A Novel Speed and Position Estimation of The Brushless DC Motor at Low Speed

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Abstract -A novel estimation technique for speed and position of BLDC motor is proposed. The new estimation method use trapezoidal waveform of back-EMF with speed information. To estimate the trapezoidal waveform of back-EMF, three phase currents information and DC line voltage information of inverter and terminal voltage are used. The proposed new estimation method solves the problem of the BLDC motor drives at low speed and zero speed in Matlab/ Simulink environment. The computer simulations show that the performance of the estimation method is better than other estimation method.

1. INTRODUCTION

The most AC variable drive requires speed or position sensors for high performance driving. The Brushless Direct Current (BLDC) motor requires a position sensor for controlling speed and position. However, the sensor increase costs and reduce the drive robustness. Sensorless BLDC motor control has been a research topic for the last decades.

To avoid using the sensor, different methods for BLDC motor sensorless control, based on measurement of electrical variables, have been investigated and developed [1].

The terminal voltage sensing method and the third harmonic back-EMF sensing method have been proposed for the trapezoidal back-EMF type of BLDC motors [2, 3]. However, the voltage can not detect at low speed because the measured terminal voltage has the large signal to noise ratio. The third harmonic back-EMF sensing method provides wider range than the terminal voltage sensing method. Nevertheless, greater than 2/3 stator winding pole pitch is required. The back-EMF integration method also proposed but the low speed operation is poor.

An adaptive sliding mode observer [4] and nonlinear reduced order observer [5] have proposed for sinusoidal back-EMF type of PMDC motor. However, these methods are still problems at low speed. In the case of sliding mode observer, if the speed is very low the load is large that means the stator current is large. the condition is not satisfied [4]. At low speed, the nonlinear reduced order observer can estimate the speed but the estimation speed has an error because the speed estimation is affected by measurement noise in this speed range.

It is well known that addition of three phase voltages and currents is zero, that means $V_a + V_b + V_c = 0$, $I_a + I_b + I_c = 0$. It is balanced condition. When the three phase BLDC motor drive with sinusoidal waveform has balanced condition, the d and q axis is suitable. However, the three phase AC drive system does not presently have balanced condition. Therefore, the equation of the system can not be transformed to the equation of the d and q axis. Especially, it is difficult to transform the equation of the trapezoidal back-EMF type of BLDC motors to the equation of the d and q axis even though the system has balanced condition because the mutual inductance of the BLDC motors have non-sine

This paper presents a new estimation technique for speed and position of BLDC motor using estimation of the back-EMF with speed information by three phase currents measured and DC line voltage of inverter and terminal voltage measured.

2. MATHEMATICAL MODEL OF BLDC MOTOR

Figure 1 shows a dynamic equivalent circuit of BLDC motor. The mutual inductance (M) of the circuit is same that means

$$L_{ab} = L_{ba} = L_{bc} = L_{cb} = L_{ca} = L_{ac} = M \qquad (1)$$

Where L_{ab}, L_{ba}, L_{bc}, L_{cb}, L_{ca}, L_{ac} and M=mutual inductance between phase in stator winding .

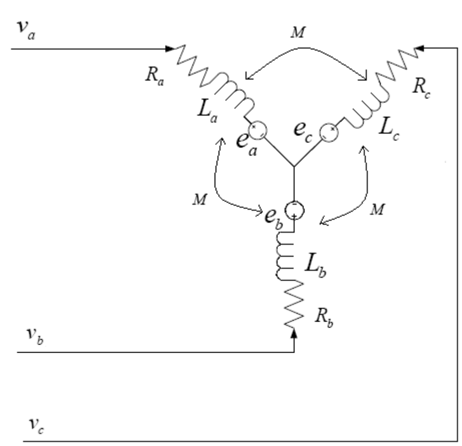


Figure 1. Equivalent circuit of BLDC motor

Moreover, if the permanent magnet inducing the rotor field is in the shape of an arc, it requires that the inductance be independent of the rotor position, hence

$$L_a = L_b = L_c = L$$
$$R_a = R_b = R_c = R \qquad (2)$$

Where L_a, L_b, L_c and L =stator inductance per phase

R_a, R_b, R_c and R =stator resistance per phase

Therefore, the circuit equation of the stator windings in term of motor electrical constant is

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \qquad (3)$$

Where I_a, I_b and I_c =stator phase currents

V_a, V_b and V_c =stator phase voltages

E_a, E_b and E_c =represent the back EMFs in the respective phases in (3)

Simplifying (3) further we get equation (4)

$$\begin{bmatrix} R+p(L-M) & 0 & 0 \\ 0 & R+p(L-M) & 0 \\ 0 & 0 & R+p(L-M) \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} V_a - E_a \\ V_b - E_b \\ V_c - E_c \end{bmatrix} \qquad (4)$$

Where $p = \dfrac{d}{dt}$ is the time derivative operator

The back-EMF is depending on magnetic flux in rotor because of permanent magnet with speed of rotor Eq. (5).

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = -\omega_r \frac{P}{2} \psi \begin{bmatrix} trapez(\theta_r) \\ trapez(\theta_r - \frac{2\pi}{3}) \\ trapez(\theta_r - \frac{4\pi}{3}) \end{bmatrix} = -\frac{P}{2} \psi Y_{abc} \qquad (5)$$

Where $trapez(.)$ = a piecewise linear and periodic signal with 2π

ω_r = rotor speed

ψ = magnitude of flux linkage

The magnitude of flux linkage (ψ) is negative constant because the output torque (T_e) and the output power should be positive when the rotor speed is positive.

The generated electromagnetic torque is given by

$$T_e = -\frac{P\psi}{2} \times [trapez(\theta_r) I_a + trapez(\theta_r - \frac{2\pi}{3}) I_b + trapez(\theta_r - \frac{4\pi}{3}) I_c] \qquad (6)$$

Where θ_r = rotor position and represented for simplicity as $\theta_r = \omega_r t$.

P = the number of poles in the motor

The load dynamics becomes

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L$$

Where J =moment of inertia

B = friction coefficient

T_L = load torque

The transient of BLDC motor is illustrated in Figure 2 which is block diagram of mathematical model of three phase BLDC motor. R, L and ψ is constant in the simulation.

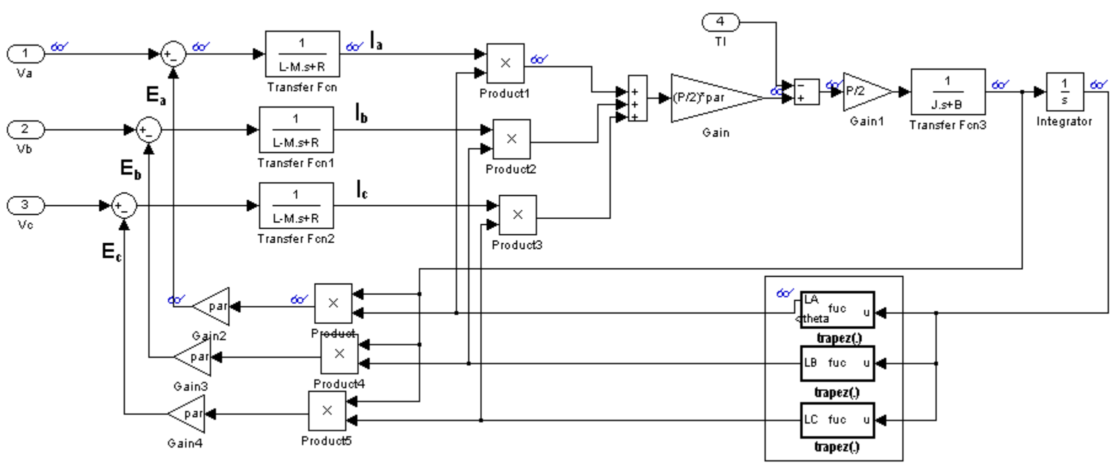


Figure 2. Block Diagram of BLDC motor

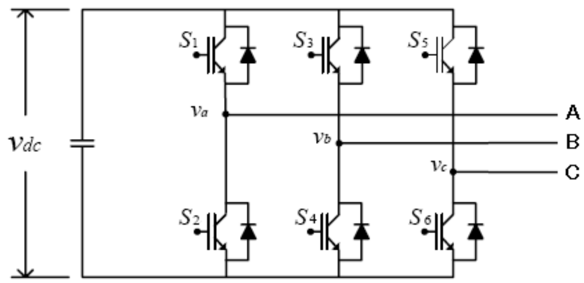


Figure 3. Three phase inverter

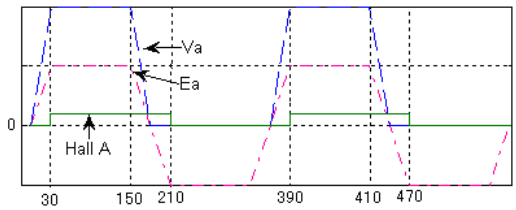


Figure 4. Waveforms of back EMF, hall sensor signal and real voltage of a phase.

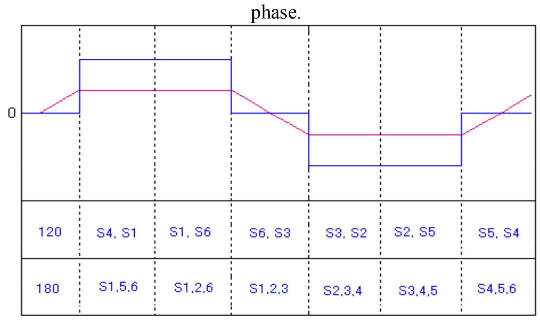


Figure 5. Waveforms of a phase reference voltage or current, beck-EMF and gate selection table for gate signal of 120 degree and 180 degree.

The electrical equivalent circuit and drive performance of the system is shown in Figure 3, Figure 4 and Figure 5.

3. PROPOSED ESTIMATION OF SPEED AND POSITION

The proposed estimation is to use the equation of machine given by (4) and Figure 2 is designed by (4). In the block diagram, we can measure currents and compute voltages by gate signal of inverter. From measurements, we can compute back-EMF following that

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R+p(L-M) & 0 & 0 \\ 0 & R+p(L-M) & 0 \\ 0 & 0 & R+p(L-M) \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$E_{abc} = V_{abc} - [R + p(L-M)]I_{abc} \qquad (7)$$

$$Y_{abc} = \frac{V_{abc} - [R + p(L-M)]I_{abc}}{-\frac{P}{2}\psi}$$

And in the E_{abc}, we can compute $trapez(.)$ with speed information because ψ and P is constant in the E_{abc}. The estimated $trapez(.)$ with speed information (Y_{abc}) is following Figure 6 and Figure 7 and the $trapez(.)$ takes extreme value of ± 1 for any given value of θ_r.

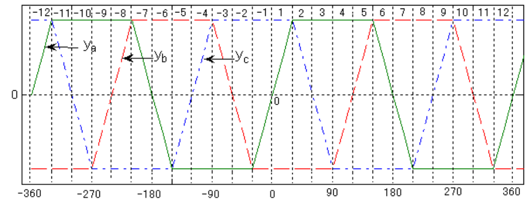


Figure 6. Waveforms of back-EMF with speed information (ω_r >0)

If we define the $trapez(.)$ with speed information is y_a, y_b, y_c, the rotor speed magnitude is simply given by

$$|\omega_r| = \max(|y_a|,|y_b|,|y_c|) \qquad (8)$$

Since the width of $trapez(.)$ is variable dependent on shape of $trapez(.)$.

1	$y_b < y_a < y_c$ & $y_a > 0$	$\theta_r = \alpha\pi y_a / \omega_r$
2	$y_b < y_c < y_a$ & $y_c > 0$	$\pi/3 - \alpha\pi y_c / \omega_r$
3	$y_b < y_c < y_a$ & $y_c < 0$	$\pi/3 - \alpha\pi y_c / \omega_r$
4	$y_c < y_b < y_a$ & $y_b < 0$	$2\pi/3 + \alpha\pi y_b / \omega_r$
5	$y_c < y_b < y_a$ & $y_b > 0$	$2\pi/3 + \alpha\pi y_b / \omega_r$
6	$y_c < y_a < y_b$ & $y_a > 0$	$\pi - \alpha\pi y_a / \omega_r$
7	$y_c < y_a < y_b$ & $y_a < 0$	$\pi - \alpha\pi y_a / \omega_r$
8	$y_a < y_c < y_b$ & $y_c < 0$	$4\pi/3 + \alpha\pi y_c / \omega_r$
9	$y_a < y_c < y_b$ & $y_c > 0$	$4\pi/3 + \alpha\pi y_c / \omega_r$
10	$y_a < y_b < y_c$ & $y_b > 0$	$5\pi/3 - \alpha\pi y_b / \omega_r$
11	$y_a < y_b < y_c$ & $y_b < 0$	$5\pi/3 - \alpha\pi y_b / \omega_r$
12	$y_b < y_a < y_c$ & $y_a < 0$	$2\pi + \alpha\pi y_a / \omega_r$

Table 1. estimated rotor position
by using y_a, y_b and y_c (ω_r >0)

We can find position by using y_a, y_b and y_c. In Figure 6, we can divide 12 parts for finding the rotor position. The table 1 is on the figure 6 summaries of the computation for the rotor position where the α is a parameter used to adjust shape of $trapez(.)$.

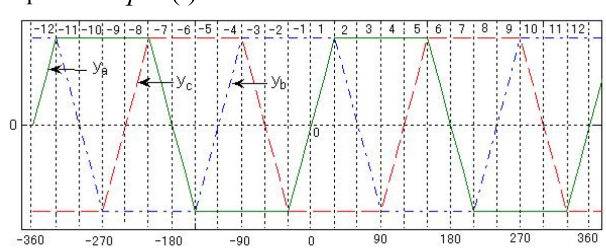


Figure 7. Waveforms of back-EMF with speed information (ω_r <0)

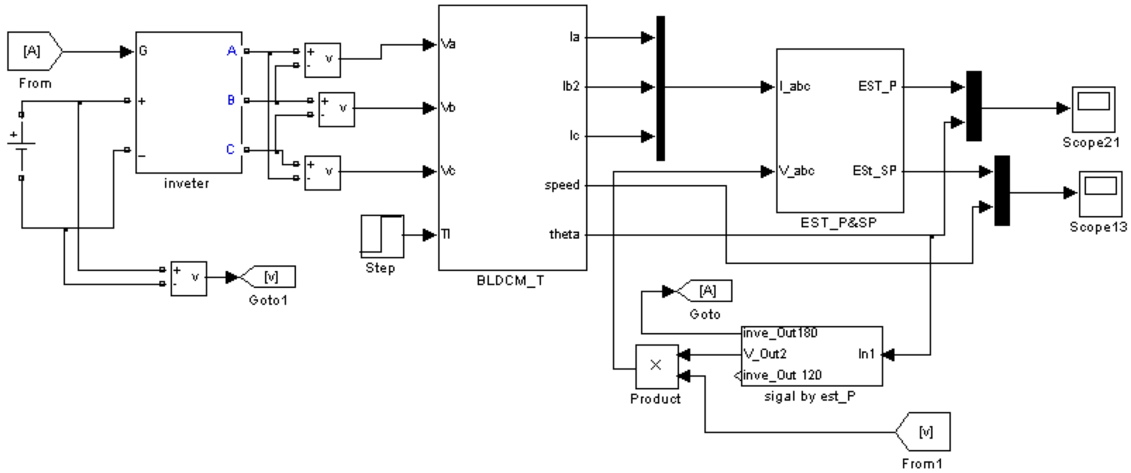


Figure 8. The overall structure of the proposed estimation of speed and position

-1	$y_c < y_a < y_b \,\&\, y_a < 0$	$\theta_r = \alpha\pi\, y_a / \omega_r$
-2	$y_a < y_c < y_b \,\&\, y_c < 0$	$-\pi/3 - \alpha\pi\, y_c / \omega_r$
-3	$y_a < y_c < y_b \,\&\, y_c > 0$	$-\pi/3 - \alpha\pi\, y_c / \omega_r$
-4	$y_a < y_b < y_c \,\&\, y_b > 0$	$-2\pi/3 + \alpha\pi\, y_b / \omega_r$
-5	$y_a < y_b < y_c \,\&\, y_b < 0$	$-2\pi/3 + \alpha\pi\, y_b / \omega_r$
-6	$y_b < y_a < y_c \,\&\, y_a < 0$	$-\pi - \alpha\pi\, y_a / \omega_r$
-7	$y_b < y_a < y_c \,\&\, y_a > 0$	$-\pi - \alpha\pi\, y_a / \omega_r$
-8	$y_b < y_c < y_a \,\&\, y_c > 0$	$-4\pi/3 + \alpha\pi\, y_c / \omega_r$
-9	$y_b < y_c < y_a \,\&\, y_c < 0$	$-4\pi/3 + \alpha\pi\, y_c / \omega_r$
-10	$y_c < y_b < y_a \,\&\, y_b < 0$	$-5\pi/3 - \alpha\pi\, y_b / \omega_r$
-11	$y_c < y_b < y_a \,\&\, y_b > 0$	$-5\pi/3 - \alpha\pi\, y_b / \omega_r$
-12	$y_b < y_a < y_c \,\&\, y_a > 0$	$-2\pi + \alpha\pi\, y_a / \omega_r$

Table 2. estimated rotor position by using y_a, y_b and y_c (ω_r <0)

4. SIMULATION RESULTS

The structure of sensored driving system is given in figure 8. The line to line voltage is calculated based on the DC link voltage and switching status of inverter. We use sensored driving system without setting an initial position to estimate back EMF and then the speed and position are calculated by estimated back EMF.

description	symbol	value	unit
Stator resistance	R	0.552	Ω
stator inductance	L	0.09	mh
magnitude of flux linkage	ψ	0.11	Wb
moment of inertia	J	20	gcm^2
Friction coefficient	B	0	
Number pole	P	6	

Table 3. BLDC motor specification

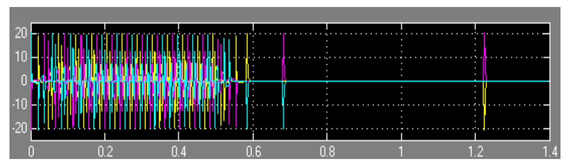
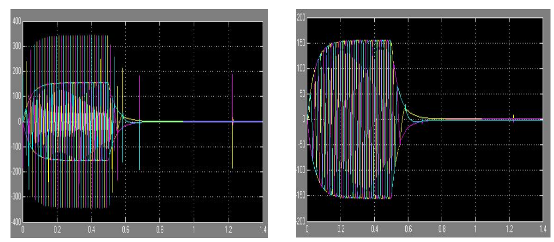


Figure 9. Pitch signal of pI_{abc} in estimation parts



Estimated back EMF without Filter

Estimated back EMF with Filter

Figure 10. Estimated back EMF without filter and with filter

Table 3 shows the BLDC motor specification to examine the performance of the proposed estimation method.

The figure 9 shows there are the pitch signals in $p(L-M)I_{abc}$. It is a problem because the estimated back EMF has pitch signal and the estimated speed and position also has pitch signal. Therefore, to estimate the speed and the position, the pitch signal has to be eliminated by low pass filter.

The figure 10 shows the estimated back EMF has pitch signal and the pitch signal is eliminated by the filter. The back EMF is shown by load torque which is increased at 0.5 seconds to reduced speed. The back EMF with pitch signal can not be calculated. Hence, the pitch signals have to be removed by using low pass filter.

The figure 11 shows the estimated and measured speed and the figure 12 shows the measured and estimated position. The both figures also show low speed and position by the load torque.

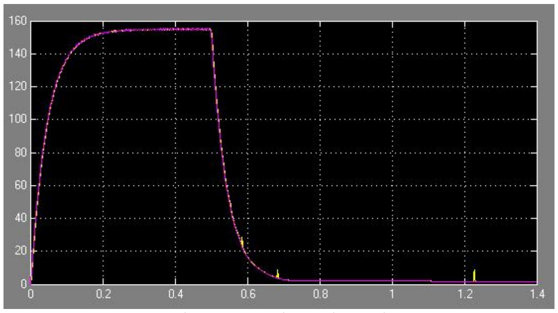


Figure 11. estimated speed

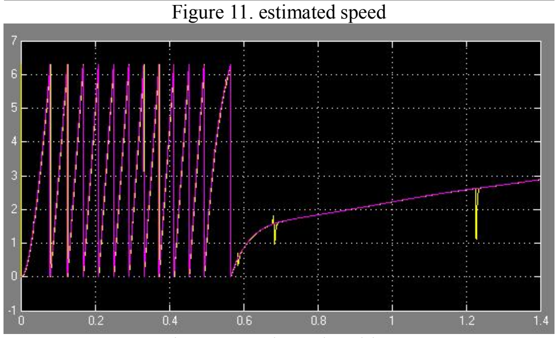


Figure 12. estimated position

5. EXPERIMENTAL RESULTS

The experimental line to line voltage and the phase voltage and the current signal are shown by Figure 13, Figure 14 and Figure15. In this figure, we can see between the experimental and simulation voltage, two differences are founded. One is the simulation voltage and back EMF are not same but the experimental voltage and back EMF signal structure are same because in the case of simulation, the back EMF of the motor is not affected and the voltage is appeared by inverter. However, in the case of the experimental voltage, the back EMF of the motor is affected. The other is the experimental voltage and current are had ripple situation by torque ripple. To calculated speed and position, the ripple signals have to be cancelled and then the speed and position should be estimated. Furthermore, to calculated speed and position, the reference voltage and measured voltage by Figure 14 (b)) are compared and to cancel ripple signals, the measured voltage is changed like Figure 14. (a), because when estimated Back EMF is obtained by measured current and changed voltage, the ripple signal should be deleted.

The estimated speed and position is shown by Figure 15 and Figure 16. The figure 16 shows that the ripple signal is cancelled. Moreover, the figure 17 we can not estimated very low speed and position because we can not measure voltage and current because in Target for TI C2000 in Matlab support maximum sampling time is only $5\mu/s$. It is not enough to measure voltage and current. Moreover, when we use real-time windows target board (NI PCI-6133), the sampling time is a problem because the sampling time is very low.

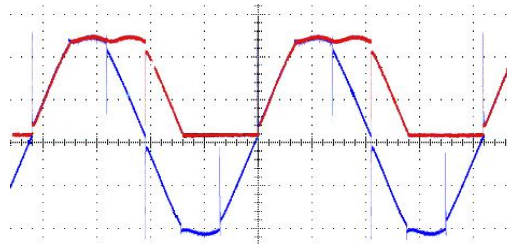
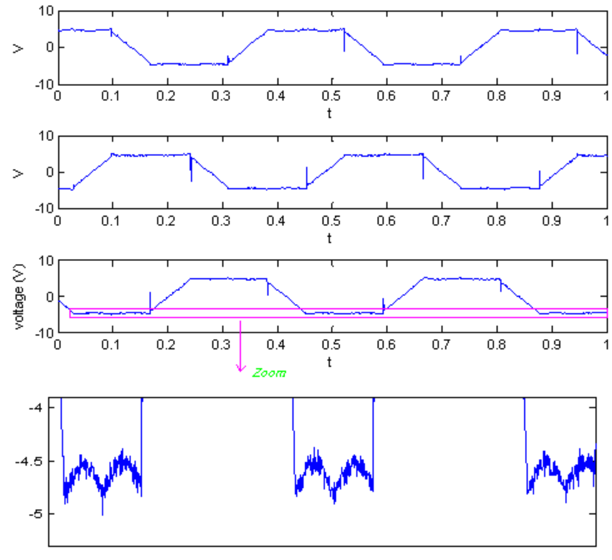
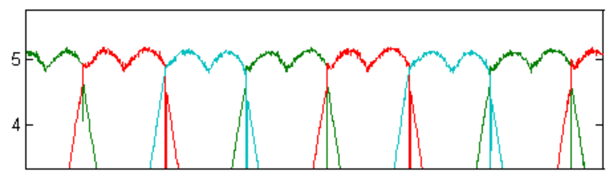


Figure 13. Lint to line voltage and phase a voltage



(a) Voltage changed of the motor



(b) Voltage measured of the motor
Figure 14. Voltage waveform of motor

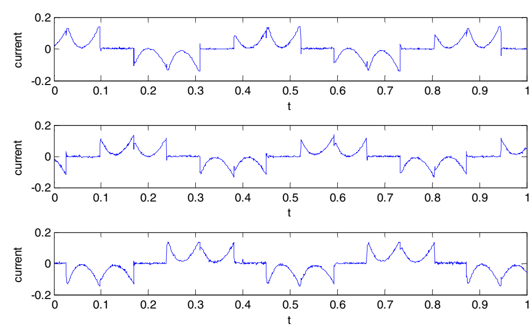


Figure 15 current waveform of motor

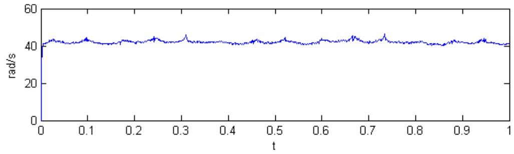


Figure 16 estimated speed

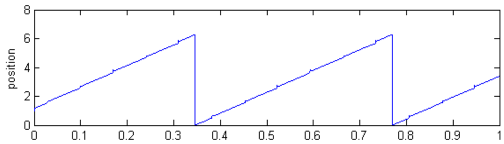


Figure 17 estimated position

6. CONCLUSION

The estimation technique is applied to a brushless DC motor with trapezoidal back EMF in this paper and show performance of estimation method for speed and position at low speed and zero speed. The computer simulations also show that the performance of the estimation method is better than other estimation method. The experiment also show the performance of estimated method.

REFERENCES

[1] J. P. Johnson, M. Ehsani, and Y. Guzelgunler, "Review of sensorless methods for brushless DC," in Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE, 1999, pp. 143-150 vol.1.

[2] K. Iizuka, H. Uzuhashi, M. Kano, T. Endo, and K. Mohri, "Microcomputer Control for Sensorless Brushless Motor, Industry Applications," IEEE Trans, vol. IA-21, pp. 595-601, 1985.

[3] J. C. Moreira, "Indirect sensing for rotor flux position of permanent magnet AC motors operating over a wide speed range," Industry Applications, IEEE Trans, vol. 32, pp. 1394-1401, 1996.

[4] T. Furuhashi, S. Sangwongwanich, and S. Okuma, A "position-and-velocity sensorless control for brushless DC motors using an adaptive sliding mode observer," Industrial Electronics, IEEE Trans, vol. 39, pp. 89-95, 1992.

[5] C. De Angelo, G. Bossio, J. Solsona, G. O. Garcia, and M. I. Valla, "A rotor position and speed observer for permanent-magnet motors with nonsinusoidal EMF waveform," Industrial Electronics, IEEE Trans, vol. 52, pp. 807-813, 2005.

[6] K. Tae-Hyung and M. Ehsani, "Sensorless control of the BLDC motors from near-zero to high speeds," Power Electronics, IEEE Trans on, vol. 19, pp. 1635-1645, 2004.

[7] V. R. Moorthi, "Power Electronics," Oxford University press, 2005

[8] P. Yedamale, "Brushless DC (BLDC) Motor Funda-mentals," Microchip Technology Inc., 2003.

[9] W. Brown and M. T. Inc, "Brushless DC Motor Control Made Easy," Microchip Technology Inc. , 2002.