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RESEARCH ARTICLE

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# A novel PWM scheme to eliminate the diode freewheeling in the inactive phase in BLDC motor



**Abstract** The brushless DC motor (BLDCM) with trapezoidal electromotive force (back-EMF) waveform is used widely. In principle, when the motor runs in the 120° conduction mode, two of the three phases are active while the other phase is inactive at all times. However, a ripple current occurs in the inactive phase due to the diode freewheeling during the non-commutation period in the traditional pulse width modulation (PWM) methods, which aggravates the torque ripples. A new PWM method is proposed in this paper to eliminate the diode freewheeling during the non-commutation period in the inactive phase. As a result, the torque ripple is suppressed using the proposed method. The simulation and experimental results are demonstrated to verify the validity of the proposed PWM method.

**Keywords** PWM, BLDCM

## 1 Introduction

The permanent magnet BLDCM, with the popular trapezoidal (back–EMF) waveform, has the advantages of higher efficiency, higher power density, and lower acoustic noise over the traditional DC motors. This kind of motor is being used increasingly but it cannot be used in cases where a high position precision or high stability is required due to its torque ripples. Much research have focused on the commutation torque ripples in BLDCM [1–3]. In practical applications, an inverter driver with a three-phase half-bridge structure is generally used and a pulse width modulation (PWM) scheme is preferred.

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The commutation torque ripples in different PWM modes are analyzed in Refs. [4–8]. In the literature [9], the effects of commutation on the phase current is analyzed and a conclusion is given that a minimum torque ripple can be gained in the ON_PWM mode. In Ref. [10], the effects of different PWM methods on the torque ripple are analyzed. All these works focus on the torque ripple in the commutation interval while different PWM schemes are adopted. Furthermore, the torque in the non-commutation zones is influenced by the PWM method due to the diode freewheeling in the inactive phase.

There is no current in the inactive phase windings in principle. The diode in the inverter, which is connected with the inactive phase windings, will be in the ON state once the terminal voltage of the inactive phase is over the DC link voltage or under the zero voltage. Thus, a ripple current flows in the inactive phase during the diode freewheeling, which aggravates the torque ripple. The diode freewheeling in the inactive phase is caused inevitably under the traditional PWM method.

The characteristics of diode freewheeling in the inactive phase are investigated in this paper, and a new PWM scheme, PWM_ON_PWM, is proposed. In the proposed PWM method, the switch is in the PWM mode in the initial 30° and the last 30° zones, and in continuous ON state in the middle 60° zone. The diode freewheeling in the inactive phase is eliminated completely using the proposed PWM method.

The paper is organized as follows: the developed procedure of the proposed PWM method is presented in Sect. 2. The characteristics of the diode freewheeling in the inactive phase with the traditional PWM schemes are analyzed in Sect.3. The experimental results with discussions are given in Sect. 4 and the conclusions are given in Sect. 5.

## 2 Approach for the new PWM method

The equivalent circuit of BLDCM with the driver inverter is shown in Fig. 1.

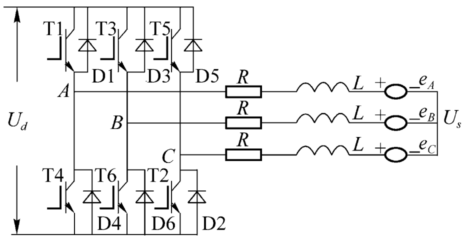


**Fig. 1** The block diagram of BLDC motor driver

The motor is assumed symmetrical and the salient effect is neglected. The self and mutual inductances are constant; the terminal voltages of three phases are given by

$$\begin{pmatrix} U_A \\ U_B \\ U_C \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} \begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} + \begin{pmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}\,t} \begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} + \begin{pmatrix} e_A \\ e_B \\ e_C \end{pmatrix} + \begin{pmatrix} U_N \\ U_N \\ U_N \end{pmatrix} \quad (1)$$

where $U_A$, $U_B$, $U_C$: are phase terminal voltages with reference to ground,

$e_A$, $e_B$, $e_C$ : Back EMF

$i_A$, $i_B$ , $i_C$ : Phase Current

$R$: Phase Resistance

$L$: Phase Inductance

$U_N$ : The voltage on the neutral node of the motor with reference to ground

$U_d$ : DC link voltage

The motor runs in 120$^o$ conduction mode. It's ideal that two of the three phases are active and the other phase is inactive at all times. However, a ripple current ($\Delta t1$ interval and $\Delta t2$ interval in Fig. 2) occurs in the inactive phase when the terminal voltage of the phase is over the DC link voltage or under the zero voltage.

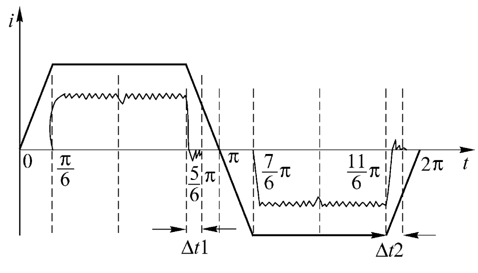


**Fig. 2** The freewheeling current occurs in the inactive phase

The values of $U_N$ are influenced by the different PWM methods. $S_X$ is defined as the function of the terminal voltage level state of the stator phase $X$ ($X$=$A$, $B$, $C$). $S_X$=1 means that the terminal voltage of the phase is equal to the DC link voltage, which indicates that the corresponding switch or diode on the upper branch of the inverter is in the ON state. $S_X$ = 0 means that the terminal voltage of the phase is equal to zero, which indicates that the corresponding switch or diode on the lower branch of the inverter is in the ON state. Then, the terminal voltage equation of the phase $X$ is given as Eq. (2):

$$U_X = U_d \times S_X = Ri_X + L\frac{\mathrm{d}i_X}{\mathrm{d}t} + e_X + U_N \quad (2)$$

Assuming that phase $X$1and phase $X$2 are active and phase $X$3 is inactive. The following result can be achieved from Eq. (2):

$$U_{X1} = U_d \times S_{X1} = Ri_{X1} + L\frac{\mathrm{d}i_{X1}}{\mathrm{d}t} + e_{X1} + U_N \quad (3)$$

$$U_{X2} = U_d \times S_{X2} = Ri_{X2} + L\frac{\mathrm{d}i_{X2}}{\mathrm{d}t} + e_{X2} + U_N \quad (4)$$

where $i_{X1}= -i_{X2}= i$, $e_{X1} = -e_{X2}= E$, $E$ represents the value of the platform of the back EMF. Combining Eqs. (3)-(4) gives us:

$$U_N = \frac{1}{2}U_d(S_{X1} + S_{X2}) \quad (5)$$

For BLDCM, the following equation can be gained:

$$E < \frac{1}{2}U_d \quad (6)$$

For the inactive phase, the phase terminal voltage can be expressed as follows:

$$U_{X3} = e_{X3} + U_N \quad (7)$$

The following result can be deduced from Eq. (5),

$$U_N = \begin{cases} 0 & (S_{X1} = S_{X2} = 0) \\ \frac{1}{2}U_d & (S_{X1} = 1, S_{X2} = 0 \quad or \quad S_{X1} = 0, S_{X2} = 1) \\ U_d & (S_{X1} = S_{X2} = 1) \end{cases} \quad (8)$$

Ideally, there is no current in the phase $X$3. When the terminal voltage of phase $X$3 is over $U_d$ or under the zero voltage, where the branch diode connected with phase $X$3 is in freewheeling state and the freewheeling current flows in the phase $X$3. Accordingly, no freewheeling occurs in the phase $X$3 only when the following condition is satisfied:

$$0 < U_{X3} < U_d \quad (9)$$

When Eq. (8) is concerned, then

$$-e_{X3} < U_N < U_d - e_{X3} \quad (10)$$

According to Eq. (10), the corresponding values of $U_N$ are shown in the shadow sections of the lower trace (left figure) in Fig. 3.

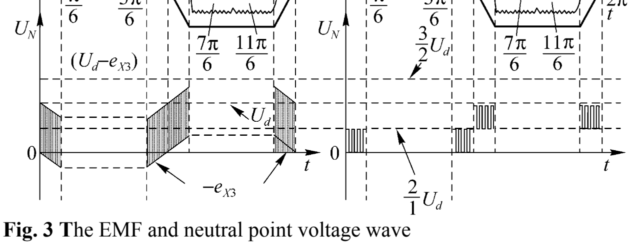


**Fig. 3 T**he EMF and neutral point voltage wave

Some discussions are performed as follows according to Fig. 3.

When the rotor position angle is in 0~π/6 and 5π/6~π zones, the value of $e_{X3}$ is positive. According to Eq. (8) and Eq. (10), the following results can be gained: $U_N$=0 ($S_{X1}$=$S_{X2}$=0) or $U_N$ =$U_d$/2 ($S_{X1}$=1, $S_{X2}$=0 or $S_{X1}$=0, $S_{X2}$=1), as shown in the lower traces (right figure) in Fig. 3. The above results indicate that a switch on the lower branch of the inverter is in the ON state and a diode on the lower branch is in the freewheeling state. Thus, the suitable PWM scheme in the two zones is that the corresponding switch on the upper branch of the inverter is in the PWM state, and the switch on the lower branch is in continuous ON state.

A similar discussion can be applied in π~7π/6 and 11π/6~2π zones, in which the value of $e_{X3}$ is negative. According to Eqs. (8) and (10), then $U_N$ =$U_d$ ($S_{X1}$=$S_{X2}$=1),or $U_N$ =$U_d$/2 ($S_{X1}$=1, $S_{X2}$=0 or $S_{X1}$=0, $S_{X2}$ =1), as shown in the lower traces (right figure) in Fig. 3. The above results indicate that a switch on the upper branch of the inverter is in the ON state and a diode on the upper branch is in the freewheeling state. Thus, the suitable PWM scheme in the two zones is that the corresponding switch on the upper branch of the inverter is in continuous ON state and the switch on the lower branch is in the PWM state.

Therefore, a new PWM scheme, PWM_ON_PWM (Fig. 4), is proposed here. The principle of the PWM mode is that the switch is in PWM mode in the beginning 30$^o$ and the last 30$^o$ zone, and in continuous ON state in the middle 60$^o$ zone.

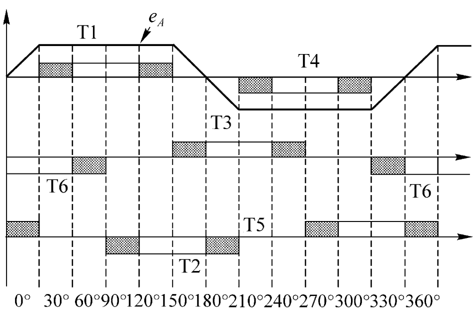


**Fig. 4** The PWM_ON_PWM mode

## 3 Analysis of the diode freewheeling in the inactive phase and the experimental results

The freewheeling current amplitude is dependent on the value of the stator inductance, the amplitude of the EMF and the state of the switches.

There are some generally used PWM schemes in practical applications. The characteristic of freewheeling in the inactive phase is analyzed in the ON_PWM mode. The switch is in continuous ON state in the former 60$^o$ zone and in PWM state in the latter 60$^o$ zone, as shown in Fig. 5.

Phase *A* is assumed to be the inactive phase, the waveform of $e_A$ is shown in Fig. 5 (upper trace) and the four inactive zones are: 0$^o$–30$^o$ zone, 150$^o$–180$^o$ zone, 180$^o$–210$^o$ zone and 330$^o$–360$^o$ zone. The terminal voltage can be gained according to Eq. (7). Whether the diode is freewheeling or not can be deduced by comparing terminal voltage with $U_d$ and the zero voltage. The analytical results are as follows:

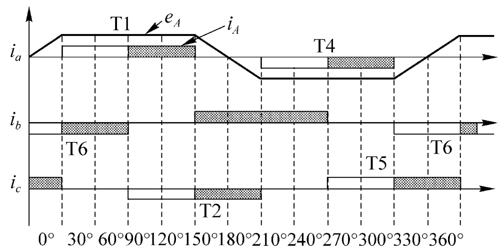


**Fig. 5** ON_PWM mode

It is obvious that there are currents in the two zones flowing in the inactive phase in ON_PWM mode. The two zones are 150°–180° interval and 330°–360°. The current flows through D1 in the 150°–180° zone and D4 in the 330°–360° zone.

The freewheeling is eliminated completely using the proposed PWM_ON_PWM method. The simulated results under two PWM modes are shown in Fig. 6. From the two figures, it is obvious that the freewheeling current is eliminated completely in PWM_ON_PWM mode. The analytical result is validated by the simulated results.

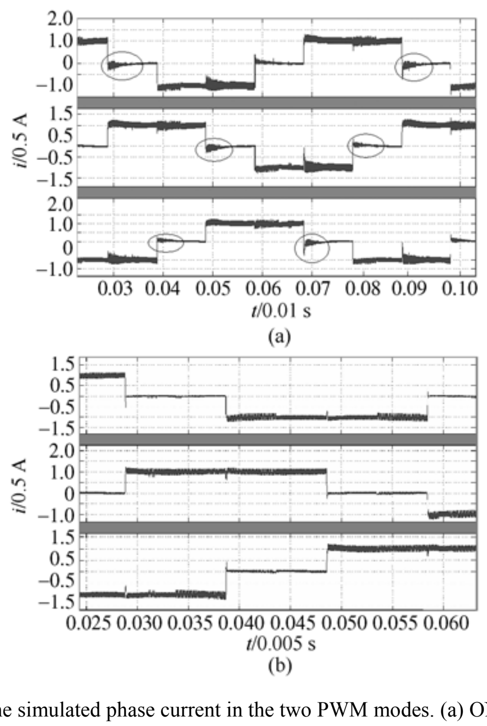


**Fig. 6** The simulated phase current in the two PWM modes. (a) ON_PWM; (b) PWM_ON_PWM

Figure 7 shows the simulated phase currents (upper trace) and the corresponding torque waveforms (bottom trace). Compared with Fig. 7(b), torque ripple is increased in

Fig. 7(a). The following definition is made: (the maxim position torque-minimum negative torque)/average torque represents the torque ripple value, then torque ripple value is up to 61.5 % caused by the freewheeling current in the inactive phase. Comparatively, the maxim commutation torque ripple is 109 %. Therefore, the torque ripple deduced by the freewheeling current cannot be ignored. Fig. 7(b) shows the results in the proposed PWM_ON_PWM, the torque wave is smoother than that in Fig. 7(a).

The parameters of the motor for the experimental setup are as follows: input voltage is 300 V; the rated power is 400 W; the pole pairs are equal to 3, and the rated speed is 3 000 rpm. The phase currents are detected in the ON_PWM mode and the PWM_ON_PWM mode respectively, as shown in Fig. 8. It is obtained from Fig. 8(a) that diode freewheeling (the regions marked with circles) occurs in the inactive phase windings when the ON_PWM mode is used, while no diode freewheeling occurs in the inactive phase using the proposed PWM_ON_PWM scheme, as shown in Fig. 8(b). Fig. 9 shows the detected phase current (upper trace) and the corresponding phase terminal voltage waveform (lower trace) in the ON_PWM mode. It is obvious that the terminal voltage is clamped at the DC link voltage due to the diode freewheeling (the regions marked with circles).

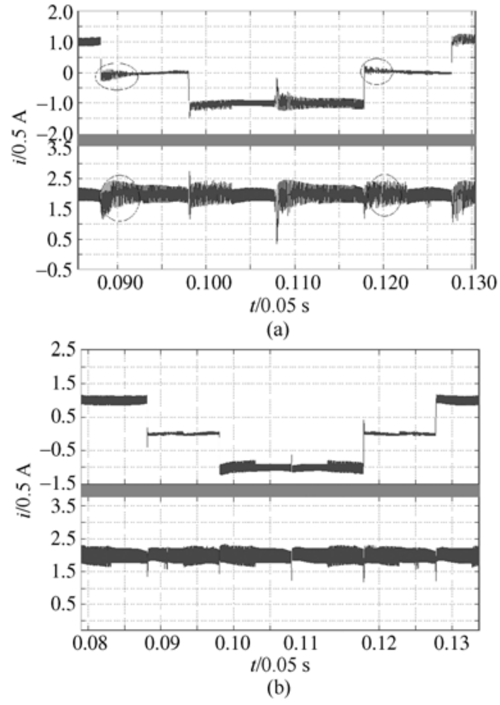


**Fig. 7** The simulated result in two PWM modes. (a) ON_PWM mode, (b) PWM_ON_PWM mode

For Figs. 8-9, it must be pointed out that large current pulsation occurs due to the large cogging torque ripples, which is attributed to the straight slot structure of the experiment motor. However, it doesn't affect the verification results.

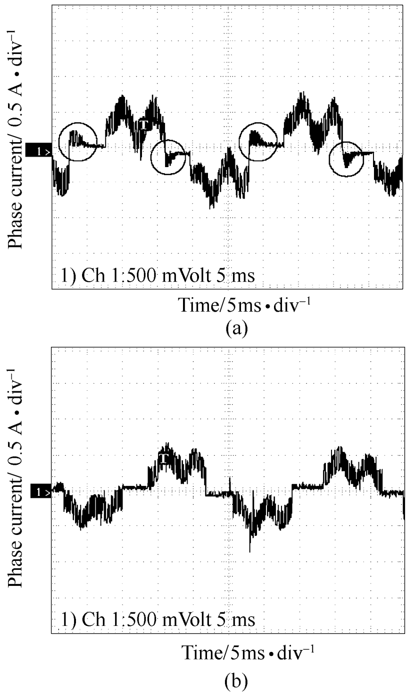


**Fig. 8** The detected phase currents in three PWM modes. (a) ON_PWM mode; (b) PWM_ON_PWM mode

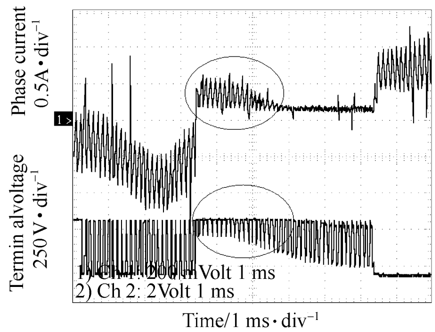


**Fig. 9** The detected phase current waveform (upper trace) and phase terminal voltage waveform (lower trace)

The duration of diode freewheeling is represented by $\theta$. The freewheeling characteristics in the inactive phase along with variable speed are shown in Fig. 10, which are performed in the ON_PWM mode. From Fig. 10, it is obvious that $\theta$ will become small along with the increase in speed. Furthermore, it is known from the above analysis that the amplitude of the freewheeling current in the higher speed zone is higher than that in the lower speed zone.

In general, when PWM_ON_PWM mode is used, the torque performances are superior compared to when the ON_PWM mode is used, especially in the middle or low speed zone.

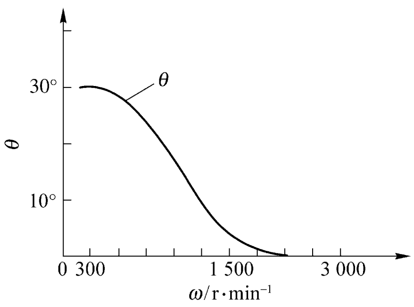


**Fig. 10** The freewheeling characteristics along with variable speed

## 4 Conclusions

1) There is freewheeling current in the inactive phase in the traditional PWM methods. In the proposed PWM method, the freewheeling in the inactive phase is eliminated completely and lower torque ripples are obtained as well.

2) The phase current and torque ripple are improved in the PWM_ON_PWM mode, especially in the middle and low speed zone. Thus, the motor runs more smoothly.

3) The proposed PWM method can be applied to any occasion and be compatible with any advanced controlling principles.

## References

1. Wang X.H., Li Q.F., Wang S., Analytical calculation of loaded magnetic field and electrical magnetic torque in brushless DC motor, Proceedings of CSEE, 2003, 23(4): 40–144
2 .Wang X.H, Li Q.F., Wang S.H, Analytical calculation of cogging torque in brushless DC motor,Proceedings of CSEE, 2002, 22(10): 104–108
3. Zhou B., Fu Y., Geng Y.L., et al., Influence of winding mutual inductance on operation characteristics of brushless DC motors based on C-DUMP converters. Proceedings of the CSEE, 2001, 21(3): 30–33
4. Xia C.L., Wen D., Wang J., A new approach of minimizing commutation torque ripple for brushless DC motor based on adapting ANN, Proceedings of the CSEE, 2002, 22(1):54–58
5. Zhou B., Dou S., Yan Y.G., PWM control modes their influence on voltage fluctuation for the brushless DC generators based on electronic converter, Proceedings of CSEE, 2001, 21(7): 56–60
6. Yoshihiro M., Yoshihiro K., et al., Torque ripple improvement for brushless DC motor miniature motors, IEEE Transactions on Industry Applications., 1989,25(3): 441–450
7. Kim. G. H., Kang S. J., et al., Analysis of the commutation torque ripple for BLDCM fed by HCRPWM-VSI, Applied Power Electronics Conference and Exposition, APEC'92, Conference Proceedings 1992, Seventh Annual, 23-27 Feb, 1992:277–284
8. Won C.H., Song J.H., Choy L., Commutation torque ripple reduction in brushless DC motor drives using a single DC current sensor, Power Electronics Specialists Conference, 2002,2:985–990
9. Du J., Sun Ch. B., The effects on the phase voltage and the phase current during the commutation interval in BLDCM, The Magazine of the Power Technology, 2003.03:5–8
10.Zhang X. G., Chen B. S., The different influences of four PWM modes on commutation torque ripples in brushless DC motor control system, Electric Machines and Control, 2003,7(2):87–91