Digital Implementation of PWM Techniques for Two-phase Eight-switch Inverter fed Brushless DC Motor Drives

Hai Lin*, Yong-Min You**, Sung-Rock Cheon*** and Byung-Il Kwon†

Abstract – This paper reports an investigation of pulse width modulation (PWM) techniques for two-phase brushless DC (BLDC) motors fed by a two-phase eight-switch inverter in a fan application. The three-phase BLDC motor is widely applied in industry; however, a lower-cost two-phase BLDC motor and drive circuit has been greatly in demand in recent years. In this paper, we introduce a mathematical model of the two-phase BLDC motor with sinusoidal back electromotive forces (EMFs) based on traditional three-phase BLDC motors. To simplify the drive algorithm and speed up its application, we analyze the principle of block commutation for a two-phase BLDC motor drive in the 180-electrical-degree conduction mode, and we further propose five PWM schemes to improve the commutation performance of the two-phase BLDC drive. The effectiveness of the proposed PWM methods is verified through experiments.

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

1. Introduction

Although single-phase induction motors have been used in a large number of low-cost fields, such as in certain home applications, they have disadvantages, such as poor speed characteristics and the need for auxiliary winding to produce the starting torque [1]. Thus, two-phase AC motors have received attention due to their small size, light weight, low electrical and acoustic noise, and high efficiency [2-5]. A two-phase AC motor is composed of two separate and symmetrical windings with a 90-electrical-degree phase shift of voltage and current. The inverter for the two-phase motor drive is a hot research topic. The most common topologies for two-phase motor drives are four, six, and eight switches [6]. The four-switch inverter has a lower switch cost compared to the other two [7-9]. However, to balance the third common end of the two-phase motor, two capacitors in the inverter are necessary, which increases the total cost. In terms of cost, the six-switch inverter is a compromise among the three types of inverters [10-12]. Better steady performance and low noise are achieved while keeping the third common end of the motor under control. The eight-switch inverter is an alternative solution for the two-phase motor drive; however, it requires more switches than the other two [13, 14]. It achieves full control of the four winding ends in the drives, a higher utilization ratio of the DC-link voltage \(V_{dc}\), and a high power output. The amplitudes of the maximum circular voltage trajectory locus of the four-, six-, and eight-switch inverter are 0.5 \(V_{dc}\), 0.707 \(V_{dc}\), and 1.0 \(V_{dc}\), respectively.

More techniques and industry applications for the eight-switch inverter have also been developed [15-20]. 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 [21, 22]. The block commutation control of the inverter is essential to brushless DC motor drives because it ensures the smooth rotation of the stator magnetic field. Various commutation control techniques have been proposed for three-phase BLDC drives [23, 24].

In the fan application, the two-phase BLDC motor with sinusoidal back-EMFs is widely preferred to reduce manufacturing costs [2, 3, 17]. In this paper, to achieve a unified fan application with a different power class, we develop five PWM schemes for a two-phase BLDC motor with sinusoidal back-EMFs that is fed by an eight-switch inverter and operating in 180-electrical-degree conduction mode. In particular, the last two of the five given PWM methods, which are totally different from the normal PWM methods, are first proposed for the two-phase BLDC motor drive [23, 24] of the three-phase BLDC motor. Our results demonstrate that the proposed two-phase BLDC motor drive with five PWM schemes is simple, convenient, practical, and easy to use, and is therefore appropriate for related industry applications. Thus, our experiments verify the proposed PWM schemes for the two-phase BLDC motor drive.

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2. Operation Principle of Two-phase BLDC Drives

The two-phase BLDC motor with sinusoidal back-EMFs fed by an eight-switch voltage source inverter is illustrated in Fig. 1.

![Fig. 1. Two-phase BLDC motor fed by two-phase eight-switch inverter](image)

The inverter can be regarded as a combination of two single-phase four-switch inverters, I and II, fed by a common DC power supply. The four legs are composed of the switches, \( Q_i \) (\( i=1,2,\ldots,7,8 \)), and the diodes, \( D_i \) (\( i=1,2,\ldots,7,8 \)), in Inverters I and II. The four ends (\( A, B, X, \) and \( Y \)) of two dependent windings are connected to the neural point of the four legs. Based on the three-phase BLDC motor [21-24], the phase voltage equation of the two-phase BLDC motor windings is

\[
\begin{align*}
V_a &= R_s i_a + L_s \frac{di_a}{dt} + e_a \\
V_b &= R_s i_b + L_s \frac{di_b}{dt} + e_b
\end{align*}
\]

(1)

where the back-EMFs of \( e_a \) and \( e_b \) are

\[
\begin{align*}
e_a &= -\phi \omega \sin \theta \\
e_b &= \phi \omega \cos \theta
\end{align*}
\]

(2)

\( V_a, V_b \) and \( i_a, i_b \) are the phase voltages and phase currents of the motor windings, respectively; \( \phi \) is the flux linkage induced by the permanent magnet; \( \omega \) and \( \theta \) are the speed and position of the motor, respectively; \( R_s \) is the resistance of the phase winding; \( L_s \) is the equivalent inductance of the phase windings; and \( L = L_s - M \), where \( L \) and \( M \) are self-inductance and mutual inductance, respectively.

For the two-phase eight-switch inverter in Fig. 1, four non-zero modes and two zero modes [3-6] can be used in the two-phase BLDC motor drives, as shown below:

As indicated in Fig. 2 and Table 1, the two-phase BLDC motor drives have four operation modes (I, II, III, and IV) and two zero modes. The six modes can also be expressed in vector form; 0110, 1010, 1001, 0101, 0000, and 1111 denote the switching states of \( Q_1, Q_3, Q_5, \) and \( Q_7 \). In Modes II and III of Inverter I, positive voltage is added to the Phase A winding by switching on \( Q_1 \) and \( Q_4 \) and switching off \( Q_2 \) and \( Q_3 \). In Modes I and IV of Inverter I, the Phase A winding is supplied with negative voltage by switching on \( Q_2 \) and \( Q_3 \), and switching off \( Q_1 \) and \( Q_4 \). Inverter II has a commutation process similar to that of Inverter I. Based on these six defined modes, the proposed two-phase BLDC motor design is described in the following sections.

![Fig. 2. Four modes for the proposed two-phase BLDC drives](image)

Table 1. Operation Scheme of the Two-phase BLDC Motor Drives

<table>
<thead>
<tr>
<th>Vector</th>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0110</td>
<td>I</td>
<td>-V(_a)</td>
<td>+V(_b)</td>
</tr>
<tr>
<td>1010</td>
<td>II</td>
<td>+V(_a)</td>
<td>-V(_b)</td>
</tr>
<tr>
<td>1001</td>
<td>III</td>
<td>+V(_a)</td>
<td>-V(_b)</td>
</tr>
<tr>
<td>0101</td>
<td>IV</td>
<td>-V(_a)</td>
<td>-V(_b)</td>
</tr>
<tr>
<td>0000</td>
<td>/</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1111</td>
<td>/</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

![Table 1. Operation Scheme of the Two-phase BLDC Motor Drives](image)

In Figs. 4 and 5, due to the inductance of the winding, the phase current cannot change immediately when the...
Fig. 3. Block commutation of two-phase BLDC drives based on two Hall signals

Fig. 4. Commutation scheme of two-phase BLDC drives

Fig. 5. Switch triggering scheme according to two Hall signals

Fig. 6. Six freewheeling modes for Phase A winding with positive and negative current directions

phase voltage changes. The values of the phase voltage and current are reported in Table 1. Assuming that the motor resistance $R_s$ is sufficiently small as to be negligible, the phase currents are calculated from (1) and (2) as follows:

$$
\begin{align*}
    i_a &\approx i_a(t_0) + \frac{1}{L_s} \int (V_{dc} S + \phi \omega \sin \theta) \, dt \\
    i_b &\approx i_b(t_0) + \frac{1}{L_s} \int (V_{dc} S - \phi \omega \cos \theta) \, dt
\end{align*}
$$

(3)

For the two-phase eight-switch inverter presented in Fig. 1, the switching triggering pattern [4, 15, 16] is different from that of the traditional three-phase six-switch inverter. The switch triggering scheme can be derived from Figs. 1-5. The relationship between the switch triggering state and the Hall position signals is shown in Fig. 5. However, the switch triggering pattern illustrated in the figure is a simple scheme for the four-step voltage control of the two-phase BLDC motor. To regulate the speed of the two-phase BLDC motor effectively, the PWM method should be incorporated in its drive. In this paper, five PWM schemes are proposed to implement the speed regulation of the two-phase BLDC motor.

3. PWM Techniques for Two-phase BLDC Drives

Based on the principle of operation shown in Figs. 1-5, the technology of PWM is introduced in the drives for the speed regulation of the two-phase BLDC motor. The PWM period of the two-phase BLDC motor drives has four operation modes for the two independent motor windings, as indicated in Fig. 1. Fig. 6 shows six freewheeling modes
[4, 15, 16] for any winding with positive and negative current directions.

During the freewheeling period, the winding current change is reversed to that of the corresponding conduction mode. Assuming that the motor resistance $R_s$ is sufficiently small as to be negligible, from (1) and (2) the phase currents of Figs. 6(a) and 6(d) are the same as in (3). The currents shown in Figs. 6(b), 6(c), 6(e), and 6(f) are calculated as follows:

$$
\begin{align*}
    i_a &\approx i_a(t_0) + \frac{1}{L_s} \int (\phi \omega \sin \theta) dt \\
    i_b &\approx i_b(t_0) - \frac{1}{L_s} \int (\phi \omega \cos \theta) dt
\end{align*}
$$

(4)

Using the given operation modes in Fig. 2 and the freewheeling modes in Fig. 6, we investigate the five PWM schemes of a two-phase BLDC motor drive in the 180-electrical-degree conduction mode.

### 4.1 USpwm-LSpwm

A PWM scheme for USpwm-LSpwm is illustrated in Fig. 8 and Table 2. Both switches in each of the four switch legs operate simultaneously in pulse-width modulation. In Fig. 7(a), $G_i$ ($i=1,2,3,4$) are the triggering pulse signals of Inverter I in Fig. 2, and $G_j$ ($j=5,6,7,8$) are the trigger pulse signals of Inverter II in Fig. 2. The PWM time duration of every switch is half of one cycle. Fig. 7(b) shows the freewheeling paths of positive and negative winding currents during Modes I and II, which use the four anti-parallel diodes of four operation switches. For instance, for the phase A winding in freewheeling Mode I, a negative freewheeling path is composed of two diodes (D1 and D4); a positive freewheeling path is also composed of two diodes (D6 and D7). In each period, any two switches in PWM mode increase the switching loss. However, this configuration can achieve fast dynamic performance suitable for motor starting and braking.

### 4.2 USpwm-LScon

Fig. 8 and Table 3 show the proposed USpwm-LScon scheme, which operates with upper switch pulse-width modulation (USpwm) and lower switch conduction (LScon) in every leg. In Fig. 8(a), $G_i$ ($i=1,2,3,4$) and $G_j$ ($j=5,6,7,8$) are the trigger pulse signals of Inverters I and II, respectively. Only the high switch of each leg is in the modulation half cycle. Fig. 8(b) shows the freewheeling paths of the positive and negative winding currents during Modes I and II, which use only two switches and two anti-parallel diodes. For instance, for Phase A winding in Mode I, the freewheeling negative freewheeling path is composed of one switch (Q2) and one diode (D4), whereas the positive freewheeling path is composed of one switch (Q8) and one diode (D6).

![Fig. 7. PWM scheme of upper switch pulse-width modulation (USpwm) and lower switch pulse-width modulation (LSpwm)](image1)

![Fig. 8. PWM scheme of upper switch pulse-width modulation (USpwm) and lower switch conduction (LScon)](image2)

**Table 2. USpwm-LSpwm scheme**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>G1 PWM</td>
<td>G2 PWM</td>
</tr>
<tr>
<td>II</td>
<td>G3 PWM</td>
<td>G4 PWM</td>
</tr>
<tr>
<td>III</td>
<td>G5 PWM</td>
<td>G6 PWM</td>
</tr>
<tr>
<td>IV</td>
<td>G7 PWM</td>
<td>G8 PWM</td>
</tr>
</tbody>
</table>

**Table 3. USpwm-LScon scheme**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>G1 PWM</td>
<td>G2 PWM</td>
</tr>
<tr>
<td>II</td>
<td>G3 PWM</td>
<td>G4 PWM</td>
</tr>
<tr>
<td>III</td>
<td>G5 PWM</td>
<td>G6 PWM</td>
</tr>
<tr>
<td>IV</td>
<td>G7 PWM</td>
<td>G8 PWM</td>
</tr>
</tbody>
</table>
4.3 UScon-LSpwm

Fig. 9 and Table 4 show the UScon-LSpwm scheme, which operates with high switch conduction and low switch modulation in every leg. In the left figure of Fig. 9 (a), Gi (i=1,2,3,4) and Gj (j=5,6,7,8) are the trigger pulse signals of inverters I and II, respectively. Only the low switch of each leg is in the modulation half cycle. Fig. 9(b) shows the freewheeling paths of the positive and negative winding currents during Modes I and II, which use only two switches and two anti-parallel diodes. For instance, for Phase A winding in Mode I, the freewheeling, negative freewheeling path is composed of one switch (Q3) and one diode (D1), whereas the positive freewheeling path is composed of one switch (Q5) and one diode (D7).

![Diagram](image1)

(a) Trigger signals  (b) Freewheeling paths of Modes I and II

**Fig. 9.** PWM scheme of upper switch conduction (UScon) and lower switch pulse-width modulation (LSpwm)

Table 4. UScon-LSpwm scheme

<table>
<thead>
<tr>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>G1</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>G2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>G3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>G4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G5</td>
<td>PWM</td>
<td>PWM</td>
</tr>
<tr>
<td>G6</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>G7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G8</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

4.4 LLpwm-RLcon

Fig. 10 and Table 5 show the LLpwm-RLcon scheme, which operates with left-leg pulse-width modulation and right leg conduction in each inverter (i.e., I and II). In Fig. 10(a), Gi (i=1,2,3,4) and Gj (j=5,6,7,8) are the trigger pulse signals of Inverters I and II, respectively. Only two switches of the left leg are in the modulation half cycle. Fig. 10(b) shows the freewheeling paths of positive and negative winding currents during Modes I and II, which only use two switches and two anti-parallel diodes. For instance, for Phase A winding in Mode I, the freewheeling, negative freewheeling path is composed of one switch (Q3) and one diode (D1), whereas the positive freewheeling path is composed of one switch (Q5) and one diode (D7).

![Diagram](image2)

(a) Trigger signals  (b) Freewheeling paths of Modes I and II

**Fig. 10.** PWM scheme of left leg pulse-width modulation (LLpwm) and right leg conduction (RLcon)

Table 5. LLpwm-RLcon scheme

<table>
<thead>
<tr>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
<td>PWM</td>
</tr>
</tbody>
</table>

4.5 LLcon-RLpwm

Fig. 11 and Table 6 show the LLcon-RLpwm scheme, which operates with high switch pulse-width modulation and low switch conduction in every leg. In Fig. 11(a), Gi

![Diagram](image3)

(a) Trigger signals  (b) Freewheeling paths of Modes I and II

**Fig. 11.** PWM scheme of left-leg conduction (LLcon) and right leg pulse-width modulation (RLpwm)

Table 6. LLcon-RLpwm scheme

<table>
<thead>
<tr>
<th>Mode</th>
<th>Inverter I</th>
<th>Inverter II</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>PWM</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
<td>PWM</td>
</tr>
</tbody>
</table>
(i=1,2,3,4) and Gj (j=5,6,7,8) are the trigger pulse signals of Inverters I and II, respectively. Only the high switch of every leg is in the modulation half cycle. Fig. 11(b) shows the freewheeling paths of the positive and negative winding currents during Modes I and II, which use only two switches and two anti-parallel diodes. For instance, for Phase A winding in Mode I, the freewheeling, negative freewheeling path is composed of one switch (Q2) and one diode (D4), whereas the positive freewheeling path is composed of one switch (Q5) and one diode (D7).

5. Experimental Results

To verify the proposed scheme, a digital signal processing (DSP) controller with Infineon XE164F was developed for the experiment presented in Fig. 12. The two-phase BLDC parameters are 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 to 150 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. The experimental results are provided in the following figures.

In the digital realization, the control scheme was implemented in an Infineon XE164F chip, as shown in Fig. 12. A compare unit with the timer T13 was used to generate one-PWM signals. Two Hall position signals were detected by a Hall compare logic unit to achieve a correct Hall enable signal, which is used for commutation triggering. A phase delay from the Hall signal detection to the initiation of commutation is generated by a compare unit with the timer T12.

Figs. 14(a)-14(f) show the waveforms of the trigger signals and phase A current of the five proposed PWM schemes under two speed commands: 400 rpm and 1000 rpm. Figs. 14(a)-14(b), 14(c)-14(d), 14(e)-14(f), 14(g)-14(h), and 14(i)-14(j) respectively present the experimental responses of the five proposed PWM schemes: USpwm-LSpwm, USpwm-LScon, UScon-LSpwm, LLpwm-RLcon, and LLcon-RLpwm. In these results, the trigger signals (Q1, Q2, and Q3) are the switch-triggering signals of the switches (Q1, Q2, and Q3), which agree well with the theoretical analysis described previously. The figures show that the proposed PWM schemes are capable of driving the two-phase BLDC motor with a more steady performance.

![Fig. 12. Configuration of a two-phase BLDC drive with the proposed PWM schemes](image)

![Fig. 13. Digital implementation scheme of two-phase BLDC drives under square wave PWM based on Hall position block commutation](image)
Fig. 15 shows the waveforms of the two phase voltages, Phase A current, and Hall signal for the two-phase BLDC drive under two speed commands, 400 and 1,000 rpm. The two output voltages have three-level PWM waveforms of 150 V, and the phase difference between the two output voltages is fixed at 90 degrees. The experimental results are consistent with the theoretical analysis described in Section 2. Therefore, we have demonstrated that the proposed schemes can effectively drive the two-phase BLDC motor and achieve an improved steady performance.
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6. Conclusion

A simple and effective low-cost drive scheme for the two-phase BLDC motor incorporating five PWM methods is proposed in this paper. The motor is fed by two single-phase four-switch inverters in the drive. The mathematical model and control principle of the two-phase BLDC motor are analyzed. Using four conduction modes and six freewheeling modes of a two-phase eight-switch inverter, five different combinations are proposed to achieve five effective PWM schemes for a two-phase BLDC drive. The experiment verified that the five proposed PWM methods can provide two balanced phase voltages and achieve improved operation performance for low-cost applications.

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References

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