

New PWM Technique for Two-Phase Brushless DC Motor Drives

Hai Lin* and Byung-il Kwon[†]

Abstract – A new PWM technique for a two-phase BLDC motor fed by a two-phase eight-switch inverter is proposed in this paper. It is well known that a two-phase eight-switch inverter can significantly improve power output compared with a two-phase six-switch inverter in a two-phase motor drive. To drive the two-phase BLDC motor simply and effectively, two normal PWM strategies are investigated to manage speed regulation. However, under the conditions of low speed and light load, especially during the braking process, the current in a short time of one period is near zero, which is a discontinuous waveform every half period. To solve it, a novel PWM technique is investigated to improve the operational performance of normal technique. Using the new PWM scheme, the current continues every half period and the braking performance is improved. The effectiveness of the proposed PWM method is verified through the experiments.

Keywords: Two-phase brushless DC motor, PWM technique, Inverter

1. Introduction

Two-phase AC motors have received attention due to their small size, light weight, low electrical and acoustic noise, and high efficiency [1-5]. A two-phase AC motor is composed of two separate, symmetrical windings with a 90-degree electrical phase shift of voltage and current. The inverter for the two-phase motor drive is a topic of intense research. The most common topologies for two-phase motor drives are four, six, and eight switches [6].

More techniques and industry applications of the eight-switch inverter have also been developed [7]. Although the basic operation principle of the two-phase motor in most applications is well known, the pulse-width modulation technique in the two-phase motor drive in block commutation mode is limited. In actuality, PWM techniques are mainly concentrated in the three-phase BLDC motor [8, 9]. The block commutation control of the inverter is essential to brushless DC motor drives because it ensures smooth rotation of the stator magnetic field. Various commutation control techniques have been proposed for three-phase BLDC drives [9, 10].

In the fan application, the two-phase BLDC motor with sinusoidal back-EMFs is widely preferred to reduce manufacturing costs [10, 11]. In this paper, based on the traditional PWM strategies of the three-phase BLDC motor drive, two normal PWM schemes are investigated for the two-phase BLDC motor drive. However, under conditions of low speed and light load, especially during the braking operation, the part sinusoidal back-emfs are larger than the amplitude of the effective square voltage, which

causes the current to be zero during the part period. The control performance significantly deteriorates because of discontinuous currents in the two stator windings. To improve the performance of the normal PWM scheme, a new PWM scheme is proposed, which operates under the 180-degree electrical conduction mode. In particular, all the switches of the new PWM method are in the PWM operation, and stator currents are continuous in half the cycle. Therefore, the operational performance of the two-phase BLDC drive is improved during conditions of low speed and light load. The experimental results show that the currents of the proposed PWM scheme are smooth every half period and the drive with the new PWM method achieves steadier, more dynamic performance compared with the normal one.

2. New PWM Scheme for Two-phase BLDC Motor Drives

In current drives of two-phase motor drives [9, 10], eight- and six-switch topology inverters are usual solutions. Compared with an eight-switch inverter, a six-switch inverter has a low cost because of reduced power switch numbers. However, from the space voltage distributions of two topologies in Fig 1, it is known that an eight-switch inverter achieves significant power output because the maximum voltage circular trajectory locus of an eight- and six- switch are V_{dc} and $\sqrt{2} V_{dc}/2$, respectively. In the paper, to achieve significant power output for the fan application with a different power class, we use an eight-switch inverter to drive the two-phase BLDC motor with sinusoidal back-emfs in the fan application. Also, a simple, fast and effective control strategy is an important requirement of a two-phase BLDC motor drive in the fan application. Therefore, we only use four voltage vectors,

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Received: December 7, 2012; Accepted: May 7, 2013

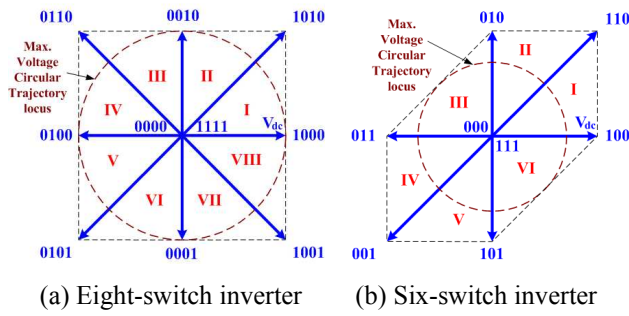


Fig. 1. Space voltage distribution of two-phase eight- and six-switch inverters

(1010), (0101), (1001), (0110) and zero vectors to realize the two-phase BLDC drives. A detailed introduction to two-phase eight-switch inverters is as follows:

2.1 Operation principle of eight-switch inverter

The topology of a two-phase eight-switch inverter [10] fed to a two-phase BLDC motor is shown in Fig. 2.

In Fig. 2, two separate windings are fed to four switch leg neutral points of A, X, B, and Y, which are supplied by a common DC power supply. Four power switches (IGBT) Q1, Q2, Q3 and Q4 and four diodes D1, D2, D3 and D4

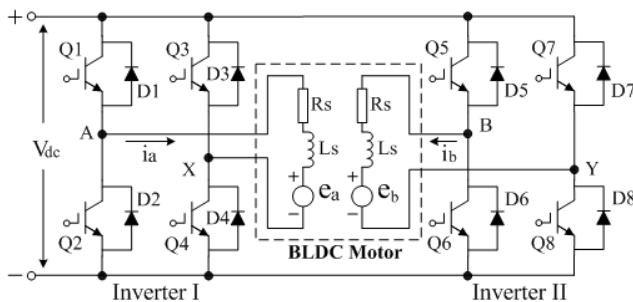


Fig. 2. Two-phase BLDC motor fed by two-phase eight-switch inverter

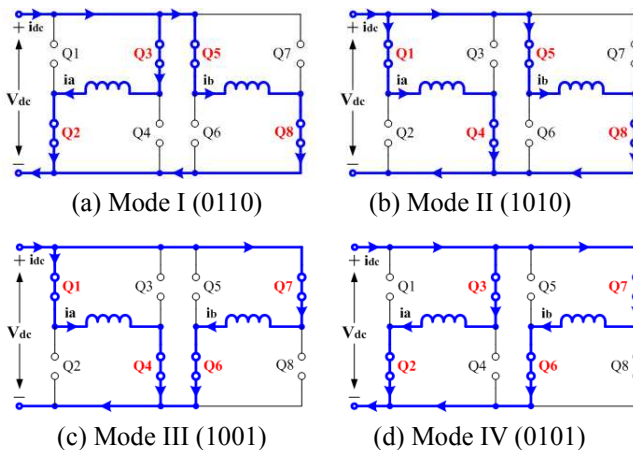


Fig. 3. Four nonzero voltage modes for proposed two-phase BLDC drives

compose Inverter I. Four switches (IGBT) Q5, Q6, Q7 and Q8 and four diodes D5, D6, D7 and D8 compose Inverter II. In the normal drives of a two-phase motor drive, if the stator flux linkage generated by two orthogonal voltages and currents in two stator windings and the rotor flux linkage from the rotor magnet are orthogonal to each other, the output torque is at a maximum. For the eight-switch inverter, four nonzero voltage switching modes (Mode I, Mode II, Mode III, and Mode IV) can achieve the maximum torque output given as follows:

The digital form of four modes (0110, 1010, 1001, and 0101) represents the switching state of Q1, Q3, Q5 and Q7. In inverter I or II, two skew-symmetric switches are alternatively turned on or off. The positive voltage is fed to the winding A or B while the switches of Q1, Q4 or Q5, Q8 are turned on. The negative voltage is fed to winding A or B while the switches of Q2, Q3 or Q6, Q7 are turned on.

2.2 PWM scheme for two-phase BLDC drive

Based on traditional PWM schemes [12, 13, 14] in three-phase BLDC motor drives under the operation mode of 120 degree conduction, two similar PWM schemes for high switches in PWM mode and low switches in turning-on mode (HpwmLon) and high switches in turning-on mode and low ones in PWM mode (HonLpwm) are developed for two-phase BLDC motor drives in the mode of 180 degree conduction.

In Fig. 4, although the two PWM schemes have different triggering strategies, their resulting voltage patterns are the same. Detailed operations of four modes, I, II, III, IV, are shown in Fig. 3. However, the principle of PWM generation of two PWM schemes is similar. At any working time in Inverter I or II, one switch is in the state of PWM and one is in the conduction mode. For example, in

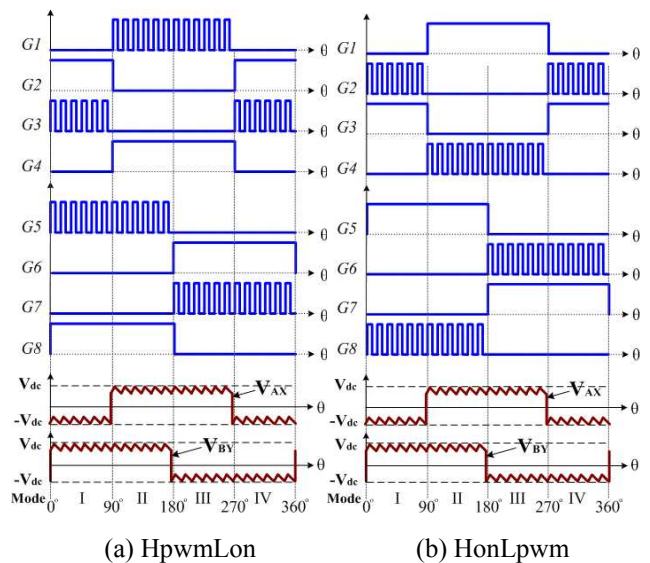


Fig. 4. Two unipolar PWM schemes of two-phase BLDC drives

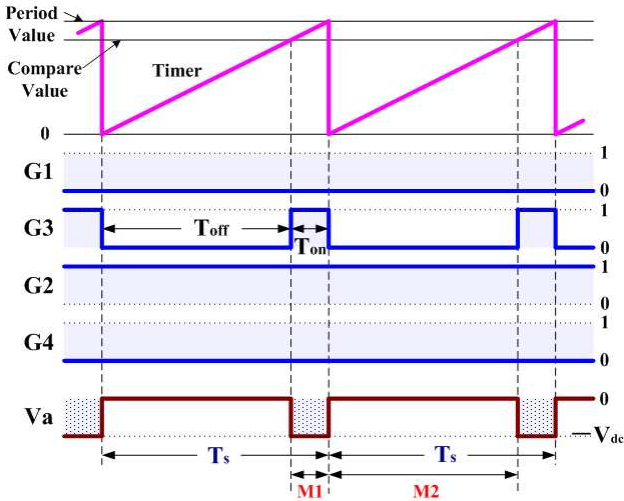


Fig. 5. PWM generation in sector I of HpwnLon scheme of two-phase BLDC drives

mode I of HpwnLon, two switches G3 and G5 are in PWM operation, and two switches G2 and G8 are in the conduction state. Other switches are in the off state. In the digital realization shown in Fig. 5, the triangular waves of a timer are treated as a modulation wave with a fixed period (T_s). A comparison value is used as a carrier wave to regulate the speed of a two-phase BLDC motor.

In Fig. 5, two PWM modes M1 and M2 are used to achieve positive and zero voltage on the phase A winding. The phase voltages of two windings in one period are given as follows:

$$\begin{cases} (S1 - S3) \cdot D_a \cdot V_{dc} = i_a \cdot R_s + L_s di_a/dt + e_a \\ (S5 - S7) \cdot D_b \cdot V_{dc} = i_b \cdot R_s + L_s di_b/dt + e_b \end{cases} \quad (1)$$

where i_a , i_b , e_a and e_b are stator phase currents and back-emfs, V_{dc} is the DC-link voltage, R_s and L_s are stator resistance and inductance, S_i ($=1$ or 0 , and $i=1,3,5$, and 7) are the triggering signals of four switches of Q1, Q3, Q5, and Q7. D_a and D_b are duty ratios during the PWM operation given as follows:

$$D_i = T_{on}/T_s, \quad (i = a, b, T_s = T_{on} + T_{off}) \quad (2)$$

where T_{on} is the effective conduction time of the switches, and T_{off} is the turn-off time.

Assuming that the inductance of the winding is so small that it is negligible, the phase currents are given as follows:

$$\begin{cases} i_a = ((S1 - S3) \cdot D_a \cdot V_{dc} - e_a)/R_s \\ i_b = ((S5 - S7) \cdot D_b \cdot V_{dc} - e_b)/R_s \end{cases} \quad (3)$$

The current directions of M1 and M2 of Fig. 5 in the motor mode are illustrated by:

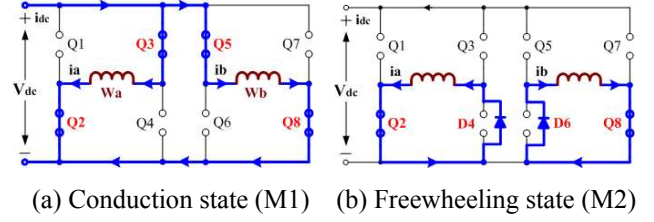


Fig. 6. Two motor modes in sector I of HpwnLon scheme

The current directions of M1 and M2 of Fig. 5 in the generator mode are illustrated by:

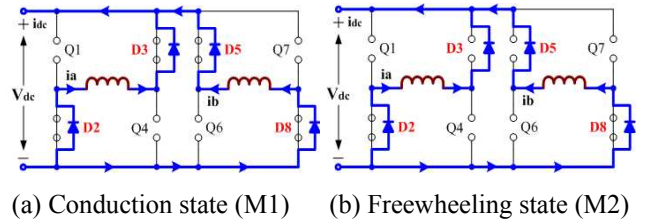


Fig. 7. Two generator modes in sector I of HpwnLon scheme

Therefore, in the conduction state of the motor mode of Fig. 6(a), $V_a > e_a$. While $Q1=0$ and $Q3=1$, then $i_a < 0$; While $Q5=1$ and $Q7=0$, then $i_b > 0$. Two phase currents are

$$\begin{cases} i_a = (-D_a \cdot V_{dc} - e_a)/R_s \\ i_b = (D_b \cdot V_{dc} - e_b)/R_s \end{cases} \quad (4)$$

In the conduction state of the generator mode of Fig. 7(a), $V_a < e_a$. While $Q1=0$ and $Q3=1$, then $i_a > 0$; While $Q5=1$ and $Q7=0$, then $i_b < 0$. Two phase currents are

$$\begin{cases} i_a = (D_a \cdot V_{dc} - e_a)/R_s \\ i_b = (-D_b \cdot V_{dc} - e_b)/R_s \end{cases} \quad (5)$$

When the inverter is in the freewheeling state of Fig. 6(b) and 7(b), $Q1=0$, $Q3=1$ or $Q5=0$, $Q7=0$. The phase currents are

$$\begin{cases} i_a = -e_a/R_s \\ i_b = -e_b/R_s \end{cases} \quad (6)$$

From (4), it is known that the currents are proportional to the back-emfs of the two-phase motor under the freewheeling mode. However, compared with the freewheeling states of Figs. 6(b) and 7(b), the discharge time in generator mode is faster than that of the former one because its freewheeling path is directly connected to the power source, which seriously affects the brake performance and causes the motor to overheat during braking, resulting in a short service life.

Fig. 8 shows the experimental results of the PWM patterns of inverter I in modes I and II for two-phase BLDC motor drives using the PWM scheme of HpwnLon. The speed of the two-phase BLDC motor is controlled at

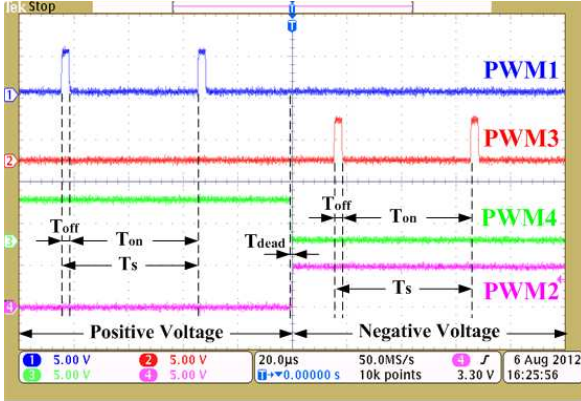
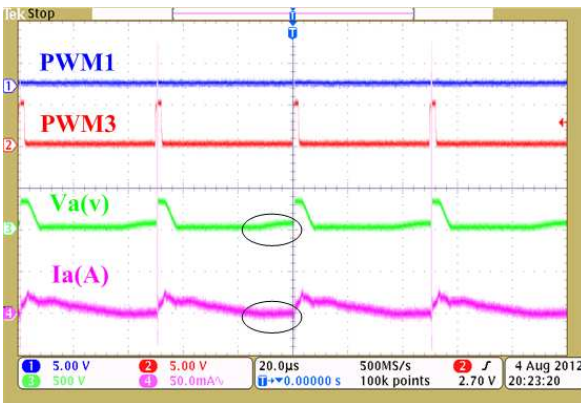
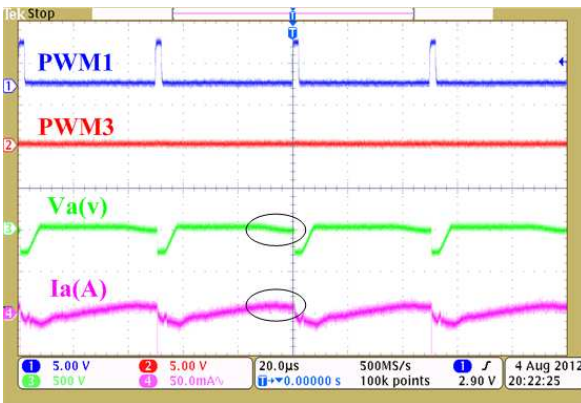


Fig. 8. Experimental results of triggering patterns of Inverter I using the HpwnLon scheme (20us/div). From the top: 1) PWM1 (5V/div), 2) PWM3 (5V/div), 3) PWM4 (5V/div), 4) PWM2 (5V/div).



(a) Positive phase voltage and current



(b) Negative phase voltage and current

Fig. 9. Experimental results of PWMs, voltage and current of Inverter I using the HpwnLon scheme (20us/div). From the top: 1) PWM1 (5V/div), 2) PWM3 (5V/div), 3) Va (500V/div), 4) Ia (50mA/div).

300 rpm and the PWM frequency is set to 20 kHz. A dead zone is inserted at an interval of 1 μs between the commutations of positive and negative voltages to avoid a short across two series switches in one leg. The experimental waveforms agree with the analysis above Fig. 4, and their effects on phase voltage and current are shown in Fig. 9.

As shown in Fig. 9, for two-phase BLDC motor with sinusoidal back-emf, under the conditions of the low speed operation and no load, the back-emf is greater than the input phase voltage in a short time of one period. Therefore, during the freewheeling, the process of discharging is fast, as shown in Fig. 7(b), and the current in the path of freewheeling is decreased or increased gradually, then clamped at zero as shown in the circles of Fig. 9. In the zero phase voltage state during freewheeling, there is still a small voltage drop because of the generator operation of the larger back-emf. From Fig. 9, the mode of the motor and generator appears during every PWM period.

2.3 Proposed PWM scheme for two-phase BLDC drive

To solve the problems of fast discharge time in generator mode and zero current during the part period in the former unipolar PWM schemes of Fig. 4, a new PWM scheme is developed in Fig. 10. To optimize the digital signal processing, four timers are used to create four triangular waves, treated as modulation waves with a fixed period (T_s). A comparison value is used as a carrier wave to regulate the speed of the two-phase BLDC motor.

In the proposed PWM scheme of Fig. 10, for inverter I of Fig. 2, three PWM states (M2, M4, and M6) are dead zones to avoid the switch short in one leg. The other three states M1, M3, and M5 are used to achieve PWM operation with high-frequency switching between positive and zero voltage on the phase A winding in one period. The state M1 is in conduction mode to achieve positive voltage.

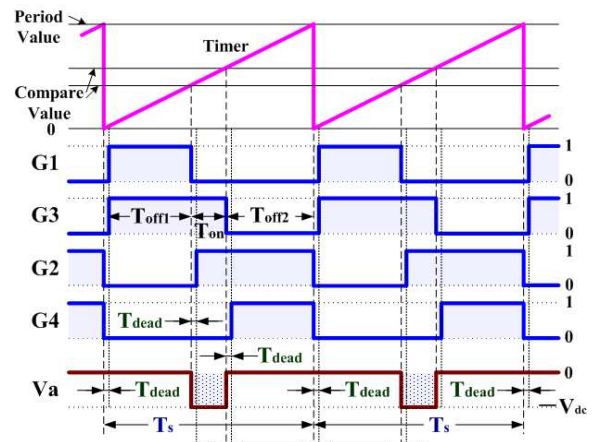


Fig. 10. DSP realization of the proposed PWM generation scheme of two-phase BLDC drives

M4 and M6 are in freewheeling mode to achieve zero voltage. It is easily seen from Fig. 10 that the freewheeling paths of M4 and M6 are different, and two pair switches G2, G4 and G1, G3 work alternately, which can distribute the switch loss on every switch evenly. The phase voltages of two windings in one period are

$$\begin{cases} (S1-S3) \cdot D_a \cdot V_{dc} = i_a \cdot R_s + L_s di_a/dt + e_a \\ (S5-S7) \cdot D_b \cdot V_{dc} = i_b \cdot R_s + L_s di_b/dt + e_b \end{cases} \quad (7)$$

The duty ratios of D_a and D_b during the PWM operation are:

$$D_i = T_{on}/T_s, \quad (i = a, b, T_s = T_{on} + T_{off1} + T_{off2} + 3T_{dead}) \quad (8)$$

where T_{on} is the turn-on time of a conduction state of M1; T_{off1} and T_{off2} are turn-off times of two freewheeling states M3 and M5; T_{dead} is the time of the dead zones of M2, M4 and M6.

The current directions of M1, M2, M3, M4, M5 and M6 of Fig. 10 in the motor mode are illustrated by:

The current directions of M1, M2, M3, M4, M5 and M6 of Fig. 10 in the generator mode are illustrated by:

In the conduction state of the motor mode of Fig. 9(a), $V_a > e_a$. While $Q1=0$ and $Q3=1$, then $i_a < 0$; While $Q5=1$ and $Q7=0$, then $i_b > 0$. Two phase currents are

$$\begin{cases} i_a = (-D_a \cdot V_{dc} - e_a)/R_s \\ i_b = (D_b \cdot V_{dc} - e_b)/R_s \end{cases} \quad (8)$$

In the conduction state of the generator mode of Fig.

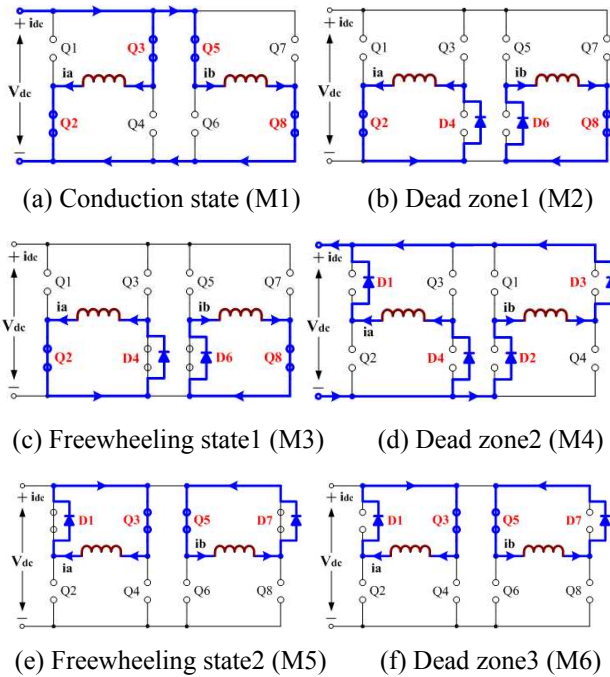


Fig. 9. Six motor modes of the proposed unipolar PWM scheme

10(a), $V_a < e_a$. While $Q1=0$ and $Q3=1$, then $i_a > 0$; While $Q5=1$ and $Q7=0$, then $i_b < 0$. Two phase currents are

$$\begin{cases} i_a = (D_a \cdot V_{dc} - e_a)/R_s \\ i_b = (-D_b \cdot V_{dc} - e_b)/R_s \end{cases} \quad (9)$$

When the inverter is in the freewheeling state of Figs. 9(c), 9(e), 10(c), and 10(e), or the dead zone of Figs. 9(b), 9(d), 10(f), 10(b), 10(d), and 10(f), the phase currents are

$$\begin{cases} i_a = -e_a/R_s \\ i_b = -e_b/R_s \end{cases} \quad (10)$$

Comparing (1)-(6) with (7)-(10), the expressions for the voltage and current equation of the normal and proposed PWM schemes are similar except for the duty ratio definition. However, during their freewheeling state, the discharging process for the normal PWM scheme is fast, and the stator current is clamped in a single direction. The proposed PWM scheme achieves a slow discharge process and makes the stator change continuously in one period.

Fig. 11 shows the PWM patterns of inverter I for two-phase BLDC motor drives using the PWM scheme of Hpwmlon in Fig. 4. Figs. 11 (a) and (b) generate positive and negative voltages on the phase A winding, respectively. The speed of the two-phase BLDC motor is 300 rpm, the PWM frequency is set to 20 kHz and the time of the three dead zones is set to 1 μ s. Their experimental waveforms agree with the analysis above in Fig. 10, and detailed voltage and current under the PWM are shown in Fig. 12.

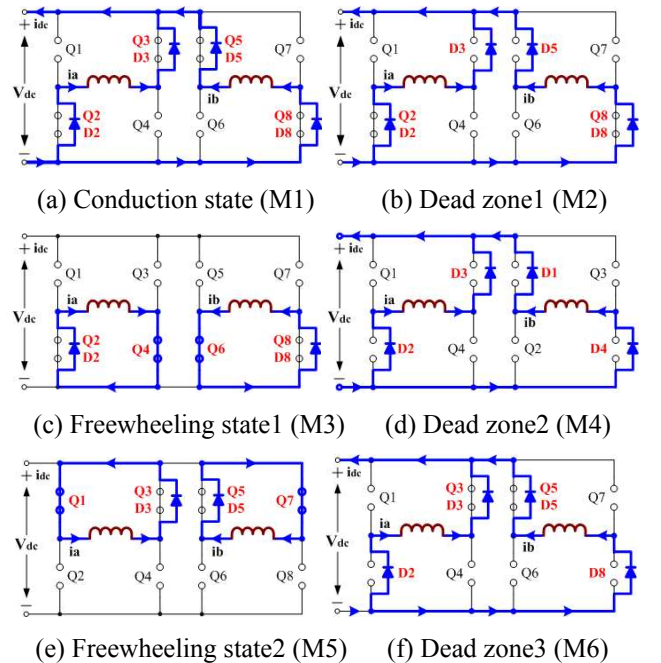
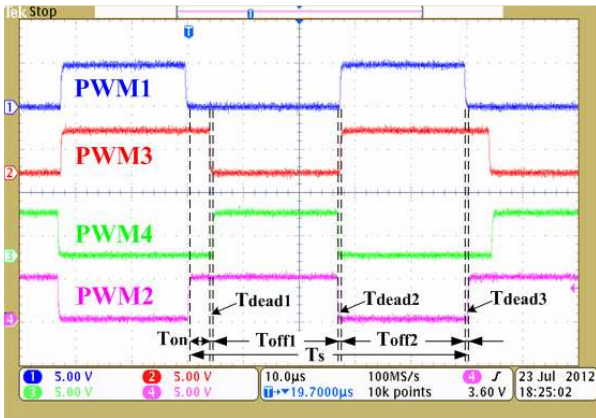
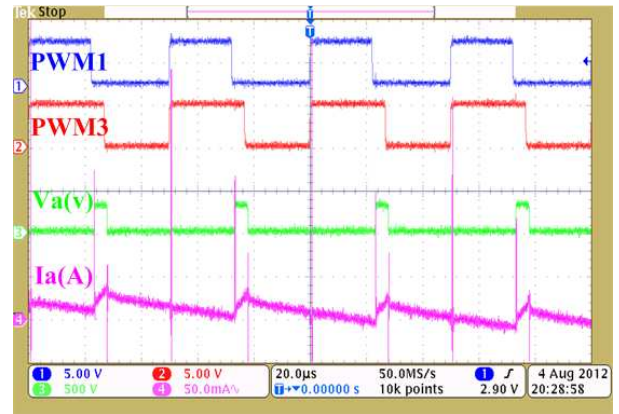


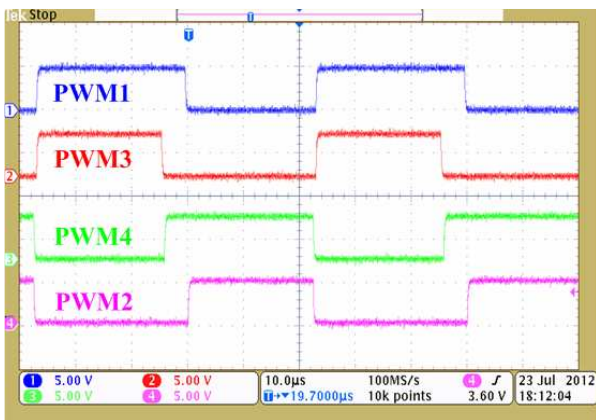
Fig. 10. Six generator modes of the proposed unipolar PWM scheme



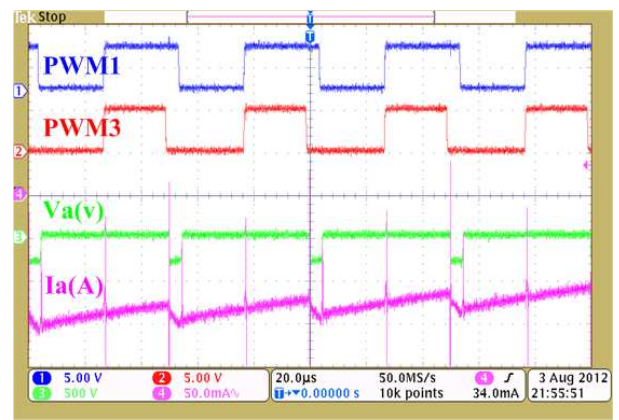
(a) Positive voltage



(a) Positive voltage and current



(a) Negative voltage



(b) Negative voltage and current

Fig. 11. Experimental results of triggering patterns of Inverter I using the proposed PWM scheme (10µs/div). From the top: 1) PWM1 (5V/div), 2) PWM3 (5V/div), 3) PWM4 (5V/div), 4) PWM2 (5V/div).

Fig. 12. Experimental results of PWMs, voltage and current of Inverter I using the proposed PWM scheme (20µs/div). From the top: 1) PWM1 (5V/div), 2) PWM3 (5V/div), 3) V_a (500V/div), 4) I_a (50mA/div).

In Fig. 12, using the proposed PWM scheme, during the freewheeling, the process of discharging is slow and the current in the path of freewheeling is decreased or increased to its minimum or maximum value gradually, even to its opposite value. The problem of zero current in the normal PWM schemes of Fig. 4 is easily solved. The proposed method is also used for braking operation with low power loss and high braking performance.

3. Experiment Results

A DSP of an Infineon XE164 based controller was developed to carry out the real-time algorithms. An eight-switch inverter with insulated gate bipolar transistor (IGBT) is used to drive the two-phase PMSM. Fig. 13 shows the experimental setup: two Hall sensors are used to detect the initial rotor position and the actual rotor speed; two current sensors are used to measure the stator currents. With the help of Real Time Interface software, the real-time code

with normal and proposed PWM algorithms, respectively, can be downloaded automatically to the flash of the XE164 from the computer through the CAN communication port. A low pass filter is used to transform the high-frequency PWM pulses to a real-time analog signal, which is observed through an oscilloscope.

Two-phase BLDC parameters are comprised of rated speed (2500 rpm), armature resistance (0.2 ohm), inductance (0.185 mH), flux induced by the magnet (0.025 Wb) and the pole pairs (9). In the system, the DC-link voltage of the inverter is set as 350 V. The reference speed of the motor is set to 1000 rpm with no load. The PWM switching frequency is set to 20 kHz and the dead time of the switches is set to 1 µs.

Fig. 14 shows the responses of four trigger signals of G1 and G3, phase voltages V_a and phase current i_a of the two-phase BLDC motor drive under conventional and proposed PWM schemes. Both PWM schemes achieve good, steady operational performance in the responses of phase voltages and currents. It is seen from Fig. 14(a) that the switches G1

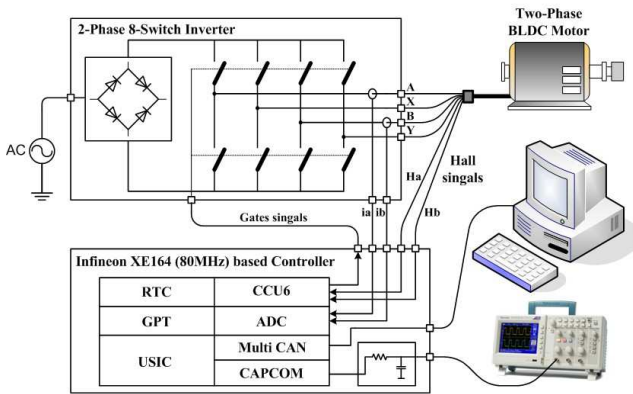
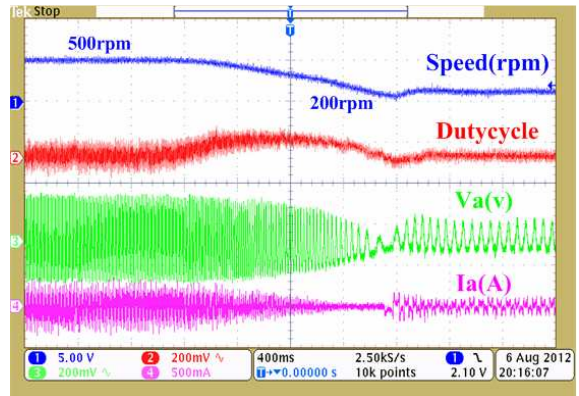
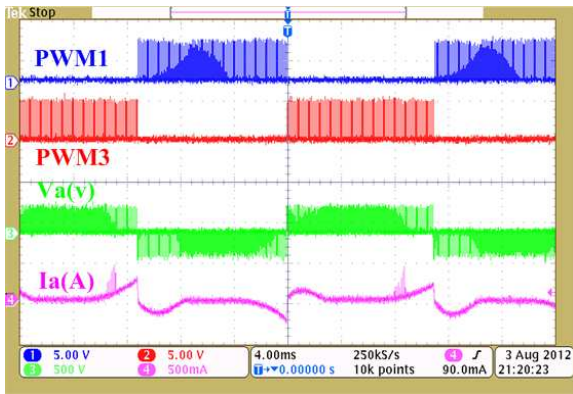


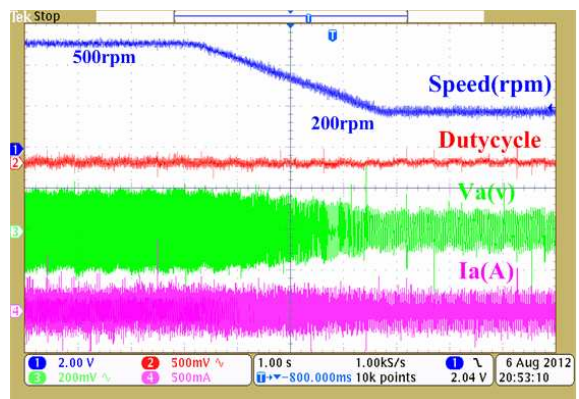
Fig. 13. The configuration of a two-phase BLDC drive with the proposed PWM schemes



(a) Normal PWM scheme (400ms/div)

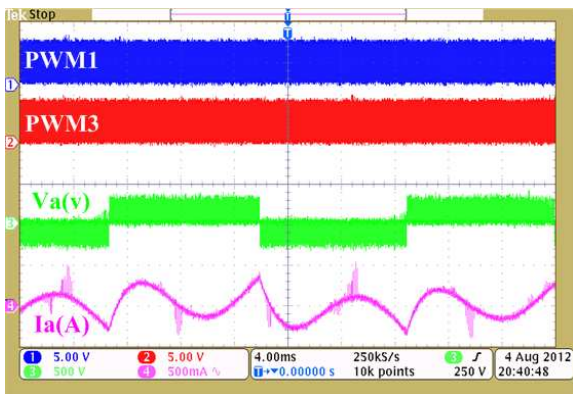


(a) Normal PWM scheme



(b) Proposed PWM scheme (1s/div)

Fig. 15. The experiment results of dynamic performance of the speed, duty cycle, phase voltage and current of a two-phase BLDC drive using the normal and proposed PWM schemes. From the top: 1) Speed (2V/div), 2) Duty cycle (500mV/div), 3) Va (200mV/div), 4) Ia (500mA/div).



(b) Proposed PWM scheme

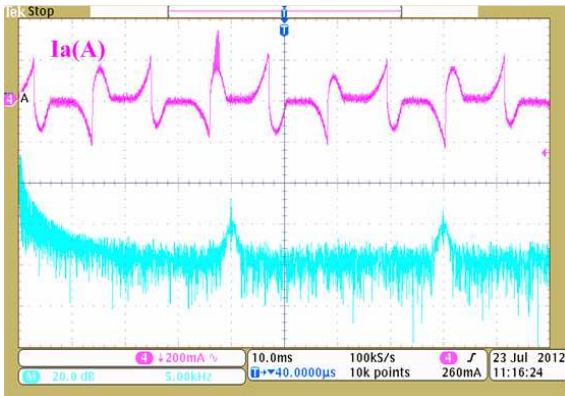
Fig. 14. The experiment results of the PWMs, phase voltage and current of a two-phase BLDC drive using the normal and proposed PWM schemes (4ms/div). From the top: 1) PWM1 (5V/div), 2) PWM3 (5V/div), 3) Va (500V/div), 4) Ia (50mA/div).

and G3 operate every half commutation cycle, alternatively, while those of Fig. 14(b) are in PWM operation all the time. Under the conditions of low speed and no load, the current waveform of the normal PWM scheme changes

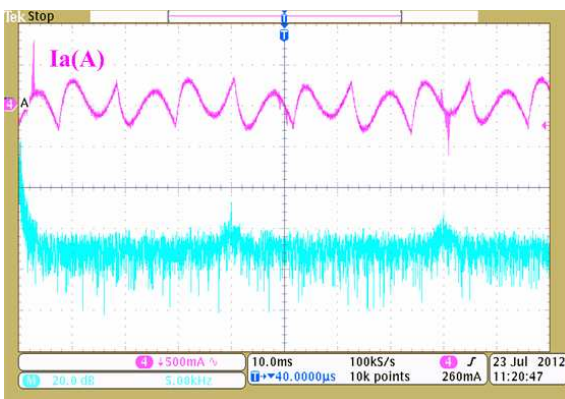
discontinuously in the non-commutation phase, during which the part of the current in one cycle is close to zero. The current of the proposed scheme changes continuously. The figures show that the proposed PWM schemes are capable of driving the two-phase BLDC motor with better steady performance, especially the smooth current response.

Fig. 15 shows the dynamic performance of the speed. Duty cycle, phase voltage and current for a two-phase BLDC drive using the normal and proposed PWM schemes under the braking. With the same parameter setting in the drive as before, the speed of the motor is changed from 500rpm to 200rpm. It is shown that two PWM schemes both achieve better dynamic performance during the process of braking operation. However, during the braking process, the duty-cycle variation of the normal PWM is higher than the proposed one. Using the proposed scheme, the voltage and current have smooth and slow changes and their response has a better robustness than that of the normal scheme.

Fig. 16 shows a frequency spectrum plot of the



(a) Normal PWM scheme (10ms/div). From the top: 1) Ia (200mA/div), 2) FFT of Ia (20dB/div).



(b) Proposed PWM scheme (10ms/div). From the top: 1) Ia (500mA/div), 2) FFT of Ia (20dB/div).

Fig. 16. The experiment results for phase current and its frequency spectrum analysis of a two-phase BLDC drive using the normal and proposed PWM schemes

generated line-to-line current of the two-phase BLDC motor drive using the normal and proposed PWM schemes. The speed of the motor are both set to 1000rpm. Notice that in addition to the fundamental frequency, the switching frequency (20 kHz and 40 KHz) harmonics also have significant magnitude. However, as shown in Figs. 16(a) and (b), the proposed PWM scheme has been proven to produce lower current harmonics than the normal one. The magnitude of the fundamental frequency is higher and the magnitude of the switching frequency is lower than that of a normal PWM.

4. Conclusion

Two simple PWM schemes of a two-phase BLDC motor are investigated in the paper. A common disadvantage of normal PWM is that the discharge process of the freewheeling operation is too fast to keep the current changing continuously in the non-commutation phase

under conditions of low speed and light load, especially during the braking operation. Based on normal PWM schemes, a new PWM technique is proposed in this paper, which can generate a smooth current change, even during braking operation. The principles of the normal and proposed PWM schemes are analyzed to show their differences. The experimental results demonstrate that the proposed PWM method is effective and achieves better operational performance.

Acknowledgements

This project was supported by the World Class University (WCU) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (R33-2008-000-10104-0).

This research was supported by a grant from the Advanced Technology Center(ATC) Program funded by the Ministry of Trade, Industry& Energy of Korea.

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