Torque Ripple Reduction Method in a Sensorless Drive for the BLDC Motor

Dae-Kyong Kim*, Kwang-Woon Lee† and Byung-Il Kwon**

Abstract - This paper presents a method to reduce the commutation torque ripple in a position sensorless brushless DC motor drive. To compensate the commutation torque ripple considerably, the duration of commutation must be known. The proposed method measures the duration of commutation from the terminal voltage of the motor, calculates a PWM duty ratio using the measured commutation interval to suppress the commutation torque ripple, and applies it to the calculated PWM duty ratio only during the next commutation. Experimental results show that pulsating currents and vibrations are considerably reduced when the proposed method is applied to a position sensorless brushless DC motor drive for the air-conditioner compressor.

Keywords: Brushless DC motor, commutation, sensorless control, torque ripple

1. Introduction

Commutation in a BLDC (Brushless DC) motor abruptly disturbs the average voltage applied to the non-commutated phase, which causes pulsating currents that produce undesirable torque ripple [1]. The pulsating currents can be suppressed in a region where the dc-link voltage of the inverter is larger than four times that of the phase back-EMF voltage by direct phase current control [1, 2]. Using a current sensor, however, the cost of the motor drive is increased. This paper presents a commutation torque ripple reduction method for the low cost position sensorless BLDC motor drive without the use of current sensors.

To suppress the voltage disturbance due to the commutation, the input for compensation must be applied to the inverter only during the commutation. If the input is applied after the commutation, some current spikes will be generated on the phase currents. In previous works [3, 4], the commutation interval was measured or estimated from the phase currents. However, this paper represents that the commutation interval is directly measured from the motor terminal voltage waveforms. The input to suppress the voltage disturbance is calculated using the output of speed controller and back-EMF constant, adjusted according to the measured commutation interval and applied to an inverter only during the next commutation. The proposed method is suitable for a low cost BLDC motor drive because it does not require the current sensors and the current control loop.

Experimental results indicate that the proposed method considerably reduces current ripples and vibrations of the compressor. The method is applied to a position sensorless BLDC compressor motor drive.

2. Sensorless Control of a BLDC Motor [5]

In a position sensorless BLDC motor drive, commutation points of the inverter can be obtained by knowing the zero-cross-point (ZCP) of the back-EMF and a speed dependent period of time delay. The phase back-EMF induced in the stator windings of a BLDC motor is trapezoidal so that the ZCP of the back-EMF can be detected by monitoring the terminal voltage waveform of a silent phase. The instance when the terminal voltage of the silent phase match with the half DC link voltage, during which point switching devices are turned on, is the zero crossing point of the back-EMF. The commutation points are estimated like this:

$$T_{cmt}(k) = T_{zcp}(k) + \frac{1}{2}\Delta T_{ZCP}(k) \quad (1)$$

$$\Delta T_{ZCP}(k) = T_{ZCP}(k) - T_{ZCP}(k-1) \quad (2)$$

where, $T_{cmt}(k)$ is the commutation time and $T_{ZCP}(k)$ is the zero crossing time of the back-EMF.

Fig. 1(a) depicts the configuration of a position sensorless BLDC motor drive, Fig. 1(b) the switching pattern of the out-going phase unipolar PWM, Fig. 1(c) the

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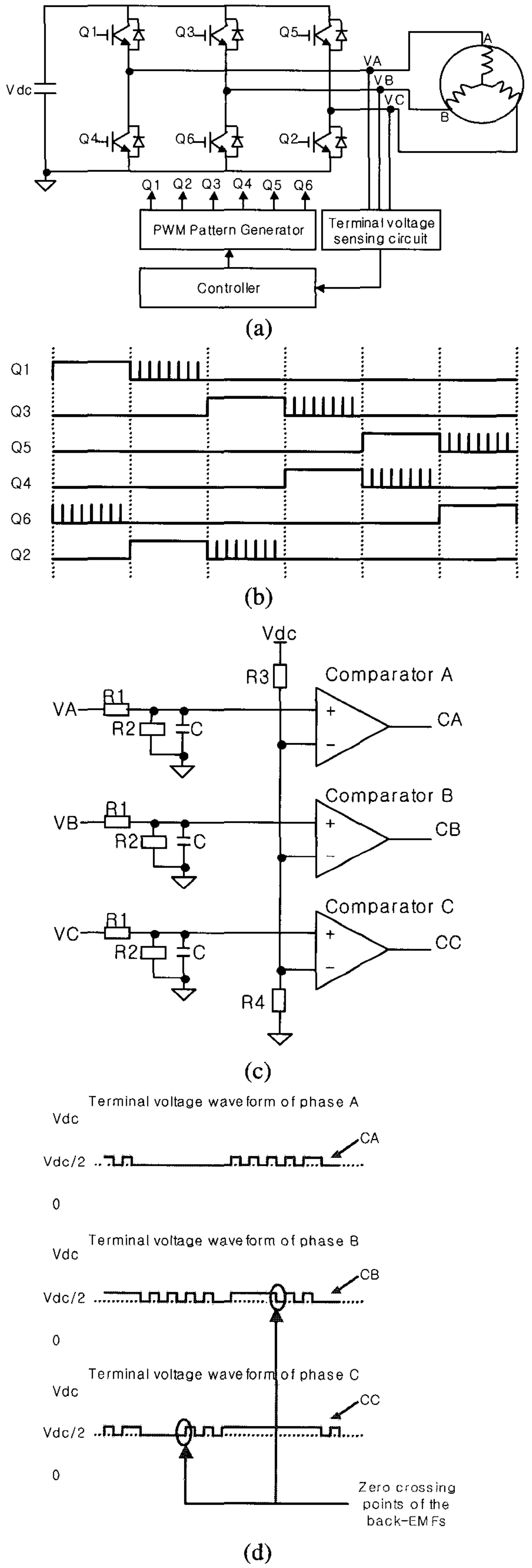


(a)

(b)

(c)

(d)

Fig. 1 (a) Configuration of a BLDC motor drive, (b) switching pattern, (c) terminal voltage sensing circuit, and (d) terminal voltage waveforms

terminal voltage sensing circuit, and Fig. 1(d) the motor terminal voltage waveforms when the out-going phase unipolar PWM is applied. The terminal voltage sensing circuit in Fig. 1(c) compares the terminal voltage of each phase with the half DC link voltage. In Fig. 1(c), capacitor C is used to reduce switching noises included in the terminal voltage.

The sensorless control method based on terminal voltage sensing cannot be used during low speeds since the back-EMF is zero at rest and proportional to the speed.

3. Commutation Torque Ripple Reduction Strategy

3.1 Analysis of Commutation Torque Ripple

The commutation in a BLDC motor disturbs the voltage of a non-commutated phase. This voltage disturbance generates a pulsating current. Since generated torque during commutation is proportional to the non-commutated phase current, the pulsating current causes undesirable torque ripple during the commutation [2].

The pulsating current can be suppressed by using the direct phase current control method [1] or voltage disturbance rejection method [2, 3]. These methods, however, require current sensors that increase the cost of a BLDC motor driver, and the direct phase current control method can suppress the pulsating current only in the region where the DC bus voltage is larger than four times that of phase back-EMF.

3.2 Measurement of Commutation Interval

When the voltage disturbance rejection method is applied to the system, the duration of commutation must be known. In order to identify the duration of commutation, a current sensor has been used. However, this paper introduces the novel method to estimate the commutation interval without current sensors. If the compensation input to reject voltage disturbance is still applied after the commutation, current spikes will be generated due to over-compensation.

In this paper, the commutation interval is measured by monitoring the terminal voltage waveform. When using the out-going phase unipolar PWM scheme, the terminal voltage of a silent phase remains as positive DC bus voltage and zero voltage during commutation and is lower (or higher) than half the DC bus voltage until the back EMF of the silent phase reaches zero. By measuring the transition time of the comparator output after starting the commutation, hence, the duration of commutation can be known as shown in Fig. 2.

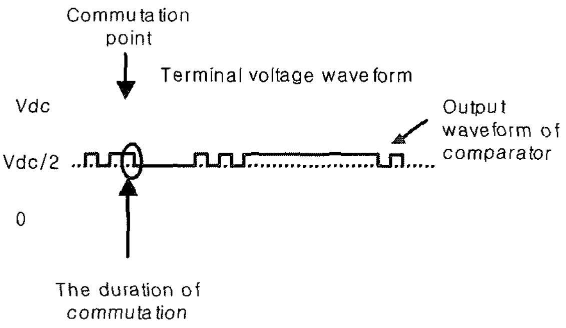


Fig. 2 Terminal voltage waveform

3.3 The Compensation Input to Suppress Torque Ripple [3]

In this paper, the voltage disturbance rejection method is used to suppress the commutation torque ripple. The average voltage V_{m1} applied to a non-commutated phase before the commutation is

$$V_{m1} = \frac{V_{dc}}{2} D_a \qquad (3)$$

where, D_a is the PWM duty ratio determined by the speed controller. In case of an out-going phase unipolar PWM, the average voltage V_{m2} applied to a non-commutated phase during the commutation is

$$V_{m2} = \frac{V_{dc}(2D_b - 1)}{3} - \frac{K_e \omega_m}{3} \qquad (4)$$

where, D_b is the PWM duty ratio during commutation, K_e is the back-EMF constant, and ω_m is the mechanical speed of a motor.

From equations (3) and (4), the compensation PWM duty ratio D_b to suppress the voltage disturbance is given as follows.

$$D_b = \frac{1}{2} + \frac{3}{4} D_a + \frac{K_e \omega_m}{2V_{dc}} \qquad (5)$$

The compensation input D_b is adjusted from the commutation interval. As the measured commutation interval is t_c, the compensation input D_b' is adjusted as in equation (6)

$$D_b' = D_b \times \frac{t_c}{T} \qquad (6)$$

where, T is PWM period. The adjusted input D_b is applied to an inverter only during the subsequent commutation. When the commutation interval has the same value every period at the steady-state, the look-up table can be used for maintaining the commutation interval. When the proposed method is applied, the commutation point must be synchronized with the starting point of the PWM carrier signal as shown in Fig. 3. If not synchronized, the average voltage of a non-commutated phase before commutation will be disturbed and some current ripples will be generated.

Fig. 4 illustrates the configuration of the proposed controller. In Fig. 4, speed controller determines the PWM duty ratio, u1, during the two-phase conduction period. When the commutation starts, the PWM duty ratio, u1, is changed to u2. The commutation interval detector outputs U_con. U_con changes u2 to u1 after the end of commutation period and u3 goes to the PWM pattern generator.

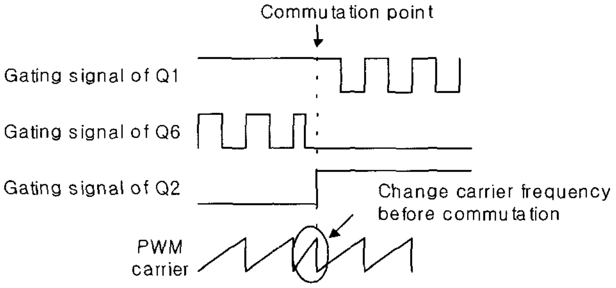


Fig. 3 Synchronization of the gating signals

Fig. 4 Configuration of the proposed controller

4. Experimental Results

Fig. 5 represents an overall system configuration of the proposed sensorless drive. In this experiment, a low-cost fixed-point digital signal processor (DSP), TMS320 LF2406A implements the Hybrid-PFC (Power Factor Correction) and sensorless control. Since the method does not require current sensors and current control loop, a low cost DSP can be used to implement the method. The carrier frequency of PWM is 5kHz.

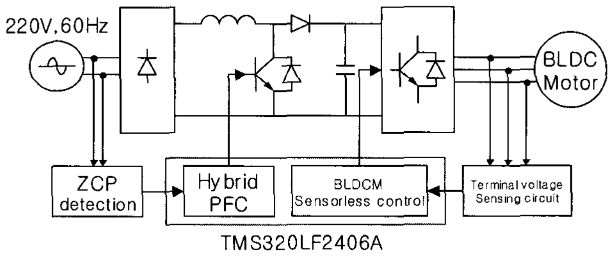


Fig. 5 Configuration of the experimental BLDC motor drive

Table 1 shows the four-pole BLDC motor parameters to examine the performance of the proposed sensorless drive technique.

Fig. 6 indicates the measured values of commutation interval in the single rotary compressor with the BLDC motor. The values are saved as a look-up table and the table is updated at each rotation as real time. So, the time of commutation is predicted.

Fig. 7 displays the terminal voltage (upper trace) and phase current (bottom trace) at running frequency 30Hz. Fig. 7(a) shows the experimental results of the conventional method. The phase current spikes are generated during the commutation. In Fig. 7(b), the spikes of the proposed method are remarkably reduced.

Table 1 Motor parameters

Rated power	1.5 [kW]
Pole number	4
Line-to-line resistance	0.82 [Ω]
Line-to-line inductance	6 [mH]
Back-EMF constant	0.0162 [V/rpm]

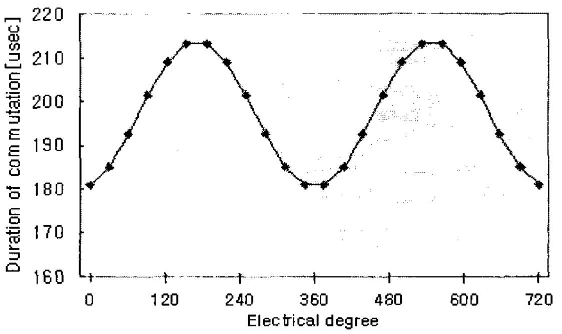
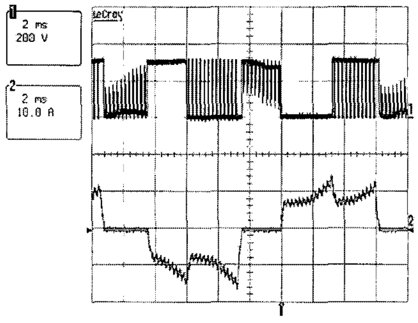


Fig. 6 Measured duration of commutation in the single rotary compressor with a BLDC motor

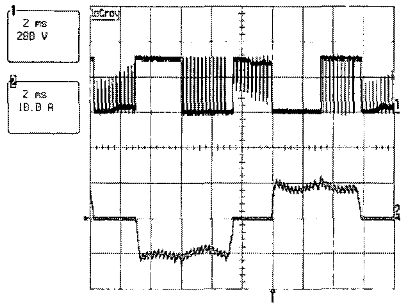
Fig. 8 illustrates the frequency spectrum at running frequency 25[Hz]. The frequency spectrum of the proposed method is lower than the conventional method over the spectrum range.

Fig. 9 depicts the total vibrations measured at the center of the compressor from running frequency 25Hz to 90Hz. Over the frequency range, total vibration value of the proposed control method is reduced by the maximum 31% compared to the conventional control method.

Therefore, it is noted that the proposed sensorless control method effectively suppresses pulsating currents and vibrations of the compressor compared to the conventional method.



(a) Conventional control



(b) Proposed control

Fig. 7 Terminal voltage [200V/div.] and phase current [10A/div.] at running frequency: 30Hz [2ms/div.]

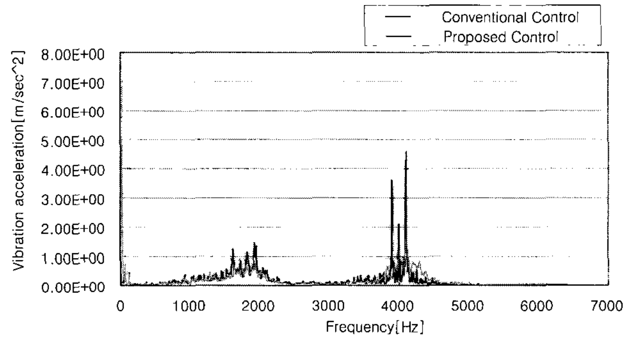


Fig. 8 Frequency spectrum at running frequency: 25[Hz]

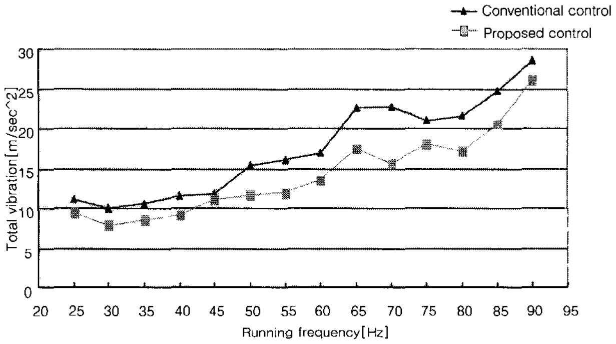


Fig. 9 Total vibration measured at the center of compressor body

5. Conclusion

This paper has proposed a commutation torque ripple reduction method for a position sensorless BLDC motor drive for air-conditioners. Experimental results have proved that the proposed control method considerably reduces not only the pulsating currents but also the maximum 31% of the total vibrations for the BLDC motor. The method does not require current sensors or current control loop, allowing it to be suitable for a low cost BLDC motor drive.

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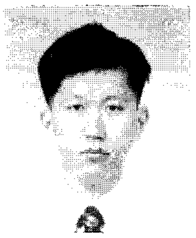

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