# CURRENT CONTROL ALGORITHM TO REDUCE TORQUE RIPPLE IN BRUSHLESS DC MOTORS

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**ABSTRACT** - This paper proposes a current control algorithm to reduce the torque ripple due to commutation in unipolar PWM inverter-fed trapezoidal brushless dc motor drives. In this paper, we analyze the average voltage variation of the conducting phase due to commutation, and design a current controller to compensate for the average voltage variation. The proposed method predicts the duration of commutation to reduce the torque ripple due to over-compensation. Experimental results are presented that validate the proposed method.

## 1. INTRODUCTION

The trapezoidal brushless dc motors fed with ideal rectangular current generate smooth instantaneous torque. However, ideal rectangular current shapes can not be realized in practice due to the phase inductance and finite inverter voltage. Because of this, noncommutated phase current undulates due to phase commutation and this pulsating current generates undesirable torque ripple. The commutation torque ripple varies with speed and may reach 50% of the average torque[1]. To apply the brushless dc motors to servo applications, it is required to minimize the commutation torque ripple, because the torque ripple generates noise and vibrations and causes errors in motion control applications.

Murai et al. introduced two different methods for reducing the commutation torque ripple when a single current sensor is used in the dc link of the inverter to regulate the current flowing through two motor phases in series[2]. This methods are inappropriate to apply to various trapezoidal brushless dc motors, because they are open loop in nature.

The introduction of independent current sensors in the motor phases provides a powerful approach for reducing commutation torque ripple, because the current regulation of each phase is possible during commutation periods[3]. Carlson et al. demonstrated that the commutation torque ripple can be minimized during low speed by the introduction of direct phase current sensing with hysteresis current controller[1]. In the hysteresis current controller. the switching frequency depends on the value of hysteresis band, which is a practical limitation on the power device switching capability[4].

The advantage of PWM current controller over hysteresis is that the switching frequency is constant. Berendsen et al. showed that the commutation torque ripple can be reduced by the introduction of feed-forward term in current controller to compensate for the average voltage variation of the noncommutated phase due to commutation in bipolar PWM inverter-fed brushless dc motor drives[5]. However, this method can not be applied to unipolar PWM, because the voltage between the neutral point of the inverter and the neutral point of the machine varies with on-off status of switching device of the inverter.

This paper proposes a current control algorithm to minimize the commutation torque ripple in unipolar PWM inverter-fed trapezoidal brushless dc motor drives. The average voltage variations of the conducting phase due to commutations are analyzed, and a current controller which compensates for average voltage variations is designed. The proposed method predicts the duration of commutation to reduce the torque ripple due to over-compensation. Experimental results are presented that validate the proposed method.

## 2. CURRENT CONTROL STRATEGY FOR REDUCTION OF COMMUTATION TORQUE RIPPLE

### 2.1 PWM Pulse Patterns in Two Phase Feeding Scheme

Fig. 1 shows the voltage source inverter and the equivalent circuit of brushless dc motor, and Fig. 2 shows commonly used PWM pulse patterns in two phase feeding scheme. As shown in Fig 2, the bipolar PWM strategy controls two conducting branches of the inverter legs simultaneously, and the unipolar PWM strategy controls only one conducting branch selectively. The switching loss of unipolar PWM strategy is less than that of bipolar, because only one branch of inverter legs is turned on and turned off.

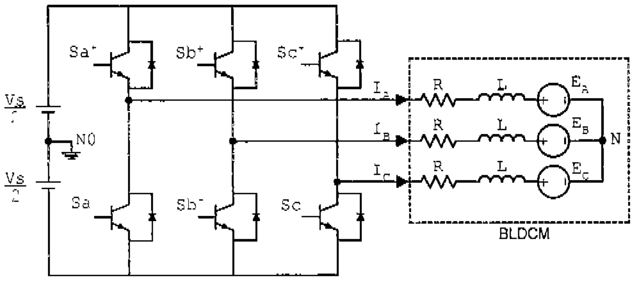


Fig. 1 Voltage source inverter and the equivalent circuit of brushless dc motor.

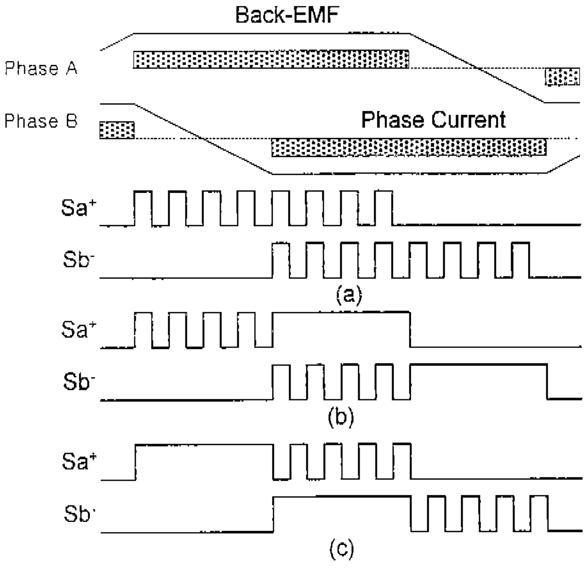


Fig. 2. PWM pulse patterns in two phase feeding scheme. (a)Bipolar PWM, (b)On-going phase unipolar PWM, (c)Out-going phase unipolar PWM.

## 2.2 Current Control Strategy to Reduce the Commutation Torque Ripple in On-going Phase Unipolar PWM

In unipolar PWM inverter-fed trapezoidal brushless dc motor drives, $V_{m1}$, the average voltage of conducting phase during two phase conduction period, is given by:

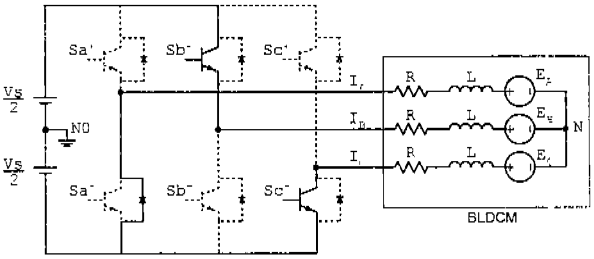
$$V_{m1} = \frac{V_S D_A}{2} \tag{1}$$

where

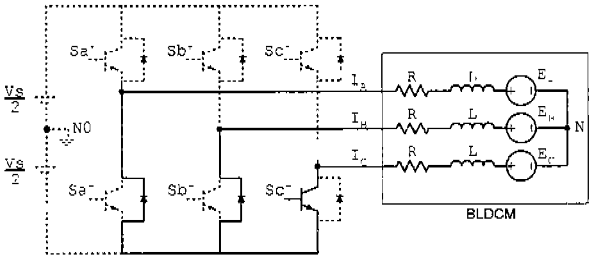
$V_S$ is the inverter dc-link voltage,

$D_A$ is the PWM duty ratio during two phase conduction period.

Fig. 3 shows current paths in on-going phase unipolar PWM scheme when the phase current is being transferred from phase A to phase B.



(a) Sb+ = Sc- = ON



(b) Sb+ =OFF, Sc- = ON

Fig. 3. Current paths in on-going phase unipolar PWM scheme when the phase current is being transferred from phase A to phase B.

From Fig. 3, the voltage equations according to the switching function is given by:

$$\begin{aligned} -\frac{V_S}{2} &= RI_A + L\frac{dI_A}{dt} + E_A + V_{NN0} \\ \frac{V_S}{2}(2S-1) &= RI_B + L\frac{dI_B}{dt} + E_B + V_{NN0} \\ -\frac{V_S}{2} &= RI_C + L\frac{dI_C}{dt} + E_C + V_{NN0} \end{aligned} \tag{2}$$

where

$S$ is the switching function(ON=1, OFF=0),

$R$ is the phase resistance,

$L$ is the phase inductance,

$I_A$, $I_B$, $I_C$ are the currents for phases A,B,C,

$E_A$,$E_B$,$E_C$ are the electromotive forces(EMF) for phases A,B,C,

$V_{NN0}$ is the voltage between the neutral point N0 of the inverter and the neutral point N of the machine.

From (2), the $V_{NN0}$ voltage during commutation is given by:

$$V_{NN0} = \begin{cases} -\dfrac{V_S}{6} - \dfrac{E_A + E_B + E_C}{3} (S_b^+ = ON) \\ -\dfrac{V_S}{2} - \dfrac{E_A + E_B + E_C}{3} (S_b^+ = OFF) \end{cases} \tag{3}$$

From (3), $V_{m2}$, the average voltage of the noncommutated phase during commutation, is derived as following:

$$V_{m2} = \frac{V_S D_B}{3} - \frac{E_A + E_B + E_C}{3} \tag{4}$$

where $D_B$ is the PWM duty ratio in commutation period.

From (1) and (4), it is apparent that the average voltage of the noncommutated phase is disturbed by commutation. This voltage disturbance causes pulsating phase current, which generates the pulsating torque. Hence, to minimize this pulsating current, the PWM duty ratio during commutation must be modified as (5) in order that the average voltage of the noncommutated phase maintains constant value.

$$D_B = \frac{3}{2} D_A + \frac{E_A + E_B + E_C}{V_S} \tag{5}$$

where

$D_A$ is the PWM duty ratio of inverter during two phase conduction period,

$D_B$ is the PWM duty ratio of inverter during commutation period.

If the amplitude of back-emf is constant during commutation and is linearly proportion to the speed, (5) can be approximated as (6).

$$D_B = \frac{3}{2} D_A + \frac{K_e \omega_m}{V_S} \tag{6}$$

where

*Ke* is the back-emf constant of machine,

$\omega_m$ is the speed of machine [rad/sec].

Fig. 4 shows the current regulation loop proposed in this paper for the purpose of reducing commutation torque ripple in on-going phase unipolar PWM scheme. In fig. 4, the PWM duty ratio of the inverter during two phase conduction period is given by PI type controller, and the PWM duty ratio during commutation is given by (6).

In the digital implementation of the proposed current controller, there is always a conversion delay time in sampling the phase currents. When the high-speed microprocessor is used, the amplitude of the phase currents sampled at the previous step is commonly used in current regulation loop. When the off-going phase current sampled at the previous step is used in deciding whether commutation is completed or not, excessive PWM duty ratio may be applied to the inverter during one current sampling period, even though commutation is completed. In this case, the pulsating current due to over-compensation is generated. To solve this problem, the algorithm which predicts the duration of commutation is included in the current controller.

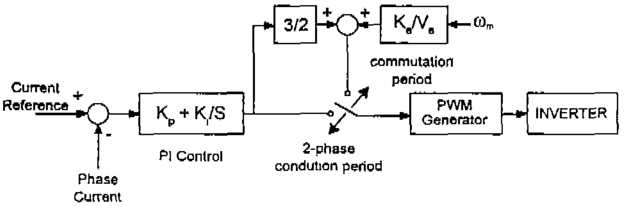


Fig. 4. Proposed current regulation loop to reduce the commutation torque ripple in on-going phase unipolar PWM scheme.

$V_{m3}$, the average voltage of the off-going phase during commutation, is given by:

$$V_{m3} = -\frac{V_S D_B}{3} + \frac{K_e \omega_m}{3} \tag{7}$$

The voltage equation of the off-going phase during commutation is given by:

$$Ri + L\frac{di}{dt} = -\frac{V_S D_B}{3L} + \frac{2K_e \omega_m}{3L} \tag{8}$$

By solving the differential equation, $T_f$, the duration of commutation, is given by:

$$T_f = -\frac{L}{R} \ln \left( \frac{\dfrac{V_S D_B + 2K_e \omega_m}{3R}}{i(0) + \dfrac{V_S D_B + 2K_e \omega_m}{3R}} \right) \tag{9}$$

where *i(0)* is the initial value of the off-going phase current.

To attenuate the torque ripple due to over-compensation, when the commutation is completed before the next current control step, the PWM duty ratio $D$ is decided as following:

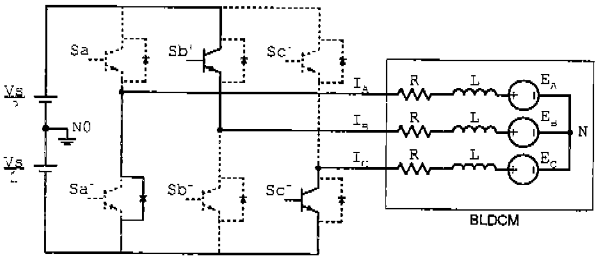
$$D = D_B \times \frac{t1}{ts} + D_A \times \frac{(ts - t1)}{ts} \tag{10}$$

where

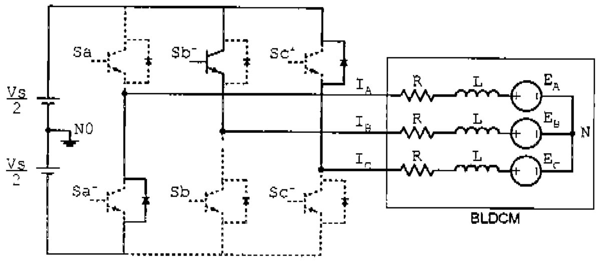
$ts$ is the sampling time of current controller,
$t1$ is the predicted end time of commutation.
($t1 = T_f$ modulus $ts$)

### 2.3 Current Control Strategy to Reduce the Commutation Torque Ripple in Out-going Phase Unipolar PWM

Fig. 5 shows current paths in out-going phase unipolar PWM scheme when the phase current is being transferred from phase A to phase B.



(a) $Sb = Sc^- = ON$



(b) $Sb^+ = ON$, $Sc^- = OFF$

Fig. 5. Current paths in out-going phase unipolar PWM scheme when the phase current is being transferred from phase A to phase B.

From Fig. 5, $V_{NN0}$ voltage during commutation is given by:

$$V_{NN0} = \begin{cases} -\dfrac{V_S}{6} - \dfrac{E_A + E_B + E_C}{3} & (S_c^- = ON) \\ -\dfrac{V_S}{2} - \dfrac{E_A + E_B + E_C}{3} & (S_c^- = OFF) \end{cases} \qquad (11)$$

From (11), $V_{m2}$, the average voltage of the noncommutated phase, is derived as following:

$$V_{m2} = \frac{2}{3} V_S D_B - \frac{V_S}{3} - \frac{E_A + E_B + E_C}{3} \qquad (12)$$

The PWM duty ratio $D_B$ during commutation in order to compensate for the average voltage variation of noncommutated phase due to commutation is given by:

$$D_B = \frac{1}{2} + \frac{3D_A}{4} + \frac{K_e \omega_m}{2V_S} \qquad (13)$$

Fig. 6 shows the current regulation loop proposed in this paper for the purpose of reducing commutation torque ripple in out-going phase unipolar PWM scheme. As mentioned earlier, the algorithm which predicts the duration of commutation is included in the current controller to solve the over-compensation problem.

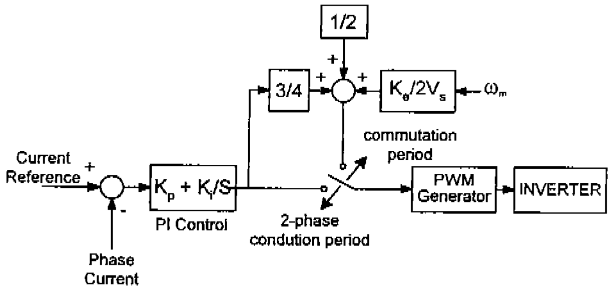


Fig. 6. Proposed current regulation loop to reduce the commutation torque ripple in out-going phase unipolar PWM scheme.

## 3. EXPERIMENT

To verify the feasibility of the proposed algorithm, experiments are carried out. The parameters of motor used in experiments are given in Table 1. Fig. 7 shows the experimental setup. The proposed current controller is realized using digital signal processor(TMS320C31). The inverter is implemented with intelligent power module, and the PWM frequency is set to 10khz

Table 1 Motor parameters

| Motor | Trapezoidal 3 phase brushless dc motor(surface mounted permanent magnet motor) |
|---|---|
| Rates power | 300 W |
| Rated speed | 3000 rev/min |
| Rated torque | 0.95 Nm |
| Continuous current | 3.44 A |
| Number of rotor pole | 6 |
| Phase resistance | 1.5 Ω |
| Phase inductance | 3.15 mH |
| Torque constant | 0.29 Nm/A |
| Back-emf constant | 0.29 V/(rad/sec) |

Experimental results when the motor rotates at 1,000 rpm are shown from Fig. 8 to Fig. 12. Fig. 8 shows the phase current waveform when the conventional PI type controller is used for current regulation in on-going phase unipolar PWM scheme. As shown in Fig. 8, the pulsating current which causes torque ripple is generated during commutation. To compensate for the average voltage variation which causes pulsating phase current, it is required to increase the loop bandwidth of the current controller. However, there is a limit in increasing the loop bandwidth of a programmable controller[5]. Thus, the pulsating current can not be minimized completely with the PI type current controller.

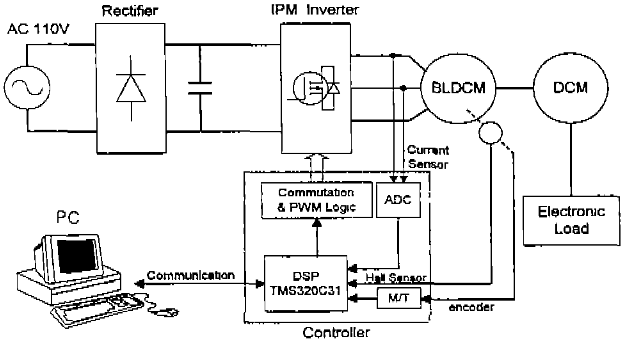


Fig. 7. Experimental setup.

Fig. 9 shows the phase current waveform when the proposed current controller without algorithm which predicts the duration of commutation is used in on-going phase unipolar PWM scheme. Fig. 10 shows the magnified phase current waveforms of Fig. 9. As shown in Fig. 9, the pulsating current due to over-compensation is generated. It is evident that the over-compensation generates the pulsating current by examining Fig. 10.

Fig. 11 shows the phase current waveform when the proposed current controller with algorithm which predicts the duration of commutation is used in on-going phase unipolar PWM scheme. Fig. 12 shows the magnified phase current waveforms of Fig. 11. As shown in Fig. 11 and Fig. 12, the pulsating current due to commutation and over-compensation is not appeared.

Fig. 13 shows the current waveform when the motor rotates at 3,000 rpm. In obtaining Fig. 13, the proposed current controller with algorithm which predicts the duration of commutation has been used with on-going phase unipolar PWM scheme.

As shown in the experimental results, the proposed current controller reduces the pulsating current due to commutation in wide speed range. However, there is a limit in the capability of the proposed current controller, because of the finite inverter voltage. The PWM duty ratio can not be larger than 1. Thus, the pulsating current due to commutation can not be minimized completely when the PWM duty ratio calculated from (5), or (12) is larger than one.

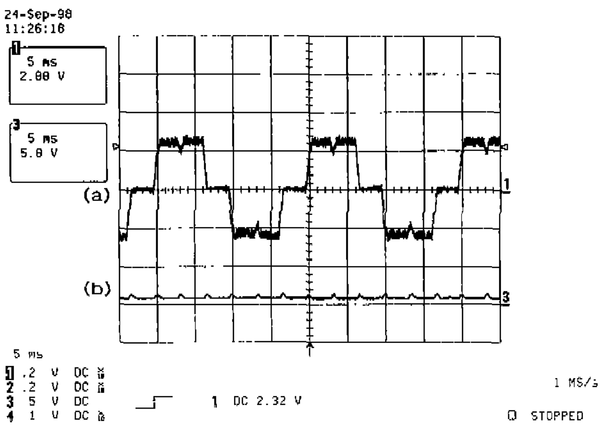


Fig. 8. Experimental results with the PI type current controller. (a) Phase current(2.5A/div)
(b) PWM duty ratio(full duty/div)

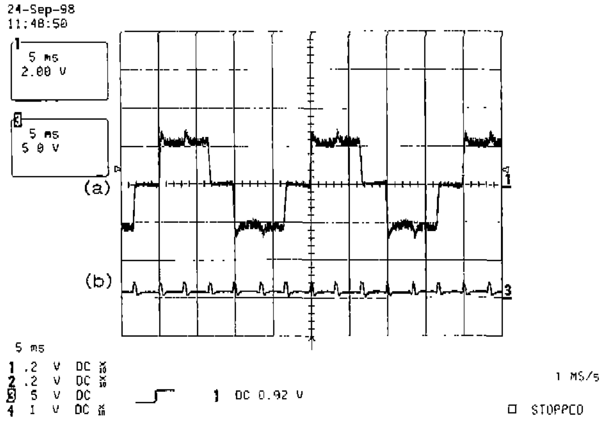


Fig. 9. Experimental results with the proposed controller without prediction algorithm of commutation duration.
(a) Phase current(2.5A/div).
(b) PWM duty ratio(full duty/div).

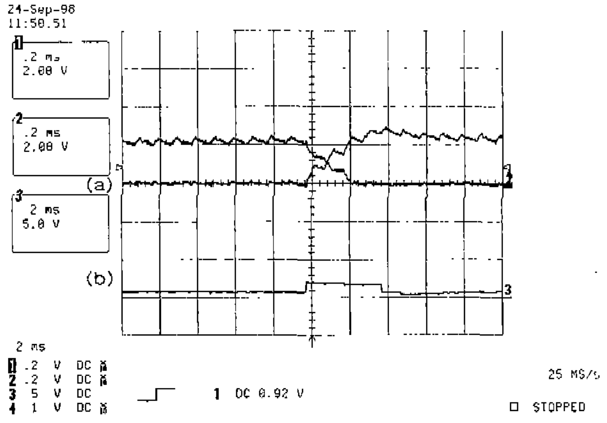


Fig. 10. Experimental results with the proposed controller without prediction algorithm of commutation duration.
(a) Phase current(2.5A/div).
(b) PWM duty ratio(full duty/div).

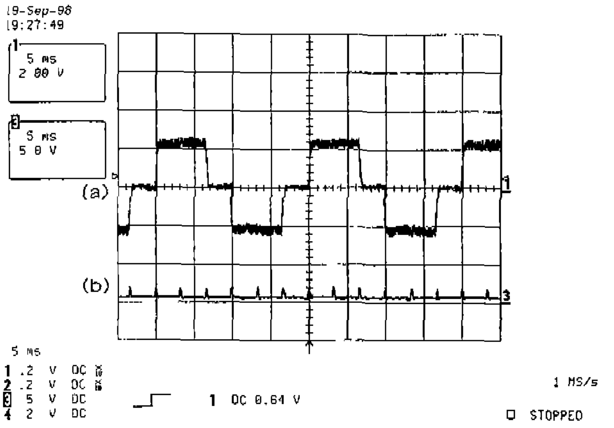


Fig. 11. Experimental results with the proposed controller with prediction algorithm of commutation duration.
(a) Phase current(2.5A/div).
(b) PWM duty ratio(full duty/div).

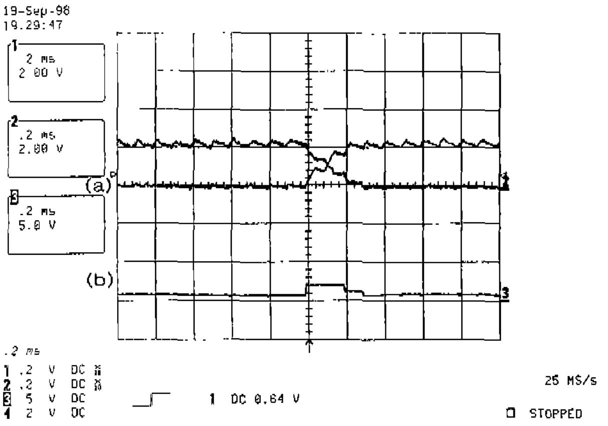


Fig. 12. Experimental results with the proposed controller with prediction algorithm of commutation duration.
(a) Phase current(2.5A/div).
(b) PWM duty ratio(full duty/div).

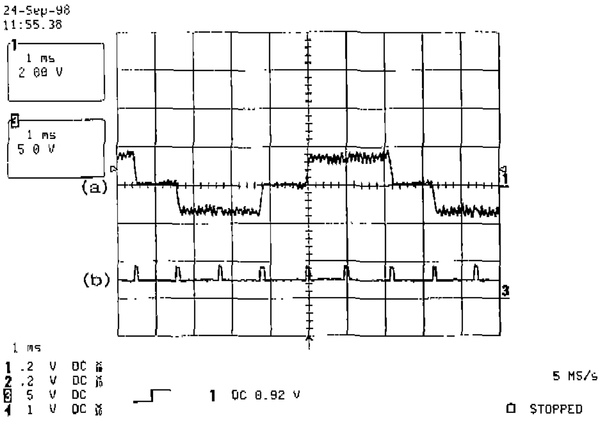


Fig. 13. Experimental results with the proposed controller with prediction algorithm of commutation duration.
(a) Phase current(2.5A/div).
(b) PWM duty ratio(full duty/div).

## 4. CONCLUSION

This paper has presented a current control algorithm to reduce the commutation torque ripple in unipolar PWM *inverter-fed trapezoidal brushless dc motor drives*. The average voltage variations of the noncommutated phase due to commutation were analyzed, and a current controller to compensate for this voltage disturbance was designed. To minimize the pulsating current due to over-compensation, the proposed algorithm predicts the duration of commutation and modifies the PWM duty ratio. To verify the feasibility of the proposed current control algorithm, experiments were carried out in wide speed range. The experimental results show that the proposed current control algorithm minimizes the pulsating torque due to commutation very well.

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