Commutation Torque Ripple Reduction in BLDC Motor Using PWM_ON_PWM Mode

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***Abstract*--The paper analyzes the steady commutation process of the BLDC motor using PWM mode, confirms the commutation time to keep non-commutation phase current amplitude constant during commutation period by way of PWM in the period to implement the compensation control to eliminate commutation torque ripple under both low speed and high speed operation, investigates the effect by PWM mode on a three-phase six-state 120° turn-on BLDC motor, and presents torque ripple compensation control in PWM_ON_PWM mode, which can not only entirely eliminate torque ripple resulted from the current emerging in the turn-off phase during non-commutation period but also compensate torque ripple caused by the commutation current during commutation period.**

***Index Terms*—BLDC motor, commutation, PWM, torque ripple.**

I. Introduction

The BLDC motors have been widely used due to its features — a simple structure, good speed adjusting performance, high power density, low noise and simple control, etc. It is a hotspot to suppress the torque ripple and improve the control performance of a BLDC motor with the trapezoidal back emf.

BLDC motors usually operate in all kinds of PWM modes, which not only affect the dynamic loss of power switches and radiation uniformity, but also influence the torque ripple. It is an effective way to suppress the torque ripple through changing dc bus chopper control to remain non-commutation phase current amplitude constant, but it results into a more complex topology [1]-[3]. It is just fit for low speed applications to control non-commutation phase current amplitude to regulate the commutation torque ripple [4]. It is analyzed about the influence resulted from PWM ON mode on the torque ripple in [5]. The ideas in [1]-[3] are to adopt different suppression methods in different speed interval, but they don't take the effect by PWM modes on the system in account. The predictive current, neural network control and active disturbance rejection control etc are introduced to suppress the torque ripple in [9]-[12], but the control algorithm is more complicated and harder for realization.

Depending on the commutation process of BLDC motors and the effect by PWM modes on the system, the paper presents a torque ripple compensation control in PWM_ON_PWM mode at different speeds by seeking different PWM modulation ratios during commutation period as the motor runs at low speed and high speed. The method retains the original topology, improves the control performance of the system dramatically, and moreover is easy to realize.

II. Electromagnetic Torque of BLDC Motor during Commutation Process

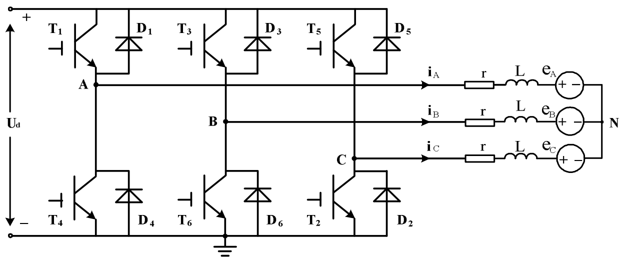

Fig.1 Block diagram of a three-phase BLDC motor and its system

Assume that the BLDC motor is three-phase symmetrical and Y-connected, and neglect eddy currents and hysteresis losses, its equivalent circuit and main circuit are shown in Figure 1. r, L are the resistance and inductance of the stator windings respectively; e_A, e_B, e_C are the counter emfs of the corresponding phase windings respectively; i_A, i_B, i_C are the corresponding phase currents respectively.

$$i_A + i_B + i_C = 0 \tag{1}$$

The counter emf of every phase winding is a trapezoidal waveform with a flat-top width greater than or equal to 120^0 electrical degree, and its flat-top amplitude is E_m. When the motor works in three-phase six-state 120^0 turn-on mode, the currents don't commutates instantaneously as a result of the inductance of the armature winding. Take the power switch T_1 and T_2's turn-on to T_2 and T_3's turn-on for example. During the commutation, it is gained as follows

$$e_A = e_B = -e_C = E_m \tag{2}$$

Suppose that the mechanical angular velocity of the rotor is Ω, the toque can be obtained as follows during the commutation process.

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega} = -\frac{2E_m i_C}{\Omega} \tag{3}$$

It is obvious from (3) that the toque is proportional to the non-commutation phase current during commutation, i.e. the commutation torque ripple can be eliminated so long as non-commutation phase current remains constant during commutation.

III. Commutation Process without Considering Effect by PWM and Armature Winding Resistant

Assume that the circuit status changes from phase A and C's turn-on to phase B and C's turn-on, phase A current flows D_4 and decays to zero gradually, while phase B current increases to the maximum gradually and reaches its steady-state value. The circuit equation during commutation without considering the effect by PWM can be written as follows.

$$\begin{cases} L\dfrac{di_A}{dt}+ri_A+e_A-(L\dfrac{di_C}{dt}+ri_C+e_C)=0 \\ L\dfrac{di_B}{dt}+ri_B+e_B-(L\dfrac{di_C}{dt}+ri_C+e_C)=U_d \end{cases} \tag{4}$$

Compared with the winding time constant L/r of a BLDC motor, PWM period can be thought small enough, and then $|ri_X| \ll |L\dfrac{di_X}{di_t}| \quad (X=A,B,C)$. So the effect of the armature winding resistant can be neglected. Moreover the initial and final values of every phase current equal every phase steady-state current value I_0 before and after the commutation. All phase currents during the commutation can be obtained from (1), (2) and (4).

$$\begin{cases} i_A = I_0 - \dfrac{U_d+2E_m}{3L}t \\ i_B = \dfrac{2(U_d-E_m)}{3L}t \\ i_C = -I_0 - \dfrac{U_d-4E_m}{3L}t \end{cases} \tag{5}$$

Then the toque during the commutation can be written

$$T_e = \frac{2E_m}{\Omega}(I_0 + \frac{U_d-4E_m}{3L}t) \tag{6}$$

From (5), the turn-off time $t_{\sim off}$ of phase A and the turn-on time $t_{\sim on}$ of phase B during the commutation process are

$$t_{\sim off} = \frac{3LI_0}{U_d+2E_m} \tag{7}$$

$$t_{\sim on} = \frac{3LI_0}{2(U_d-E_m)} \tag{8}$$

From (5)~(8), the commutation between two phases can't be completed in the same time as $U_d > 4E_m$, i.e. the motor speed is less than a certain value, and as a result i_B has reached its steady-state value before i_A falls to 0, shown in Fig.2(I). What's more, the commutation leads to an increase in the amplitude of torque. The torque ripple can be obtained

$$T_r = \frac{E_m I_0}{\Omega} \bullet \frac{U_d-4E_m}{U_d-E_m} \tag{9}$$

The commutation between two phases can be completed in the same time as $U_d = 4E_m$, i.e. the motor runs at a certain speed, and as a result i_B has exactly reached its steady-state value just as i_A falls to 0, shown in Fig.2(II). In this case, the torque remains constant during the commutation and its value equals the torque during the non-commutation process.

$$T_e = \frac{2E_m I_0}{\Omega} \tag{10}$$

As $U_d < 4E_m$, i.e. the motor speed is greater than a certain value, the commutation between two phases can't be completed in the same time, and as a result i_B doesn't reached its steady-state value when i_A falls to 0, shown in Fig.2(III). The commutation leads to a decrease in the amplitude of torque. The torque ripple can be obtained

$$T_r = \frac{2E_m I_0}{\Omega} \bullet \frac{U_d-4E_m}{U_d+2E_m} \tag{11}$$

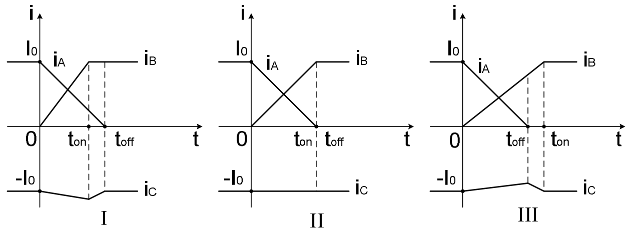

Fig.2 Waveforms of phase currents during commutation in different cases

IV. Commutation Torque Ripple Compensation Control in PWM Mode

It is known based on the previous analysis that the torque ripple caused by commutation can be finally eliminated by two ways-reducing current rate of increase in the turn-on phase to suppress the current pulsation in the non-commutation phase as the motor speed is less than a certain value; commutation overlapping to keep the turn-on phase constantly on and use PWM mode in the power switches of the turn-off phases to decrease current rate of descend to suppress the current pulsation in the non-commutation phase as the motor speed is greater than a certain value.

Assume that S_X is the electric level state variables (X=A, B, C), S_x=1 represents turn-on of power switch or diode in the upper arm of the corresponding phase whie S_x=0 represents turn-on of power switch or diode in the lower arm of the corresponding phase.

As the motor runs at a low speed, PWM is implemented on the turn-on phase, i.e. turn off phase A while PWM on phase B, in order to reduce current rate of increase in the turn-on phase during commutation. The circuit equation during commutation is

$$\begin{cases} L\dfrac{di_A}{dt}+ri_A+e_A-(L\dfrac{di_C}{dt}+ri_C+e_C)=0 \\ L\dfrac{di_B}{dt}+ri_B+e_B-(L\dfrac{di_C}{dt}+ri_C+e_C)=S_BU_d \end{cases} \tag{12}$$

It can be obtained from (1), (2) and (12)

$$\begin{cases} L\dfrac{di_C}{dt}+ri_C=-\dfrac{U_d-4E_m}{3} & \text{as } S_B=1 \\ L\dfrac{di_C}{dt}+ri_C=\dfrac{4E_m}{3} & \text{as } S_B=0 \end{cases} \tag{13}$$

So non-commutation phase current can be got

$$-i_C=I_0-(I_0-\frac{D_{BB}U_d-4E_m}{3r})(1-e^{-\frac{r}{L}t}) \tag{14}$$

Where D_{BB} is control pulse duty cycle of the turn-on phase during the commutation.

From (12) and (13), we can get

$$\begin{cases} L\dfrac{di_A}{dt}+ri_A=-\dfrac{U_d+2E_m}{3} & \text{as } S_B=1 \\ L\dfrac{di_A}{dt}+ri_A=-\dfrac{2E_m}{3} & \text{as } S_B=0 \end{cases} \tag{15}$$

Therefore turn-off phase current can be worked out.

$$i_A=-\frac{D_{BB}U_d+2E_m}{3r}+(I_0+\frac{D_{BB}U_d+2E_m}{3r})e^{-\frac{r}{L}t} \tag{16}$$

The turn-off time of the turn-off phase t_{off} is

$$t_{off}=\frac{L}{r}\ln(1+\frac{3rI_0}{D_{BB}U_d+2E_m}) \tag{17}$$

From (14), the following equation must be satisfied in order to keep the amplitude of non-commutation phase current unvaried during commutation.

$$D_{BB}=\frac{4E_m+3rI_0}{U_d} \tag{18}$$

Because $0\le D_{BB}\le 1$ during commutation, it means that the inequation will be satisfied only if $4E_m+3rI_0\le U_d$, i.e. the motor runs at a low speed. Furthermore as the machine operates at a low speed, it can be obtained from (14)

(1) When $D_{BB}<\dfrac{4E_m+3rI_0}{U_d}$, i.e. under-compensated control during commutation, the amplitude of non-commutation phase current decreases during commutation.

(2) When $D_{BB}>\dfrac{4E_m+3rI_0}{U_d}$, i.e. over-compensated control during commutation, the amplitude of non-commutation phase current increases during commutation.

Substitute (18) into (17), we can get the commutation time that keeps the amplitude of non-commutation phase current constant during commutation as the machine operates at a low speed.

$$t_c=\frac{L}{r}\ln(1+\frac{rI_0}{rI_0+2E_m}) \tag{19}$$

As the motor runs at a high speed, overlapping commutation is adopted to implement PWM on the turn-off phase and turn on the turn-off phase constantly, i.e. PWM on phase A while turn on phase B constantly, in order to reduce non-commutation current ripple during commutation. The circuit equation during commutation is

$$\begin{cases} L\dfrac{di_A}{dt}+ri_A+e_A-(L\dfrac{di_C}{dt}+ri_C+e_C)=S_AU_d \\ L\dfrac{di_B}{dt}+ri_B+e_B-(L\dfrac{di_C}{dt}+ri_C+e_C)=U_d \end{cases} \tag{20}$$

It can be obtained from (1), (2) and (20)

$$\begin{cases} L\dfrac{di_C}{dt}+ri_C=-\dfrac{2U_d-4E_m}{3} & \text{当 } S_A=1 \\ L\dfrac{di_C}{dt}+ri_C=-\dfrac{U_d-4E_m}{3} & \text{当 } S_A=0 \end{cases} \tag{21}$$

So non-commutation phase current can be got

$$-i_C=I_0-(I_0-\frac{U_d+D_{AA}U_d-4E_m}{3r})(1-e^{-\frac{r}{L}t}) \tag{22}$$

Where D_{AA} is control pulse duty cycle of the turn-off phase during the commutation.

From (20) and (21), we can get

$$\begin{cases} L\dfrac{di_B}{dt}+ri_B=\dfrac{U_d-2E_m}{3} & \text{as } S_A=1 \\ L\dfrac{di_B}{dt}+ri_B=\dfrac{2U_d-2E_m}{3} & \text{as } S_A=0 \end{cases} \tag{23}$$

Therefore turn-on phase current can be worked out.

$$i_B=\frac{2(U_d-E_m)-D_{AA}U_d}{3r}-\frac{2(U_d-E_m)-D_{AA}U_d}{3r}e^{-\frac{r}{L}t} \tag{24}$$

The turn-on time of the turn-on phase t_{on} is

$$t_{on}=\frac{L}{r}\ln[\frac{2(U_d-E_m)-D_{AA}U_d}{2(U_d-E_m)-D_{AA}U_d-3rI_0}] \tag{25}$$

From (22), the following equation must be satisfied in order to keep the amplitude of non-commutation phase current unvaried during commutation.

$$D_{AA}=\frac{4E_m+3rI_0}{U_d}-1 \tag{26}$$

Because $0\le D_{AA}\le 1$ during commutation, it means that the inequation will be satisfied only if $4E_m+3rI_0\ge U_d$, i.e. the motor runs at a high speed. Furthermore as the machine operates at a high speed, it can be obtained from (22)

(1) When $D_{BB} < \frac{4E_m + 3rI_0}{U_d} - 1$, i.e. under-compensated control during commutation, the amplitude of non-commutation phase current decreases during commutation.

(2) When $D_{BB} > \frac{4E_m + 3rI_0}{U_d} - 1$, i.e. over-compensated control during commutation, the amplitude of non-commutation phase current increases during commutation.

Substitute (26) into (25), we can get the commutation time that keeps the amplitude of non-commutation phase current constant during commutation as the machine operates at a high speed.

$$t_c = -\frac{L}{r}\ln(1 - \frac{rI_0}{U_d - 2E_m - rI_0}) \tag{27}$$

The same conclusion can be drawn when a similar analysis is carried out for the lower arms

V. TORQUE RIPPLE REDUCTION IN PWM MODE

In [14] and [15], a new PWM mode is presented—PWM_ON_PWM, i.e. using PWM mode in the first 30° and the last 30° while keeping constant turn-on mode in the middle 60°. The mode can entirely eliminate the emerging current in the turn-off phase during non-commutation and thus reduce the torque ripple during non-commutation.

PWM_ON_PWM is a bilateral modulation, but the dynamic losses of power switches in the mode are equal to those of unilateral modulation. Six switches are modulated in turn, so the power switches have a uniform radiation and the system has a higher reliability. The mode is employing PWM on the turn-on power switches and thus it can suppress the torque ripple during commutation to a certain extent even if a compensation control is not applied at a low speed.

In PWM_ON_PWM mode, it can not only eliminate the torque ripple during non-commutation but also suppress the commutation torque ripple at low speed operation by keeping $D_{BB} = \frac{4E_m + 3rI_0}{U_d}$ in the commutation compensation control time $t_c = \frac{L}{r}\ln(1 + \frac{rI_0}{rI_0 + 2E_m})$ at low speed operation, i.e. $4E_m + 3rI_0 \le U_d$. At high speed operation i.e. $4E_m + 3rI_0 \ge U_d$, overlapping commutation is used to keep the turn-on phase constantly on and make the control pulse duty cycle of the turn-off phase $D_{AA} = \frac{4E_m + 3rI_0}{U_d} - 1$ in the commutation compensation control time $t_c = -\frac{L}{r}\ln(1 - \frac{rI_0}{U_d - 2E_m - rI_0})$, which can not only eliminate the torque ripple during non-commutation but also suppress the commutation torque ripple at high speed operation

A simulation is carried out to verify the method. The parameters are

L=26mH, r=0.66Ω, J=0.0157kg·m^2, U_N=48V, n_N=1600r/m, T_L=0.4N.

In non-full-bridge modulation mode such as H_PWM-L_ON mode, power switches in the upper arms use PWM mode while the others in the lower arms use constant turn-on mode in 120^0 turn-on interval. The simulation waveform of phase current is shown in Fig. 3. It is obvious that a current emerges in the turn-off phase during non-turn-on period and its pulsating frequency is the same as the modulating frequency while its amplitude varies with the variation of back emf amplitude, which produces a reverse torque.

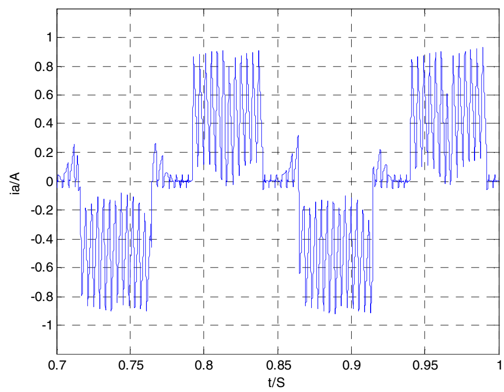

Fig.3 Waveform of phase current in H_ PWM -L_ ON mode

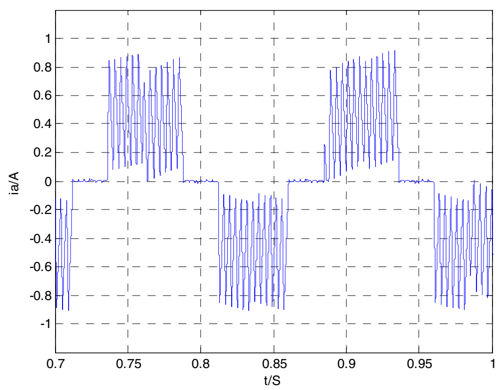

Fig.4 Waveform of phase current in PWM_ON_PWM mode

The simulation waveform of phase current in PWM ON_PWM mode is shown in Fig. 4. It is obvious that no current emerges in the turn-off phase during non-turn-on period, which reduces the torque ripple during non-commutation compared with other PWM mode.

Fig. 5 shows the waveforms of the phase current and torque at low speed with PWM pulse duty cycle D_A=0.2 without compensation control. Fig. 6 shows the waveforms of the phase current and torque at low speed with the control pulse duty cycle D_{BB}=0.4 in the turn-on phase within the commutation time t_c=0.0013 by a compensation control. The comparison indicates that the torque ripple caused by commutation can be almost eliminated by means of a commutation compensation control at low speed application.

It is found from Fig.3 to Fig.8 that using a commutation compensation control in PWM_ON_PWM mode can not only avoid the torque ripple caused by the emerging current in the turn-off phase during non-commutation but also effectively suppress the commutation torque ripple at both low speed and high speed applications.

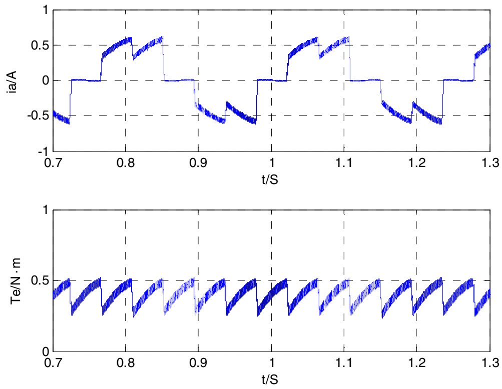

Fig.5 Waveforms of phase current and torque at low speed

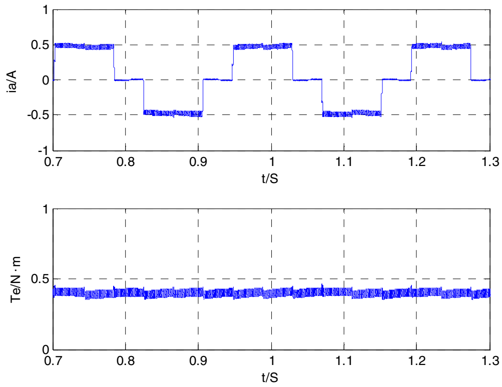

Fig.6 Waveforms of phase current and torque at low speed by compensation control

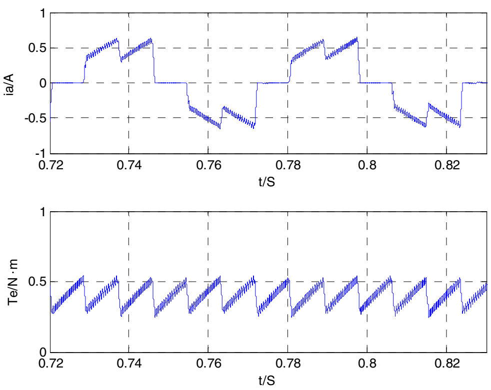

Fig.7 Waveforms of phase current and torque at high speed

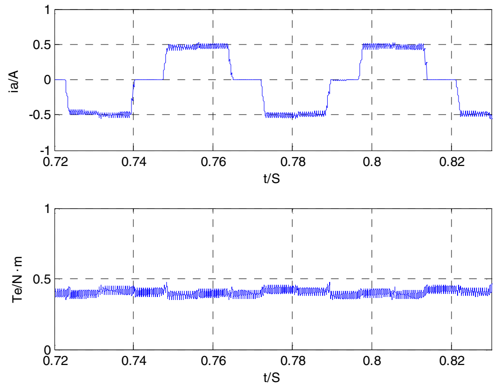

Fig.8 Waveforms of phase current and torque at high speed by compensation control

VI. CONCLUSIONS

Based on the analysis of commutation process of BLDC motor and the effect by PWM mode on the control system, a commutation compensation control in PWM_ON_PWM mode is worked out, which can not only eliminate torque ripple resulted from the current emerging in the turn-off phase during non-commutation period but also compensate commutation torque ripple. A control system without torque ripple can be realized through the method under both low speed and high speed operation,

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