Commutation Torque Ripple Reduction in a Position Sensorless Brushless DC Motor Drive

Kwang-Woon Lee, Dae-Kyong Kim, Tae-Duck Kim, and Jae-Young Choi

Living Appliances R&D Center, Samsung Electronics,
416 Maetan-3Dong, Yeongtong-Gu, Suwon-City, Gyeonggi-Do 442-742, KOREA
Email: kw_lee@samsung.com

***Abstract*—This paper presents a novel method to reduce commutation torque ripple in a position sensorless brushless DC (BLDC) motor drive. To compensate the commutation torque ripple completely, conventional methods should know commutation interval, so that they need current sensors. However, the proposed method measures commutation interval from the terminal voltage of a brushless DC motor, calculates a PWM duty ratio using the measured commutation interval to suppress the commutation torque ripple, and applies to the calculated PWM duty ratio only during the next commutation. Experimental results verify that the proposed method implemented in an air-conditioner compressor controller considerably reduces not only the pulsating currents but also vibrations of a position-sensorless BLDC motor.**

I. Introduction

Commutation in a BLDC motor abruptly disturbs average voltage applied to non-commutated phase, which causes pulsating currents that produce the undesirable torque ripple [1]. The pulsating current can be suppressed by using the direct phase current control method [1] or the voltage disturbance rejection method [2,3]. The direct phase current control method can suppress the pulsating current only in the region where DC bus voltage is larger than four times of phase back-EMF [1,2]. In the voltage disturbance rejection method, the input for compensation must be applied to the inverter only during the commutation. For the reason, the voltage disturbance rejection method uses commutation interval that can be measured or estimated from phase current [3,4]. However, using current sensors increases the cost of a motor driver.

This paper proposes a novel strategy for reducing commutation torque ripple in a position sensorless BLDC motor drive. Since the proposed method directly measures commutation interval from motor terminal voltage waveforms, it does not require a current sensor and current control loop. Therefore, the proposed method is suitable for a low cost BLDC motor driver. In addition, the proposed method synchronizes the commutation points at the starting point of PWM carrier signal.

The proposed method is implemented on the out-door unit of a commercial air-conditioner using a BLDC compressor. The experimental results show that the proposed method considerably reduces not only current ripples but also vibrations of compressor. The proposed method makes possible that home appliances using BLDC motor, such as refrigerator, air-conditioner and washing machine, reduce torque ripple without additional cost.

II. Conventional Method for Reducing Commutation Torque Ripple

A. Analysis of Commutation Torque Ripple

Commutation in a BLDC motor disturbs the voltage of a non-commutated phase. This voltage disturbance generates pulsating current as shown in Fig. 1. Since generated torque during commutation is proportional to non-commutated phase current, the pulsating current causes undesirable torque ripple during the commutation [2].

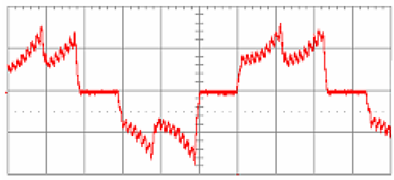


Fig. 1. Phase current waveform of a BLDC motor

B. Voltage Disturbance Rejection Method [3]

Average voltage V_{m1} applied to a non-commutated phase before commutation is

$$V_{m1} = \frac{V_{dc}}{2} D_a \tag{1}$$

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

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

where D_b is PWM duty ratio during commutation, K_e is back-EMF constant, and ω_m is mechanical speed of a motor. From equation (1) and (2), the compensation PWM duty ratio D_b to suppress the voltage disturbance is given as follows.

$$D_b = \frac{1}{2} + \frac{3}{4} D_a + \frac{K_e \omega_m}{2V_{dc}} \tag{3}$$

If the compensation input to reject voltage disturbance is still applied to D_b after the commutation, current spikes will be generated due to over-compensation. In order to apply the strategy for reducing commutation torque ripple to a BLDC motor drive, the accurate start and end point of commutation must be known.

For prohibiting the over-compensation, 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 like equation (4)

$$D_b = D_b \times \frac{t_c}{T} \tag{4}$$

where T is PWM period. The adjusted input D_b is applied to an inverter only during the next commutation.

III. Novel Strategy for Reducing Commutation Torque Ripple

When the voltage disturbance rejection method is applied to the system, the duration of commutation must be known. In order to know the duration of commutation, a current sensor has been used. However, this paper introduces the novel method to measure the commutation interval without current sensors.

A. *Position Sensorless Control of BLDC Motor [5]*

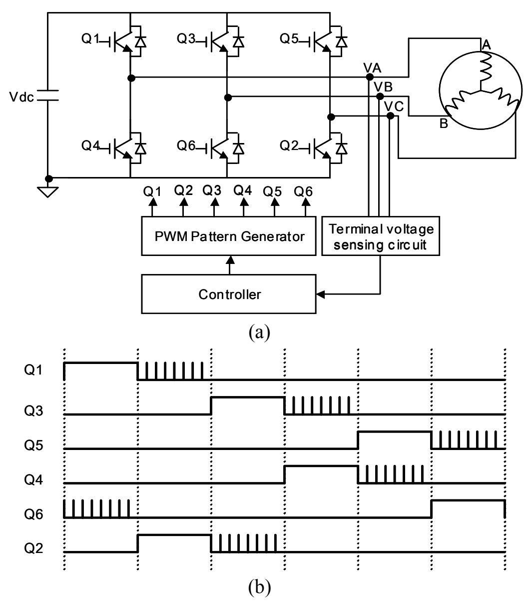


Fig. 2. (a) Configuration of a BLDC motor drive, (b) switching pattern

Fig. 2(a) shows the configuration of a position sensorless BLDC motor drive, Fig. 2(b) the switching pattern of the out-going phase unipolar PWM.

In a position sensorless BLDC motor drive, the commutation points of the inverter can be obtained by knowing the zero-cross-point (ZCP) of the back-EMF and the speed dependent period of time delay as shown in Fig. 3. The commutation points are estimated like this:

$$T_{cmt} = T_{zcp} + \Delta T_{zcp}/2 \tag{5}$$

where T_{cmt} is a commutation point, T_{zcp} is a zero crossing point of the back-EMF, and ΔT_{zcp} is a time difference between the current and the zero crossing point. 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 half the DC link voltage, during switching devices are turned on, is the zero crossing point of the back-EMF.

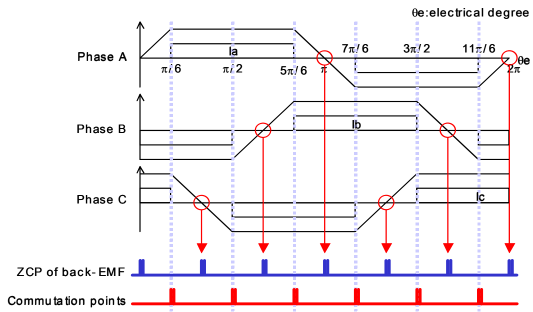
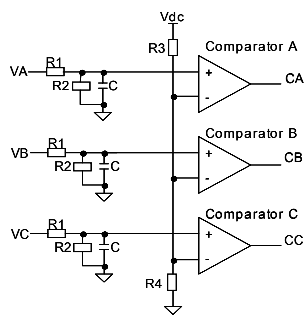
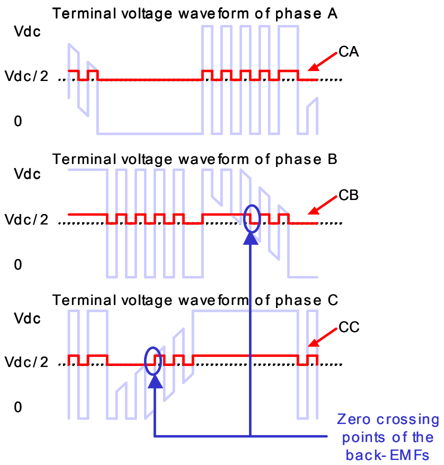


Fig. 3. Zero crossing points of the back-EMFs and commutation points

Fig. 4(a) shows the terminal voltage sensing circuit and Fig. 4(b) shows the motor terminal voltage waveforms when the out-going phase unipolar PWM is applied. The terminal voltage sensing circuit in Fig. 4(a) compares the terminal voltage of each phase with the half of DC link voltage. In Fig. 4(a), capacitor C is used to reduce switching noises included in the terminal voltage.



(a)



(b)

Fig. 4. (a) terminal voltage sensing circuit and (b) terminal voltage waveforms

B. Measurement of Commutation Interval

As explained in preview section, the position sensorless controller already uses the terminal voltages for obtaining the ZCP of phase back-EMF. If the terminal voltages can give information related to the commutation interval for the voltage disturbance rejection method, the current sensors are no more required. When using the out-going phase unipolar PWM scheme, the terminal voltage of a silent phase remains positive (or negative) DC bus 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. 5.

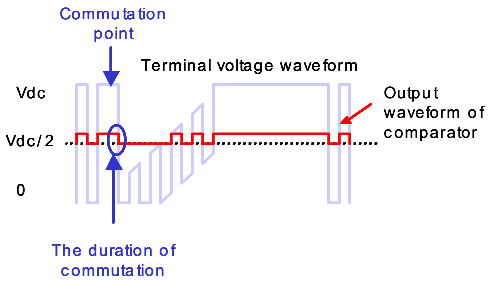


Fig. 5. Terminal voltage waveform

C. Implementation of the Proposed Strategy

When the commutation interval has the periodic shapes, the look-up table can be used for keeping the commutation interval. When applying the proposed method, the commutation point must be synchronized at the starting point of PWM carrier signal as shown in Fig. 6. If not synchronized, the average voltage of a non-commutated phase before commutation will be disturbed and some current ripples will be generated.

Fig. 7 shows the configuration of the proposed controller. In Fig 7, the speed controller determines the PWM duty ratio, u1, during two-phase conduction period. When the commutation starts, a PWM duty ratio, u1, is changed to u2. The commutation interval detector outputs two kinds of control signals, G_con and U_con. G_con adjusts gain K from equation (5) and U_con changes u2 to u1 after the end of commutation period and gives the starting point of PWM carrier signal to synchronization of gating signal. u3 goes to PWM pattern generator.

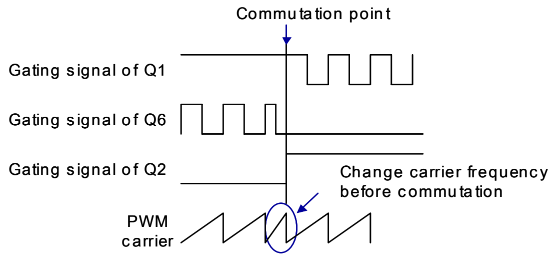


Fig. 6. Synchronization of the gating signals

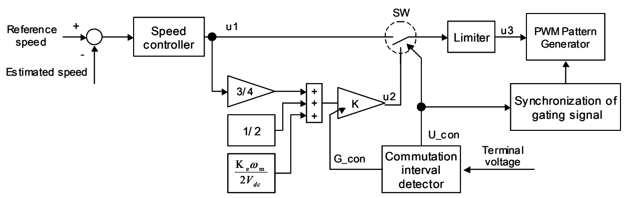


Fig. 7. Configuration of the proposed controller

IV. EXPERIMENTAL RESULTS

Fig. 8 shows an overall system configuration of the proposed sensorless drive. In this experiment, a fixed-point digital signal processor(DSP), TMS320LF2406A implements the Hybrid- PFC(Power Factor Correction) and the proposed sensorless control. The carrier frequency of the inverter is 5kHz. Since the method does not require current sensors and current control loop, the DSP can implement the method.

Fig. 9 shows the outdoor unit of an air-conditioner for experimental test. The outdoor unit has a single rotary compressor driver by the BLDC motor and the sensorless motor driver.

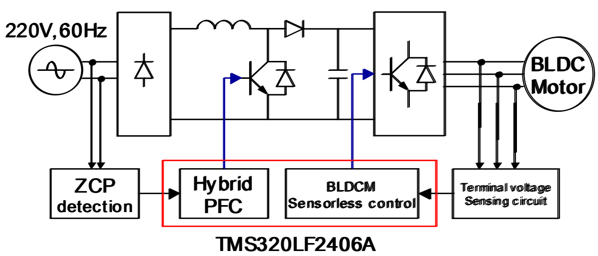


Fig. 8. Configuration of the experimental BLDC motor drive

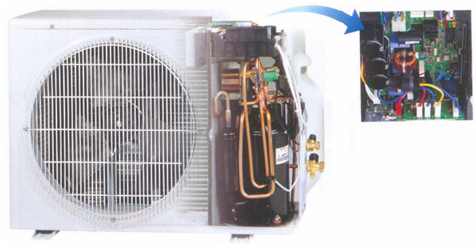


Fig. 9. Outdoor unit of air-conditioner for experimental test

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

Fig. 10 shows the measured values of commutation interval in the rotary compressor with the BLDC motor. The values are saved as a look-up table and the table is updated every one rotation as real time. So, the time of commutation is predicted.

TABLE I. 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]

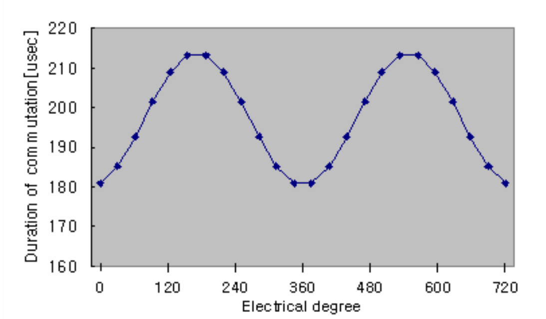


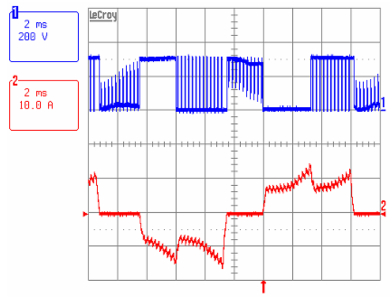
Fig. 10. Measured duration of commutation in the rotary compressor with a BLDC motor

Fig. 11 and 12 show terminal voltage and phase current at running frequency 30Hz and 75Hz, respectively. Fig. 11(a) and 12(a) show the experimental results of without the proposed method. The phase current spikes are generated during the commutation. Fig. 11(b) and 12(b) shows that the proposed method remarkably reduces the current spikes.

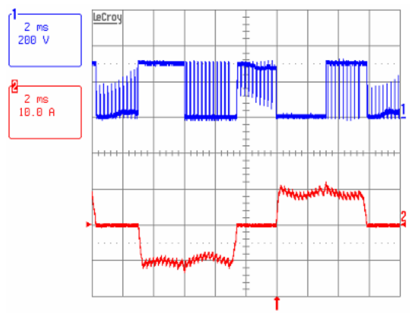
Fig. 13 and Table II show the frequency spectrum at running frequency 30Hz and the maximum values of measured vibration on the compressor that is separated from an outdoor unit of air-conditioner, respectively.

Fig. 14 shows total vibrations measured at the center of the compressor in an outdoor unit of air-conditioner from running frequency 25Hz to 90Hz. Over the frequency range, total vibration value of the proposed control method reduces up to 31% compared to the result without the proposed method.

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

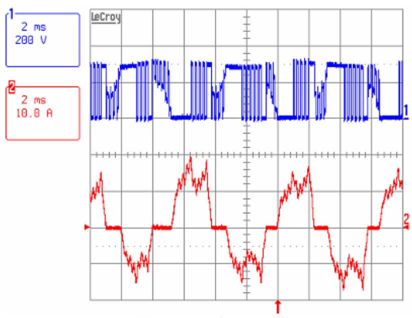


(a) Normal control

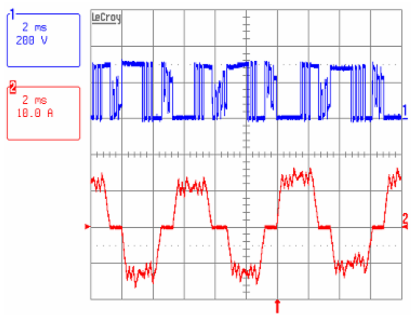


(b) Proposed control

Fig. 11. Terminal voltage [200V/div.] and phase current [10A/div.] at running frequency : 30Hz [2ms/div.]



(a) Normal control



(b) Proposed control

Fig. 12. Terminal voltage [200V/div.] and phase current [10A/div.] at running frequency : 75Hz [2ms/div.]

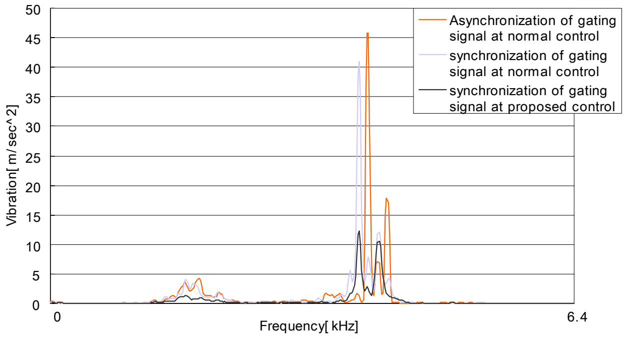


Fig. 13. Frequency spectrum at running frequency : 30Hz

TABLE II. MEASURED RESULTS OF VIBRATION

Running frequency [Hz]	Vibration [m/sec^2]		
	Normal control		Proposed control
	Asynchronization of gating signal	Synchronization of gating signal	
22	13.39	10.05	4.97
24	15.38	7.73	4.35
26	25.65	8.08	4.71
28	20.49	5.00	3.26
30	22.93	20.46	6.11

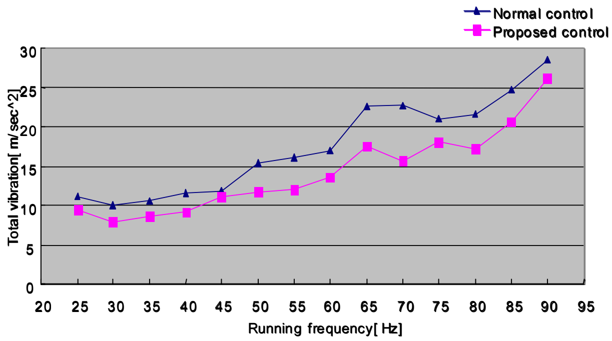


Fig. 14. Total vibration measured at the center of compressor body

V. CONCLUSION

This paper has proposed a commutation torque ripple reduction method for a position sensorless BLDC motor drive for the air-conditioner. Since the proposed method uses terminal voltage for measuring commutation interval, the method does not require current sensors and current control loop so that it is suitable for a low cost BLDC motor drive. Experimental results have proved that the proposed control method considerably reduces not only the pulsating currents but also up to 31% of the total vibrations for the BLDC motor.

REFERENCES

[1] C. Berendsen, et. al., "Commutation strategies for brushless DC motors: Influence of instant torque", *IEEE Trans. on Power Electronics*, vol. 8, no. 2, pp. 231-236, Apr. 1993.

[2] R. Calson, et. al., "Analysis of torque ripple due to phase commutation in brushless DC machines", *IEEE Trans. on Ind. Appl.*, vol. 28, no. 3, pp. 632-638, May/June 1992.

[3] Kwang-Woon Lee, et. al., "A commutation torque ripple minimization method for brushless DC motors with trapezoidal electromotive force", *ICPE'98*, vol.1, pp.380-385, 1998.

[4] Xiangjun Zhang, et. al., "A new method to minimize the commutation torque ripple in trapezoidal BLDC motor with sensorless drive", *PIEMC 2000*, vol. 2, pp. 607-611, 2000.

[5] K. Iizuka, et al., "Microcomputer control for sensorless brushless motor", *IEEE Trans. on Industry Applications*, vol. 27, pp. 595-601, May-June 1985.