An Improved Current Control Method for Torque Improvement of High-Speed BLDC Motor

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***Abstract*— The BLDC (Brushless DC) motor is characterized by linear torque to current and speed to voltage. It has low acoustic noise and fast dynamic response. Moreover, it has high power density with high proportion of torque to inertia in spite of small size drive. However, at high-speed operation, torque and speed response characteristic is deteriorated by the motor inductance components in stator windings. It is difficult that the BLDC motor is used to the industrial application requiring a wide range of operating speeds. Phase advance angle control method of different methods used to improve torque and speed response is used widely at high-speed operation. However, conventional phase advance angle control method was considered about forward motoring mode. Therefore, position information error of rotor that reverse motoring mode has phase lag angle of double comparing with forward motoring mode is occurred. Consequently, torque performance is destroyed significantly. In this paper, a control method using adjustment of the phase advance angle is proposed. This proposed method improves the torque and speed response characteristic by minimizing delay of current at high-speed operation. Simulated results prove the effectiveness of the proposed method through comparison with the conventional control method.**

Keywords- Phase Advance Angle, Forward Motoring, Reverse Motoring

I. INTRODUCTION

BLDC motors have been popular with industrial fields, because it has the high efficiency, high power density, low acoustic noise, and low maintenance cost due to the removal of the mechanical commutators and brushes [1]. BLDC motor is operated ideally, when phase current of rectangular shape is injected at the flat part of back-EMF waveform. However, practically, phase current is not achieved to rated current level instantaneously due to the inductance component of stator windings. At low-speed, this will not cause any serious problem since the inductance effect is negligible. However, at high- speed the motor performance will be significantly deteriorated [2]. Therefore, an optimization of the drive system is required to improve the performance of phase current, since this is a paramount factor to improve the output torque and speed response characteristic of the BLDC motor used to industrial application as electric vehicle. To improve the performance of BLDC motors, different control methods have been developed by many researchers. Those are such as the field weakening control method, overlapping method, PWM chopping method [3]-[6].

In this paper, proposed method improves output torque and speed response characteristic by adjusting phase advance angle to drive in optimum operation according to change of the various speed, particularly such as high-speed operation. In conventional phase advance angle control method, had varied position of hall sensor or had used algorithm considered to forward motoring mode. Therefore, position information error of rotor that have phase lag angle of double comparing with forward motoring mode in case of reverse motoring mode is occurred and phase advance angle was applied circumscriptively in industrial fields that need both forward and reverse motoring, because torque performance destroyed significantly. However, BLDC motor is driven efficiently by applying proposed phase advance angle technique. The developed phase advance angle control method generates optimum torque and accurate speed response. Therefore, the proposed control scheme of BLDC motor drive based on the phase advance angle control is a good alternative to the conventional counterpart with respect to optimization of BLDC motor drive. The validity of the proposed control scheme is verified through the simulated results in comparison with the conventional control method.

II. PRINCIPLE OF BLDC MOTOR

A. Modeling of BLDC Motor

The BLDC motor is an ac synchronous motor with permanent magnet mounted on the rotor and stator windings. The block diagram of BLDC motor drive is shown in Fig. 1.

The modeling is based on the following assumptions:

(1) The motor is not saturated.

(2) Stator resistances of all windings are equal and self and mutual inductances are constant.

(3) Power semiconductor devices in the inverter are ideal.

(4) Iron losses are negligible.

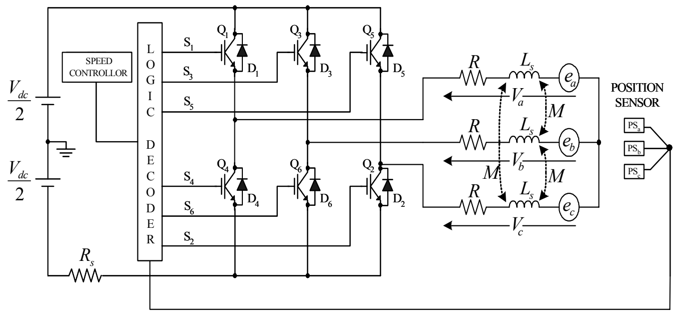

Figure 1. Block Diagram of BLDC Motor Drive.

Under the above assumptions, a BLDC motor can be represented as

$$\begin{bmatrix} v_a \\ v_b \\ v_b \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where, *e_a, e_b, and e_c are trapezoidal shaped back -EMFs, and i_a, i_b, and i_c are rectangular shaped currents, and $L=L_s - M$.*

The electromagnetic torque is expressed as

$$T_e = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \tag{2}$$

Assuming that there is no phase difference between current and back-EMF, we can write the electromagnetic torque as

$$T_e = \frac{2EI}{\omega_m} \tag{3}$$

The interaction of T_e with the load torque determines how the motor speed is built up

$$T_e = T_L + J\frac{d\omega_m}{dt} + B\omega_m \tag{4}$$

where, *T_L is load torque, J is inertia, and B is the viscous damping.*

B. Relations of Back-EMF and Current

The general type of position sensing for the BLDC motor is use to Hall-effect position sensors to detect the flux distributions of rotor magnets [7]. Fig.2 shows the relative waveforms of back-EMF and winding current. Fig. 2(a) shows ideal back-EMF and current waveform. But the ideal currents input is impossible actually because of resistance and inductance component of stator windings, as shown in Fig. 2(b). Furthermore, as motor speed increases, phase current has the lager delay of phase-shift, θ, as shown in Fig. 2(c). Nevertheless, phase current is achieved to rated current level rapidly by predicting magnet flux of rotor observed from hall-effect position sensors, which is achieved through phase advance angle of ϕ, as shown in Fig. 2(d).

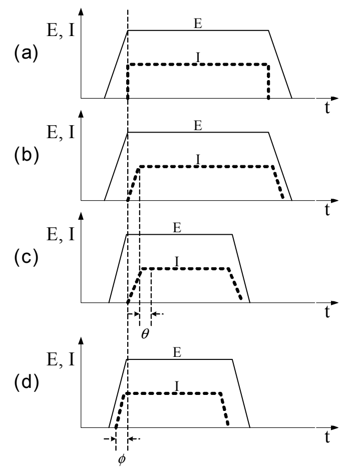

Figure 2. The Relative Waveforms of Back-EMF and Phase Current; (a) Ideal Waveforms, (b) Actual Waveforms, (c) Waveforms at High Speed, (d) Waveforms Using Phase Advance Angle.

C. Operation of BLDC Motor

Consider the forward and reverse motoring operation of the BLDC motor with six-switch inverter topology. The forward motoring is shown in Fig. 3(a), where the phase sequence is maintained **a-b-c**, with the current injected into the windings when their respective induced back-EMFs experience flat region with the 120 electrical degree. Fig. 3(b) shows reverse motoring, which is obtained by changing the phase sequence to **a-c-b** to obtain the reverse motoring direction. The other words, this mode is very similar to the forward motoring.

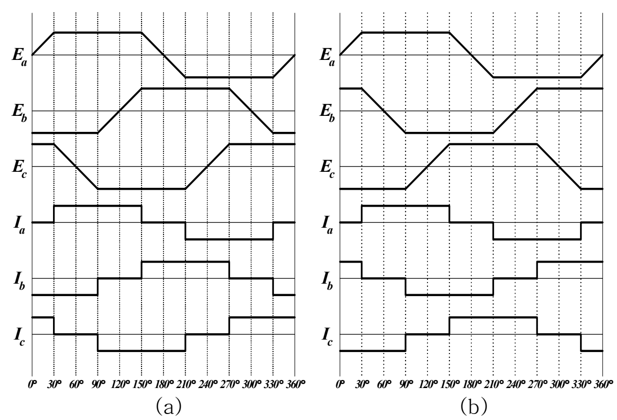

Figure 3. Back-EMF and Phase Current Waveforms during Forward and Reverse Motoring; (a) Forward Motoring Mode, (b) Reverse Motoring Mode.

III. APPROACH FOR OBTAINING OPTIMUM PHASE ADVANCE ANGLE

In most previous works, it has been assumed that each phase back-EMF waveform has a half-wave symmetrical and identical form and also has same magnitude for three phase windings except phase offset of $2\pi/3$ [rad]. Also, a current is achieved to rated level by using current controlled unipolar PWM strategy.

At low-speed, the current waveform is close to the rectangular waveform, with a short pulse of voltage applied at the beginning and end of each phase-conduction interval to force the necessary change in current level. During each interval, the average voltage slightly exceeds the back-EMF by an amount equal to the voltage drop across the winding resistance.

At high-speed, the inductive reactance of the windings results in a significant time delay and, as a consequence, the time taken for the current to reach its rated value is a large portion of the phase conduction interval and the rated current level is attained only at the end of the interval. The output torque of the drive decreases, since the current magnitude is low and it is out of phase with the back-EMF. This situation can be compensated to some extent by changing each phase earlier. If the phase advance procedure is employed, phase current in the motor winding is allowed to be building up before the back-EMF reaches any significant level. Also, the current waveform is closed to rectangular waveform so that the output torque is improved [8]. To ensure a reasonable rectangular current waveform and operate BLDC motor effectively over a wide range, the switches must be turned on or off in advance of the rising back-EMF region so as to allow time for the current to be built up.

The optimum current waveforms for each phase by proposed method can be obtained as follows. At first, back-EMF waveforms in a-b-c reference frame are transformed to d-q-0 reference frame.

$$\begin{bmatrix} e_d \\ e_q \\ e_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\theta_e+\delta) & \sin(\theta_e+\delta-\frac{2\pi}{3}) & \sin(\theta_e+\delta+\frac{2\pi}{3}) \\ \sin(\theta_e+\delta) & \sin(\theta_e+\delta-\frac{2\pi}{3}) & \sin(\theta_e+\delta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

where, $\theta_e = \omega_e t$, δ *is angular displacement between the stator current and the rotor flux linkage, and is zero usually.*

Torque is induced as following.

$$T_e = \frac{3}{2}\frac{p}{\omega_e}(e_d i_d + e_q i_q + e_0 i_0) \quad (6)$$

where, *p is number of pole pairs,* ω_e *is electrical angular frequency, and* ω_e/p *is mechanical speed of motor.*

Torque is produced by the q-axis current i_q, the current i_d and i_0 related with field are zero usually. Therefore following equation is obtained.

$$T_e = \frac{3}{2}\frac{p}{\omega_e} e_q i_q \quad (7)$$

From the above equation, i_q component can be obtained as following.

$$i_q = \frac{2}{3} T_e \frac{\omega_e}{p}\frac{1}{e_q} \quad (8)$$

By using field component of the stator current to reduce air gap field produced by permanent magnets, the BLDC motor drives are reached in constant power operation. The principle of proposed phase advance angle control method is shown in Fig. 4. When the motor operating at the high speed, q-axis component of the back-EMF is increased from $e_{q\text{-}base}$ to e_{q1} and q-axis component of current is decreased from $i_{q\text{-}base}$ to i_{q1}. However, q-axis component of back-EMF and current are became to e_{q2} and i_{q2} by given phase advance angle ϕ, respectively. These relations are explained by equations as following.

$$T_e \frac{\omega_e}{p} = \frac{3}{2} e_q i_q = P_m = const. \quad (9)$$

where, P_m *is mechanical power.*

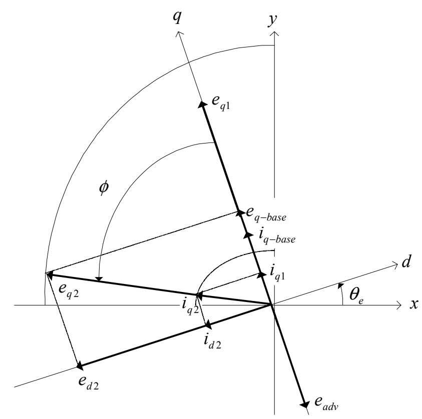

Figure 4. Vector Diagram for Phase Advance Angle Control

When the phase advance angle control method was used, back-EMF e_{adv} produced by i_{d2} can be written as following.

$$e_{adv} = \frac{\omega_r}{\omega_b} e_{q-base} \quad (10)$$

where, ω_r *is the rotor speed when the phase advance angle control method was used,* ω_b *is base speed, and* $e_{q\text{-}base}$ *is the back-EMF of q-axis component when the motor is operating at the base speed.*

Then, i_q component can obtained by the same procedure.

$$i_q = \frac{2}{3} T_e \frac{\omega_r}{p}\frac{1}{e_{adv}} \quad (11)$$

Consequently, the phase advance angle ϕ can be obtained as following.

$$\phi = \frac{e_{adv}}{e_{q-base}} = \cos^{-1}\frac{\omega_b}{\omega_r} \quad (12)$$

In addition, this achieves control of BLDC motor efficiently in the various speeds by adjusting phase advance angle according to speed change.

Conventional phase advance angle control method was used in forward motoring mode. When conventional phase angle control method is used to BLDC motor drive, because algorithm that consider forward motoring mode had been applied, it had a good alternative in forward motoring mode, but when this is applied in reverse motoring mode, position information error of rotor of 2ϕ is occurred. Therefore, torque performance and speed response characteristic is deteriorated significantly. So, conventional control algorithm had hard problem more or less to use forward and reverse motoring. This paper is proposed by method that compensate conventional algorithm so that forward and reverse motoring mode may be possible. And, BLDC motor is driven in wide range operation speed by proposed method. In addition, phase advance angle control method is not applied at low-speed because is unnecessary and it is applied only at high-speed.

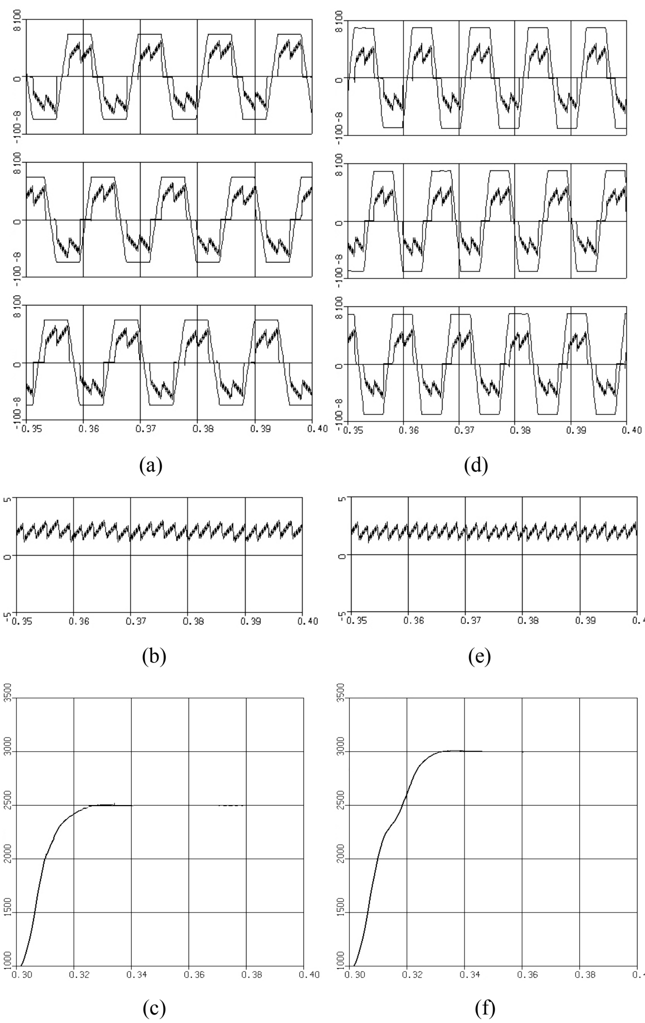

Figure 5. Forward Motoring with Conventional Control Method; (a) Back-EMFs and Phase Currents at 2500[rpm], (b) Torque at 2500[rpm], (c) Speed at 2500[rpm], (d) Back-EMFs and Phase Currents at 3000[rpm], (e) Torque at 3000[rpm], (f) Speed at 3000[rpm]

IV. SIMULATION RESULTS

To verify the proposed phase advance angle control, simulation was performed. The switching operation of the inverter is modeled by using ideal six-switches. Table I shows the simulation condition.

Fig. 5 and 7 show the simulated results of conventional unipolar PWM control method and conventional phase advance angle method at forward and reverse motoring mode, respectively. Fig. 6 and 8 show the simulated results of back-EMFs, phase currents, torque and speed waveform using proposed phase advance angle control method. Proposed control method applied 19°, and 20° phase advance angle at 2500[rpm], and 3000[rpm], respectively. Due to winding inductance, BLDC motor is delayed time that reach in rated current level when rotate with various high speed, as shown in Fig. 5(a), and (d). However, when phase advance angle control method is applied, phase current is approximated to rectangular

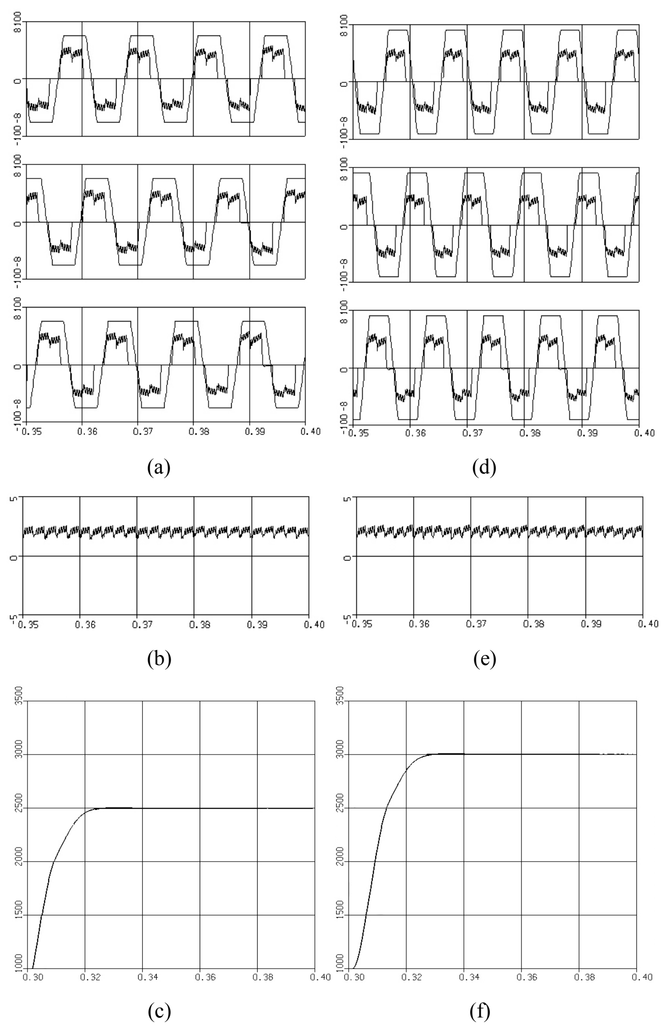

Figure 6. Forward Motoring wint Proposed Control Method(Phase Advance Angle of 19° at 2500[rpm] and 20° at 3000[rpm], respectively); (a) Back-EMFs and Phase Currents at 2500[rpm], (b) Torque at 2500[rpm], (c) Speed at 2500[rpm], (d) Back-EMFs and Phase Currents at 3000[rpm], (e) Torque at 3000[rpm], (f) Speed at 3000[rpm]

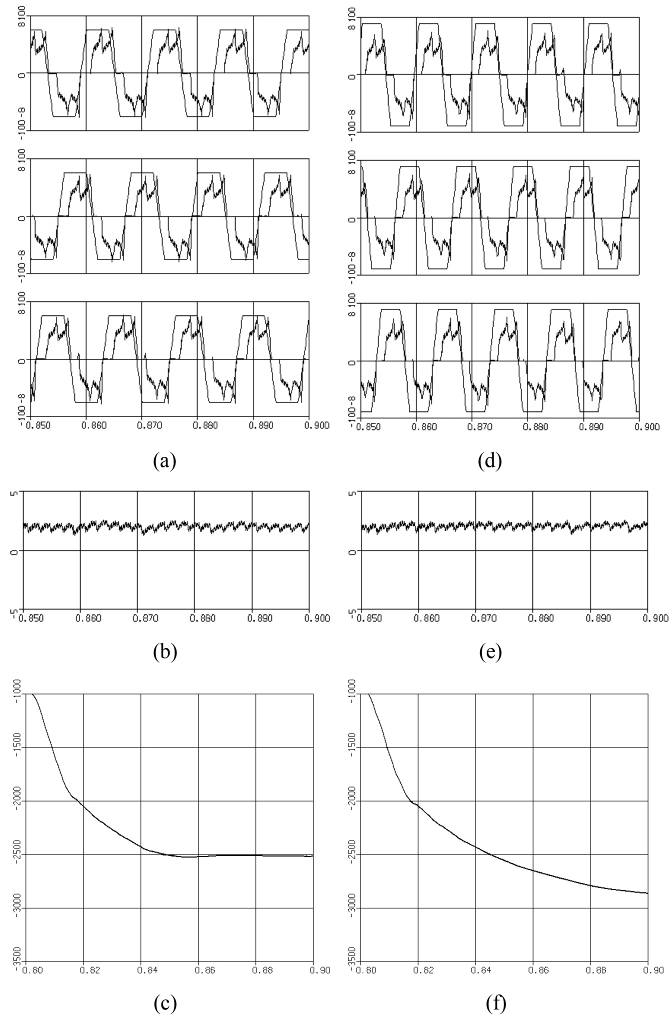

Figure 7. Reverse Motoring with Conventional Phase Advance Angle Control Method(Phase Advance of 19° at 2500[rpm] and 20° at 3000[rpm], respectively); (a) Back-EMFs and Phase Currents at 2500[rpm], (b) Torque at 2500[rpm], (c) Speed at 2500[rpm], (d) Back-EMFs and Phase Currents at 3000[rpm], (e) Torque at 3000[rpm], (f) Speed at 3000[rpm]

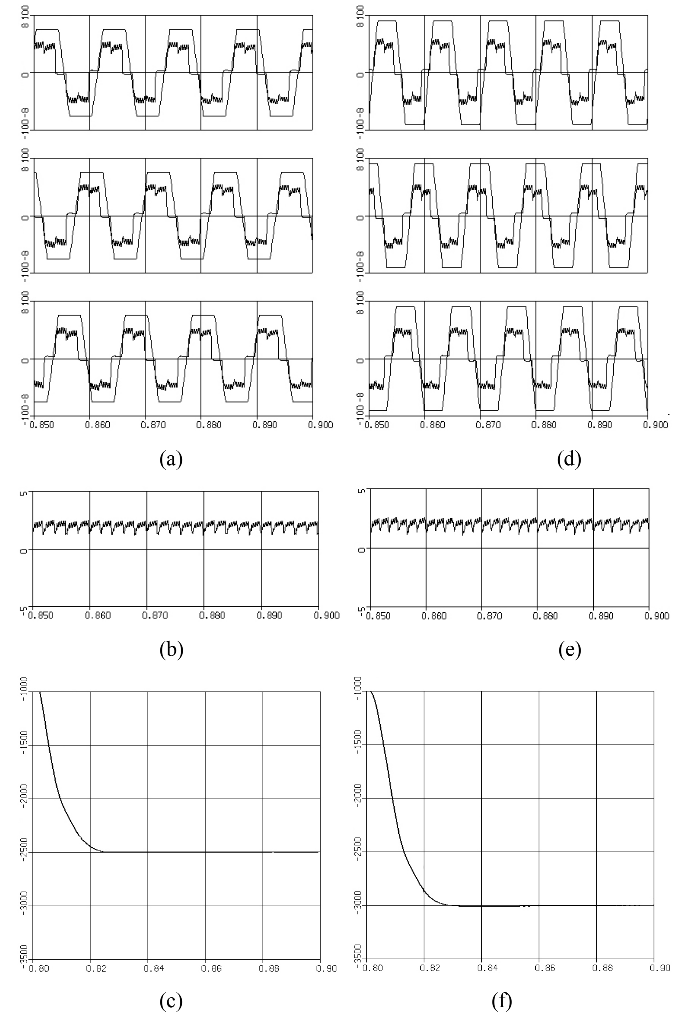

Figure 8. Reverse Motoring with Proposed Phase Advance Angle Control Method(Phase Advance of 19° at 2500[rpm] and 20° at 3000[rpm], respectively); (a) Back-EMFs and Phase Currents at 2500[rpm], (b) Torque at 2500[rpm], (c) Speed at 2500[rpm], (d) Back-EMFs and Phase Currents at 3000[rpm], (e) Torque at 3000[rpm], (f) Speed at 3000[rpm]

waveform, as shown in Fig. 6(a), and (d). In this way, torque ripple is reduced and average torque is increased in comparison with Fig. 5(b), and (e), as shown in Fig. 6(b), and (e). Also, speed response is reached to rapidly reference speed in comparison with Fig. 5(c), and (f), as shown in Fig. 6(c), and (f).

However, motor performance is significantly deteriorated, since phase advance angle method causes rotor position information error of double of phase advance angle at reverse motoring mode, as shown in Fig. 7.

In this paper, BLDC motor drive control is implemented efficiently by using proposed phase advance angle method at reverse motoring mode, as shown in Fig. 8. The phase sequence is changed from **a-b-c** to **a-c-b**, when the rotor is reverse motoring. As shown in simulated results, phase current is approximated to rectangular waveform by applying proposed control method, and torque performance and speed response characteristic is improved.

V. Conclusion

The performance of BLDC motors switched by a PWM inverter is investigated, with a view to improving the output torque and speed response characteristic. During the course of this work a practical technique for predicting the steady state performance of the BLDC motor drive is presented.

The corresponding current, torque and speed performances using the proposed control method are simulated, and are compared with those using the conventional control method. From the results, the main features of the proposed control scheme are the same as the followings;

♦ The proposed current control method is implemented simply by adjusting phase advance angle.

♦ Output torque and speed response characteristic are improved by the current waveform, which is closed to rectangular waveform

♦ When phase advance angle control method is applied, proposed method solved problem, which is appeared at reverse motoring mode.

♦ Proposed method can be used to industrial applications requiring a wide range of operation speed, because the operation of forward and reverse motoring is possible at high speed.

♦ Proposed method is suitable for high-speed and high power density applications.

TABLE I. PARAMETER OF BLDC MOTOR

Rated Voltage	V	300 [V]
Rated Torque	T_e	2 [Nm]
Resistance	R_s	0.5 [Ω]
Inductance	L_s	10 [mH]
Back-EMF Constant	K_e	0.145 [V (rad/sec)]
Poles	P	4

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