compare the performance of the speed reversal, the speed reference and the current waveforms are shown in Fig. 19. The unipolar PWM is used in Fig. 19(a), the conventional bipolar PWM is used in Fig. 19(b), and the proposed bipolar PWM is used in Fig. 19(c). All of the experimental waveforms are saved in following steps. In the first step, the BLDC motor is operated at 600rpm in the forward direction. At that time, the speed reference is also 600rpm in the forward direction and the motor is operated in the motoring mode. In the next step, the speed reference is changed to 600 rpm in the reverse direction. In this period, the direction of the motor speed reference and the direction of the real speed are opposite. For this reason, the motor operation mode is the braking operation. After the motor speed becomes zero, the directions of the speed reference and the real speed are the same. Therefore, the operating mode of the BLDC motor becomes the motoring mode. In this experiment, a current controller is used and the maximum current is limited to 7A. A PI speed controller is used. Since a PI speed controller is used, the current command is a small value at the moment the speed reference is changed. However, the current command is increased by the integral action of the PI speed controller.



(a) Unipolar PWM.



(b) Bipolar PWM.



(c) Proposed PWM.

Fig. 19. Current waveform comparison of the time of speed reversal.

In the unipolar PWM method, the current is regulated by the current controller in the motoring mode, as can be seen in Fig. 19(a). However, the current ripple is very high and the current can not be regulated in the braking mode, because the current is larger than 7A in some instants. In the conventional bipolar PWM method, the current seems to be controlled in the braking mode, as can be seen in Fig. 19(b). However, the current is largely changed in every moment, because the voltage applied to the inductance is largely changed by the PWM action as is known from equation (18) and (19). In the proposed PWM method, the current ripples of the motoring mode and the braking mode are both small and the current is also well controlled in the motoring mode and the braking mode as can be seen in Fig. 19 (c).

V. CONCLUSIONS

Generally, BLDC motors are used for speed control applications. In these applications the unipolar PWM method is used. However, in the application of the direction of a speed change, the unipolar PWM method cannot be applied. In this case the bipolar PWM method must be applied. In this paper, the current dynamics of the motoring mode and the braking mode for the unipolar and bipolar PWM methods are analyzed. Also, a new bipolar PWM method is proposed. The proposed PWM method can be applied to the motoring mode and the braking mode. Furthermore, the proposed PWM method can reduce the current ripple more than the conventional PWM method. The experimental results are shown for the current waveforms of the steady state for the unipolar PWM, the conventional bipolar PWM, and the proposed bipolar PWM. According to these results, the proposed bipolar PWM method has a low current ripple, which is as much as the unipolar PWM. The experimental results are represented for the current waveforms of the transient state based on the PWM method. According to these results, the proposed bipolar PWM method can control the current waveforms in both the motoring mode and the braking mode. However, the current cannot be controlled by the unipolar PWM method in the braking mode. The performance of the proposed bipolar PWM method is verified by experimental results.

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REFERENCES

[1] D. K. Kim, K. W. Lee, and B. I. Kwon, "Commutation torque ripple reduction in a position sensorless brushless DC motor drive," *IEEE Trans. Power Electron.*, Vol. 21, No. 6, pp. 1762-1768, Nov. 2006.

[2] C. S. Berendsen, G. Champenois, and M. Bolopion, "Commutation strategies for brushless DC motors: influence on instant torque," *IEEE Trans. Power Electron.,* Vol. 8, No. 2, pp. 231-236, Apr. 1993.

[3] T. M. Jahns and W. L. Soong, "Pulsating torque minimization techniques for permanent magnet AC motor drives-a review," *IEEE Trans. Ind. Electron.,* Vol. 43, No. 2, pp. 321-330, Apr. 1996.

[4] G. Meng, H. Xiong, and H. Li, "Commutation torque ripple reduction in BLDC motor using PWM_ON_PWM mode," *Proceedings of* ICEMS 2009, pp. 1-6, 2009.

[5] Z. Xiangjun and C. Boshi, "Influences of PWM mode on the current generated by BEMF of switch-off phase in control system of BLDC motor," *Proceedings of ICEMS 2001*, Vol. 1, pp. 579-582, 2001.

[6] H. S. Chuang, Y. L Ke, and Y. C. Chang, "Analysis of commutation torque ripple using different PWM modes in BLDC motors," *Proceeding of Industrial & Commercial Power Systems Technical Conference*, pp. 1-6, 2009.

[7] W. Kun, R. Junjin, T. Fabghau, Zhonohao, "A novel PWM scheme to eliminate the diode freewheeling in the inactive phase in BLDC motor," *Proceedings of 35th Annual IEEE Power Electronics Specialists Conference*, Vol. 3, pp. 2282-2286, 2004.

[8] Y. Xu, Y. Tang, J. Zhu, J. Zou, and C. Ma, "Control of a BLDC motor for electromechanical actuator," *Proceedings of ICEMS 2008,* pp. 3266-3269, 2008.

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