A Neutral-Voltage-Compensated Sensorless Control of Brushless DC Motor

Chang-hee Won*, Joong-Ho Song, Ick Choy*** and Myotaeg Lim******

Abstract - This paper presents a new rotor position estimation method for brushless DC motors. The estimation error of the rotor position clearly provokes the phase shift angle misaligned between the phase current and the back-EMF waveforms, which causes torque ripple in brushless DC motor drives. Such an estimation error can be reduced with the help of the proposed neutral- voltage-based estimation method, which is structured as a closed loop observer. A neutral voltage appearing during the normal mode of the inverter operation is found to be an observable and controllable measure, which can be used for estimating an exact rotor position. This neutral voltage is obtained from the DC-link current, the switching logic, and the motor speed values. The proposed algorithm, which can be easily implemented by using a single DC-link current and the motor terminal voltage sensors, is verified by simulation and experiment results.

Keywords: brushless DC motor, rotor position estimation, neutral voltage compensation

1. Introduction

Brushless DC motors with trapezoidal back-EMF waveforms require a rotor position sensor such as a hall sensor, or a rotary encoder for the inverter commutation. The rotor position sensor may raise the motor price, weaken the system reliability, and worsen the power density of the drive system. To overcome these problems, many studies have attempted to obtain accurate rotor position information without using a position sensor [1-4].

A sensorless control method, in which the timing points of the inverter phase commutation are determined by proper phase-shifting of the zero crossing points obtained from the unexcited winding terminal voltage, is reported to be sensitive to the frequency characteristics of the phase shifter over a wide speed range [1-3]. A low-cost sensorless control to reduce the number of sensing circuit components of the motor terminal voltage is presented [3]. A self-tuning algorithm of the commutation point is based on searching for a certain control variable to draw the minimum stator current required to produce a certain load torque [4].

This paper deals with a new estimation method based on neutral voltage compensation. As sensing signals for sensorless brushless DC motor drives, only DC link current and motor terminal voltages are measured. Neutral voltage of the inverter-motor system that is observed within the normal mode interval of the inverter operation results from the out-of-phase shift between the phase current and the back-EMF waveforms, which intrinsically reflects the estimation error of the rotor position. Combining with the coarse rotor position estimator using the motor terminal voltage, the neutral voltage compensation facilitates accurate estimation of the rotor position. The proposed method can offer a wide speed range and smooth torque generation to position sensorless brushless DC motor drives based on the motor terminal voltage measurement.

2. System description

A basic configuration of trapezoidal brushless DC motor drives with DC link current controlled is shown in Fig. 1, where rotor position required to determine the commutation timing points of the phase currents is basically estimated from the motor terminal voltage signals. The back-EMF signals, which produce the corresponding inverter commutation signals, can ideally be derived from the motor terminal voltages. In practice, however, several problems appear in the signal processing through the low pass filters that are used to implement the 90° phase shift as the pure integrators do. Accurate rotor position detection is reported to be hardly obtained in this method.

The final goal for taking an accurate rotor position is to get the 120° quasi-square waveform of the phase currents feeding brushless DC motor completely in phase with the 120° flat top waveform of the back-EMF of the motor. This achievement can bring smoothed torque production to

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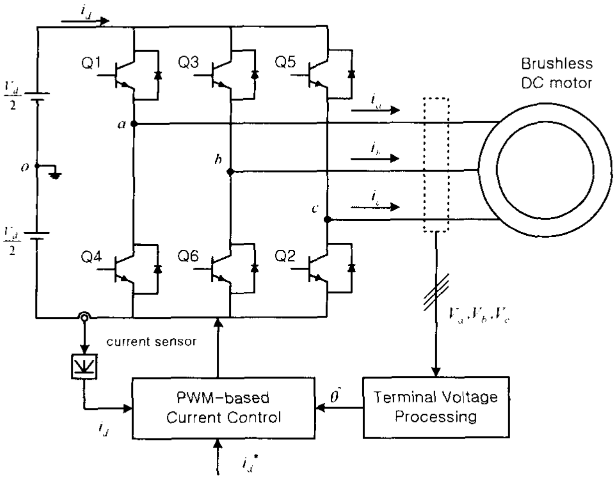
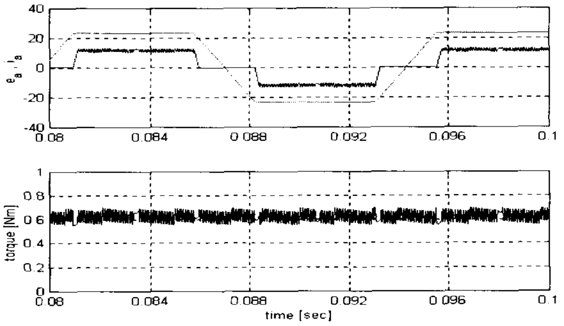
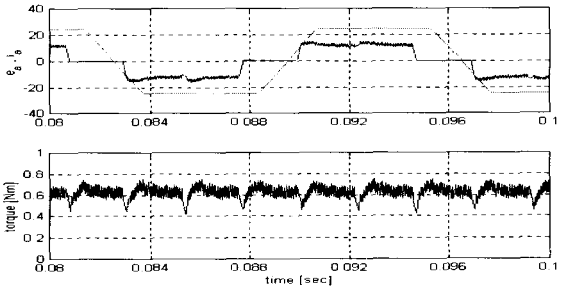


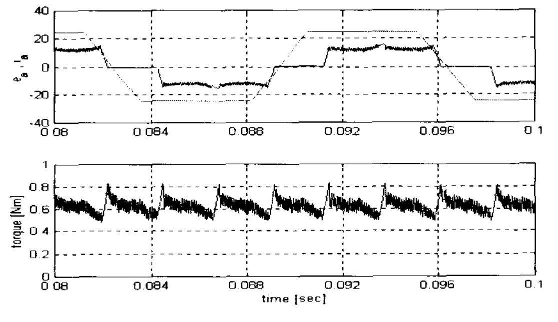
Fig. 1 Basic configuration of brushless DC motor drives



(a) α = 0°



(b) leading α



(c) lagging α

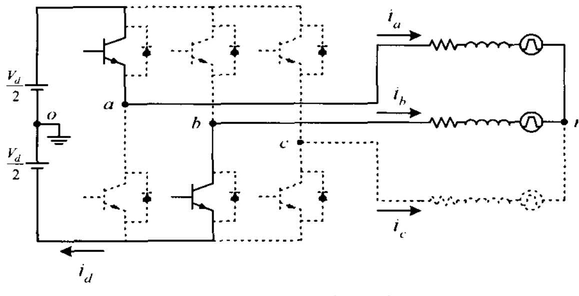
Fig. 2 Influences of the rotor position estimation error

brushless DC motor drives. In the position sensorless system, the rotor position estimation error's influences on the motor torque ripples can be illustrated as shown in Fig. 2, where the phase angle α is defined in Fig. 4. In this figure, typical waveforms of ideal back-EMF, phase current, and generated torque are illustrated according to the phase shift angle between the phase current and the back-EMF. Figs. 2 and 4 show that the waveforms of the torque ripple depend on the phase shift of the phase difference and that the magnitude of the ripple torque component becomes larger than that of the commutation torque ripple. In addition, the phase difference error between the phase current and the back-EMF is shown to need suppressing.

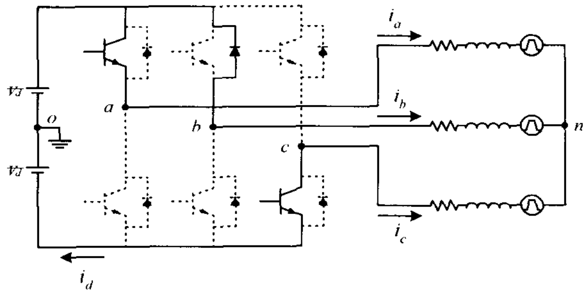
3. Neutral Voltage

As described in the preceding section, finding an observable measure is necessary to reflect the phase shift angle between the phase current and the back-EMF. As a good candidate of the observable measure, a neutral voltage appearing during the normal mode operation of the inverter is developed in this section. For convenience's sake, let us take a look at only one commutation mode of the inverter operation. In Fig. 3, the inverter switches Q1 and Q6 operate in the PWM mode and then the commutation mode, with Q6 outgoing and Q2 incoming.

In the normal mode, the phase voltages can be expressed as equations (1) and (2) and the neutral voltage can be calculated by equation (3), considering $i_a = |i_d|$, $i_b = -|i_d|$.



(a) normal mode



(b) commutation mode

Fig. 3 PWM operation of the inverter

$$V_a = \frac{V_d}{2}\cdot S = Ri_a + L\frac{di_a}{dt} + e_a + v_{no} \qquad (1)$$

$$V_b = -\frac{V_d}{2}\cdot S = Ri_b + L\frac{di_b}{dt} + e_b + v_{no} \tag{2}$$

$$\begin{aligned} v_{no} &= -\frac{1}{2}\left[R(i_a + i_b) + L\left(\frac{di_a}{dt} + \frac{di_b}{dt}\right) + e_a + e_b\right] \\ &= -\frac{1}{2}(e_a + e_b) \end{aligned} \tag{3}$$

Here, V_d represents DC link voltage, V_a, V_b, and v_c represent terminal phase voltage, e_a, e_b, and e_c are phase back-EMF, R is winding resistance, L is winding inductance, i_a, i_b, and i_c represent phase current, i_d is the DC link current, and V_{no} is the neutral voltage.

Next, in the commutation mode, the respective phase voltages and neutral voltage are given by

$$V_a = \frac{V_d}{2}\cdot S = Ri_a + L\frac{di_a}{dt} + e_a + v_{no} \tag{4}$$

$$V_b = -\frac{V_d}{2} = Ri_b + L\frac{di_b}{dt} + e_b + v_{no} \tag{5}$$

$$V_c = -\frac{V_d}{2}\cdot S = Ri_c + L\frac{di_c}{dt} + e_c + v_{no} \tag{6}$$

$$v_{no} = -\frac{V_d}{6} - \frac{e_a + e_b + e_c}{3}. \tag{7}$$

3.1 Occurrence of neutral voltage

The phase shift angle between the phase current and the back-EMF is defined as shown in Fig. 4, where the angle α describes the phase shift of the phase current with respect to the developed back-EMF. Along with the phase shift definition, the resultant neutral voltage can be plotted as shown in Fig. 5. This figure illustrates that narrow pulsed waveforms are the neutral voltages produced in the commutation intervals, whereas ramp-up or ramp-down waveforms represent the neutral voltages generated during the normal mode. Note that the phase shift angle error also makes the corresponding neutral voltage component.

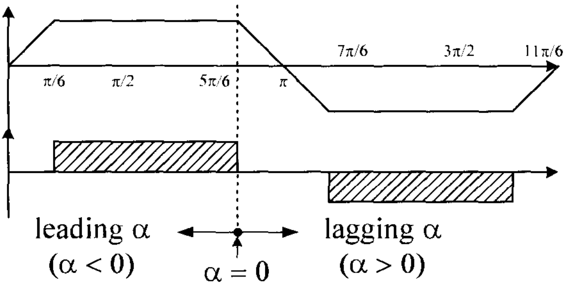


Fig. 4 Definition of the phase shift angle

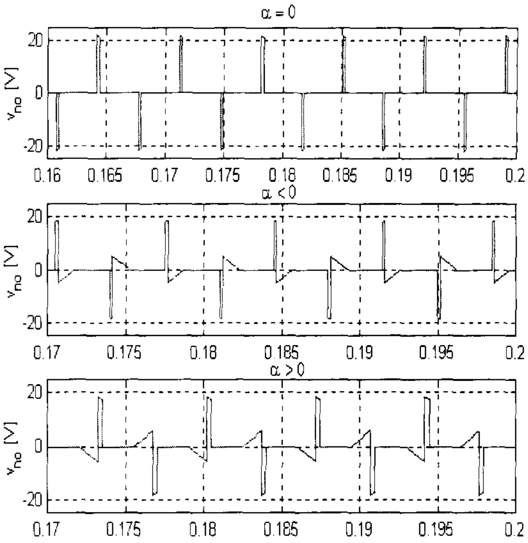


Fig. 5 Neutral voltage with respect to the phase shift angle

3.2 Estimation of neutral voltage

From the results in the preceding sections, the neutral voltage appearing in the normal modes can be said to attract attention for the rotor position estimation. The neutral voltage in the normal mode is described as shown in equation (3). However, this equation cannot be utilized directly to obtain the value since the back-EMF terms involved cannot be measured practically. Revisiting the respective voltage equations is necessary to develop a routine for obtaining the neutral voltage information. In case the phase shift shows a leading angle, use equation (2), $i_b = -|i_d|$, and $e_b = -E$ and assume that the estimated neutral voltage equation is expressed as

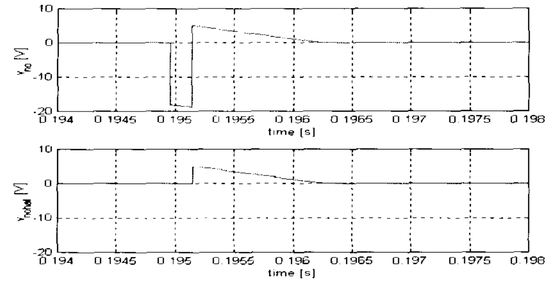
$$\hat{v}_{no} = -\frac{V_d}{2}\cdot S + R|i_d| + L\frac{d|i_d|}{dt} + E. \tag{8}$$

This equation is confirmed to imply the practical neutral voltage of equation (3). The confirmation is explained below; the following equation can be arranged by using $i_a = i_d$ and equation (1).

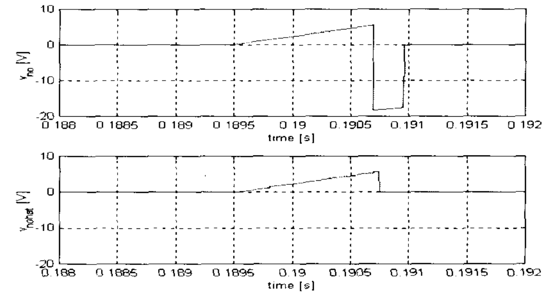
$$\begin{aligned} R|i_d| + L\frac{d|i_d|}{dt} &= \frac{V_d}{2}\cdot S - e_a - v_{no} \\ &= \frac{V_d\cdot S - e_a + e_b}{2} \end{aligned} \tag{9}$$

Inserting equations (3) and (9) into (8) provides a resultant neutral voltage estimation that is the same as that in equation (3).

When the neutral voltage estimation of equation (8) is taken as an observable and controllable variable, the waveform of the estimation with respect to the phase shift angle is shown in Fig. 6. This figure illustrates that the estimated neutral voltage in the normal mode, which is obtained by equation (8), reflects faithfully the normal mode component of the actual neutral voltage.



(a) leading phase shift angle



(b) lagging phase shift angle

Fig. 6 Estimated and actual neutral voltages

3.3 Compensation of neutral voltage

The neutral voltage in the normal mode interval described in the preceding section can be eliminated by a proper compensation scheme. The rotor position can be estimated accurately by a neutral voltage compensation loop. The rotor position estimation loop is shown in Fig. 7 and is basically accomplished by compensating for the neutral voltage occurring in the normal mode operation. Looking into the rotor position estimation scheme, the neutral voltage compensation loop $\hat{\theta}_2$ is additionally applied to the basic terminal voltage processing loop $\hat{\theta}_1$.

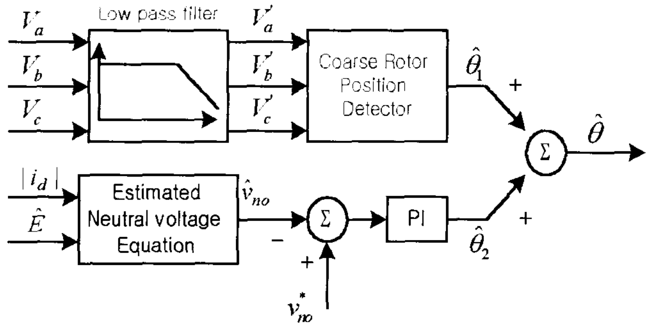


Fig. 7 Rotor position estimation based on neutral voltage compensation

4. Simulations and Experiments

An overall control block diagram is presented in Fig. 8, which includes the rotor position estimation scheme of Fig. 7. A brushless DC motor with nameplate data of 4 poles, 40V, 45W, and 1500 rpm is used in this paper. To implement the proposed estimation algorithm, dSpace DS1102 is employed in the controller set-up, as shown in Fig. 9.

To confirm whether the rotor position correction directly reflects the phase shift correction between the phase current and the back-EMF, simulation results are obtained and shown in Fig. 10. In this case, the motor operates at 500 rpm

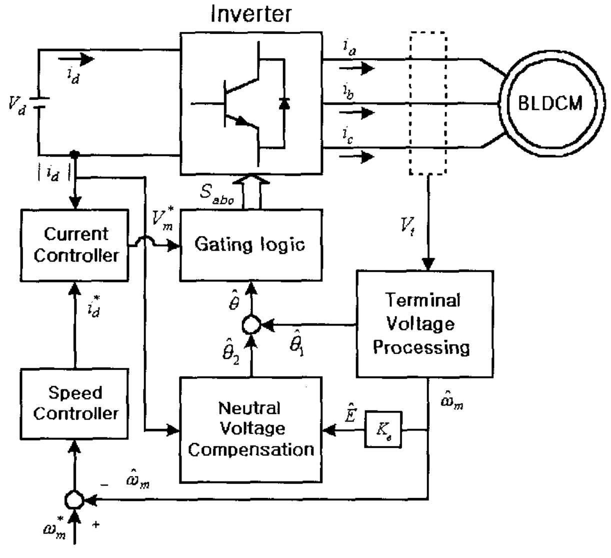


Fig. 8. Overall control block diagram

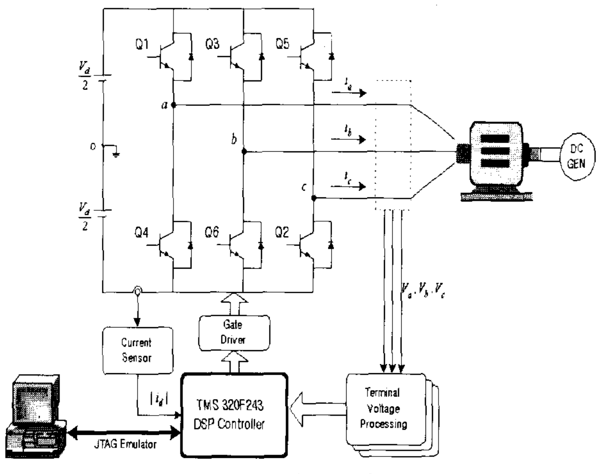
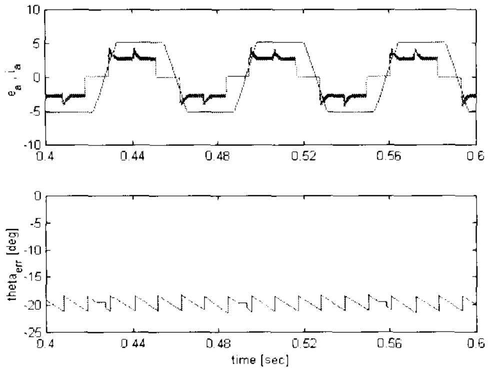
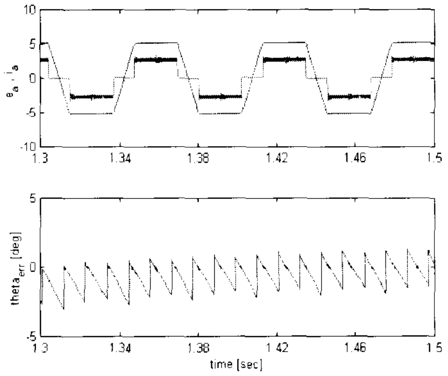


Fig. 9 Experimental set-up

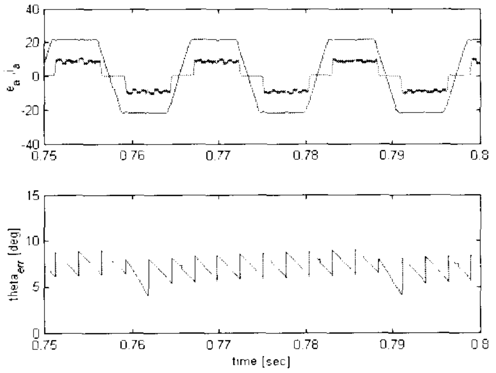


(a) without compensation

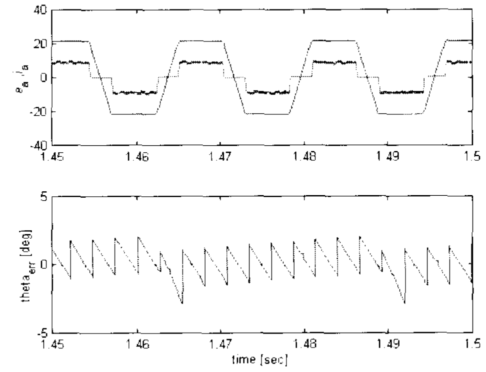


(b) with compensation

Fig. 10 Responses of rotor position error estimated at 500 rpm

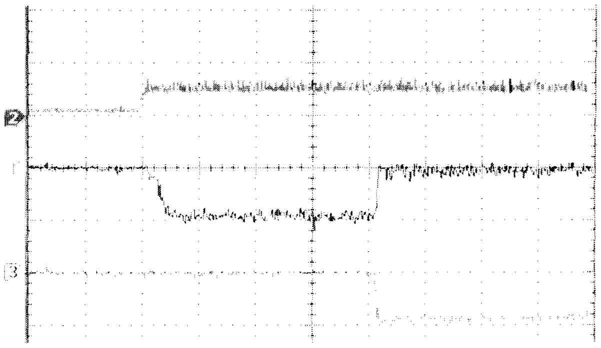


(a) without compensation

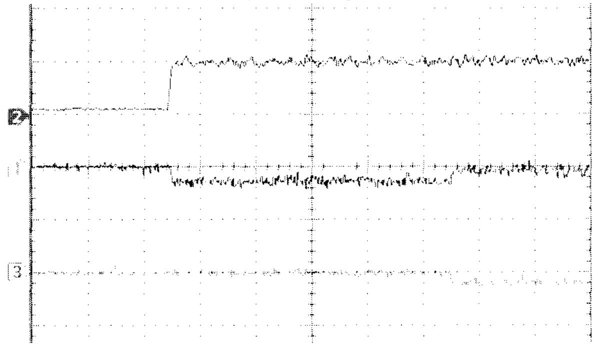


(b) with compensation

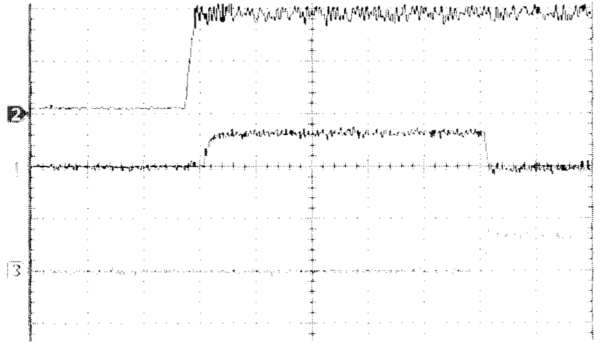
Fig. 11 Responses of rotor position error estimated at 2000 rpm



(a) at 500 rpm



(b) at 1000 rpm



(c) at 2000 rpm

Fig. 12 Experimental results of rotor position error estimated; (from top to bottom) motor speed ω_m : 1000rpm/div , position error θ_{err} : 18°/div, compensating signal $\hat{\theta}_2$:18°/div; time: 4 sec/div

and the corresponding phase shift error of about -20° appears in the leading angle mode. In addition, the phase shift error correction is clearly accomplished in leading shift. Fig. 11 shows the capability of the phase shift correction when the motor operates at 2000 rpm. This result confirms correction of the approximately 7° phase error in the lagging shift mode as well.

Fig. 12 shows the results of several experiments performed at the operation speed of 500, 1000, and 2000 rpm. Fig. 12(a) shows that the rotor position error of about −18° (leading angle) converges steadily to zero after the proposed compensation algorithm ($\hat{\theta}_2$) starts operating at 500 rpm. Fig. 12(b) shows that the position error of −5° is reduced to zero level when the algorithm operates at 1000 rpm. Fig.

12(c) shows that the position error of 10°(lagging angle) is reduced to the zero level when the algorithm is employed at 2000 rpm. Note that in this experimental result the rotor position error correction is completely accomplished through the effective suppression of the undesirable neutral voltage developed during the normal mode interval of the inverter operation.

5. Conclusion

A new position sensorless control method for brushless DC motor drives is proposed with the basic idea of extracting and compensating for the neutral voltage occurring during the normal mode interval of the inverter operation. This neutral voltage shows property that it shows no appearance when the phase current waveforms are in phase with the respective back-EMF waveforms, whereas the phase-shift- proportional occurrence when out of phase. Based on the results obtained by this neutral voltage compensation, the newly proposed control method offers a wide speed range and smooth torque development to sensorless brushless DC motor drives.

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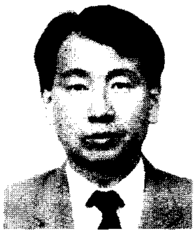

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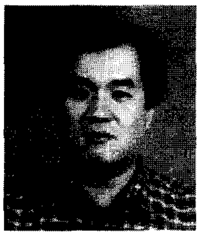

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