An Approach to Position Sensorless Drive for Brushless dc Motors

Satoshi Ogasawara and Hirofumi Akagi

Abstract—**This paper describes a brushless dc motor without a position sensor. Variable speed is achieved by adjusting the average motor voltage, just like chopper control of dc motors. The position sensorless drive proposed in this paper is based on detection of the conducting interval of free-wheeling diodes connected in antiparallel with power transistors. This approach makes it possible to detect the rotor position over a wide speed range, especially at a lower speed. Experimental results obtained from a prototype brushless dc motor of 300 W rating are shown to confirm the validity of sensorless drive from 45 to 2300 r/min. A starting procedure of the motor is also discussed because it is impossible to detect the rotor position at a standstill.**

I. Introduction

Brushless dc motors have been put into practical use because of high efficiency and good controllability. A brushless dc motor requires an inverter and a position sensor to perform "commutation" because a permanent magnet synchronous motor takes the place of a dc motor with brushes and commutators [2], [3]. Three Hall sensors have been used as a position sensor for the brushless dc motor. According to the way the motor rating decreases, the volume ratio of the Hall sensors to the motor increases so that the miniaturization of the motor becomes hard. Furthermore, the Hall sensors need at least eight signal wires.

In recent years, a position sensorless brushless dc motor that produces the commutation signal from back electromotive forces in the motor [5], [6] has been studied. It is, however, difficult for a conventional sensorless drive to detect the back emf's in a lower speed range because the back emf's are in proportion to the rotor speed. For that reason, the conventional one needs a complicated starting procedure [5].

In this paper, the authors propose a position sensorless dc motor that is based on a new position detecting method. The position information is detected on the basis of the conducting state of free-wheeling diodes connected in antiparallel with power transistors because a current flowing in a phase, in which no active drive signal is given to the positive and negative side transistors, results from the back emf's produced in the motor windings. This approach makes it possible to detect the rotor position over a wide speed range, especially at a lower speed, and to simplify the starting procedure. Experimental results obtained from a prototype sensorless drive is shown to confirm the validity of the position-detecting method proposed in this paper.

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The authors are with the Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka, Niigata, Japan.

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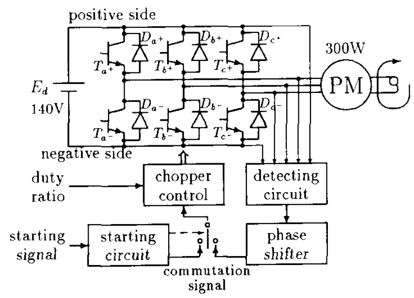
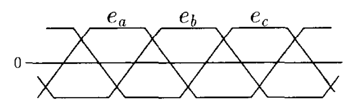


Fig. 1. System configuration of the proposed position sensorless drive.



positive side		a^+		b^+		c^+		
negative side	b^-		c^-		a^-		b^-	
open phase	a	c	b	a	c	b	a	c

Fig. 2. Relationship between drive signals and back emf's.

II. Brushless dc Motors

Generally, a brushless dc motor consists of a permanent magnet synchronous motor that converts electrical energy to mechanical energy, an inverter corresponding to brushes and commutators, and a position sensor. Fig. 1 shows the system configuration of a position sensorless drive proposed in this paper. The three-phase permanent magnet synchronous motor of rating 300 W has the trapezoidal back electromotive forces as shown in Fig. 2. The inverter used here is the same as a conventional three-phase voltage source inverter, but the conducting interval is 120° by electrical angle, as shown in Fig. 2. Therefore, only two transistors, i.e., a positive side transistor in one phase and a negative side transistor in another phase, are on state at a time. The other phase, in which no active drive signal is given to the positive and negative side transistors, is called the "open phase." To continue producing the maximum torque, the inverter commutation should be performed every 60° so that the rectangular-shaped motor line current is in phase with the back emf. The position information is obtained every 60° by detecting whether the free-wheeling diodes are conducting or not.

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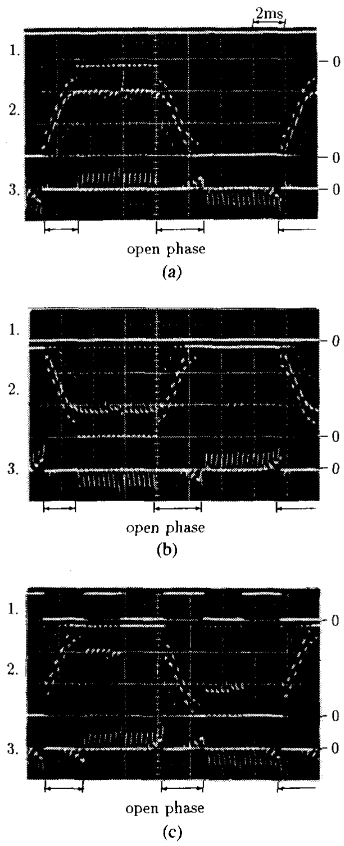


1. chopper selecting signal 5V/div

H:positive-side chopper, L:negative-side chopper

2. inverter phase voltage 50V/div

3. motor line current 0.2A/div

Fig. 3. Experimental waveforms under chopper control: (a) Positive side chopper control; (b) negative-side chopper control; (c) alternate chopper control.

Since the detected position signal leads next commutation by 30°, the commutation signal of the inverter is given through a phase shifter. A starting circuit gives a commutation signal for starting, which will be discussed later.

III. Chopper Control

If one of the two transistors in the on state is turned on and off at a chopper frequency, the drive system is able to control the motor speed by adjusting the duty ratio, just like the chopper control of dc motors. Fig. 3 shows experimental waveforms resulting from chopper control, which are somewhat complicated. Fig. 3(a) and (b) are the waveforms for when the chopper signal is applied to the positive and negative side transistors, respectively. The motor line current waveforms indicate that 1) the motor line current flows even in the period of an open phase, and 2) the beginning or ending point of the current in the open phase is in between the two commutations.

In the proposed brushless dc motor, alternate chopper control shown in Fig. 4 is adopted to make the motor line current symmetrical and to distribute the switching losses among both the positive and negative side transistors. Fig. 3(c) shows experimental waveforms in the case of the alternate chopper control. The current in the open phase always begins to flow at the middle point. Note that the rotor position is detected at this point.

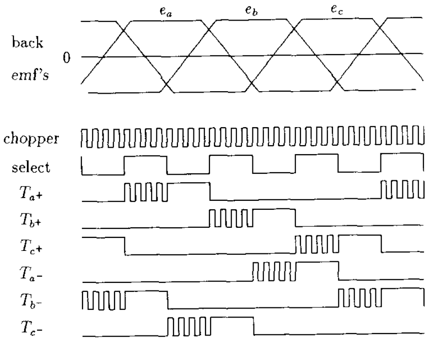


Fig. 4. Drive signals under alternate chopper control.

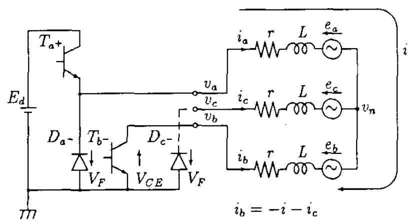


Fig. 5. Simplified circuit in which active signal is given to T_{a^+} and T_{c^-}.

IV. Position Detecting Method

Fig. 5 shows the simplified circuit in which the active signal is given to T_{a^+} and T_{b^-}. In this case, the chopper signal is applied to T_{a^+} so that the c phase is open. If T_{a^+} is on state, the dc link voltage increases the main current i. If T_{a^+} is turned off, i continues to flow through the free-wheeling diode D_{a^-} and decreases. Then, the c-phase voltage is given by

$$v_c = e_c + \frac{V_{CE} - V_F}{2} - \frac{e_a + e_b}{2} \tag{1}$$

where V_{CE} and V_F are the forward voltage drop of the transistors and diodes, respectively (see Appendix A). Equation (1) holds good even in transient states because no motor constants are included in (1), although the resistances and inductances of the motor windings are taken into consideration in the derivation of (1). The conducting condition of the diode D_{c^-} is given by

$$v_c < -V_F. \tag{2}$$

Substituting (1) into (2) gives the following:

$$e_c - \frac{e_a + e_b}{2} < -\frac{V_{CE} + V_F}{2}. \tag{3}$$

Since the back emf's are trapezoidal, $e_a + e_b$ is approxi-

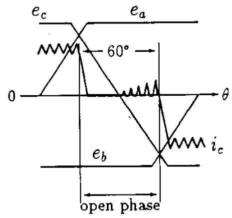


Fig. 6. Current waveform in open phase.

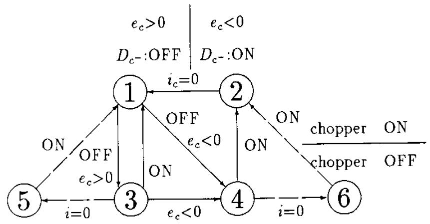


Fig. 7. Node sequence diagram.

TABLE I
INVERTER MODES

Mode	Chopper	Condition		T_{a^+}	T_{b^-}	D_{a^-}	D_{c^-}	v_n
1	ON	$i > 0$	$i_c = 0$	ON	ON	OFF	OFF	$(E_d - e_a - e_b)/2$
2			$i_c > 0$				ON	$(E_d - e_a - e_b - e_c)/3$
3	OFF		$i_c = 0$	OFF		ON	OFF	$(-e_a - e_b)/2$
4			$i_c > 0$				ON	$(-e_a - e_b - e_c)/3$
5		$i = 0$	$i_c = 0$			OFF	OFF	$-e_b$
6			$i_c > 0$				ON	$(-e_b - e_c)/2$

mately zero near the zero point of e_c. Therefore, the conducting condition of D_{c^-} is given by

$$e_c < -\frac{V_{CE} + V_F}{2}. \tag{4}$$

Generally, V_{CE} and V_F are much smaller than the back emf's. When the c-phase back emf e_c becomes negative, the open-phase current flows through the negative-side diode D_{c^-}.

Table I shows the inverter modes, where V_{CE} and V_F are neglected in the calculation of v_n. Fig. 6 shows a current waveform in an open phase (phase c). Fig. 7 shows the mode sequence diagram. The instant of the first appearance of mode 4 is the zero point of e_c. The rotor position can be detected at this time by detecting whether D_{c^-} is conducting or not. This point leads the next commutation by 30°. The commutation signal is given through a digital phase shifter using two counters, as is shown in Fig. 8. The detection is blocked immediately following the previous commutation in order to avoid being falsely triggered by the decaying main current, which flows through D_{c^-} as soon as T_{c^+} is turned off at the previous commutation.

Fig. 9 shows a specially designed circuit to detect whether the free-wheeling diodes are conducting or not. A resistor and a diode are connected to a comparator for voltage clamping. The reference voltage V_{ref} is slightly smaller than the forward voltage drop of the free-wheeling diodes V_F. The detecting circuit needs two isolated power supplies, but it is not influenced by the dc link voltage variation.

Fig. 10 shows experimental results of the proposed position sensorless drive in steady states. Stable and good driving performance is attained up to 2300 r/min by the proposed position detecting method. The detecting characteristics are invariant with the load because of no variation of current in the open phase, as is shown in Fig. 10.

V. Starting Procedure

The amplitude of the back emf's is proportional to the rotor speed. Since the open-phase current results from the back emf's, it is impossible to detect the rotor position at a standstill. Therefore, a suitable starting procedure is necessary to the position sensorless brushless dc motor drive.

The conducting condition of the free-wheeling diode is given by (4). To detect the open-phase current, the open-phase back emf has to be at least greater than $(V_{CE} + V_F)/2$. The back emf coefficient of the motor used in this experimental system K_v is 27.7 mV/r/min (phase crest value), and $V_{CE} + V_F = 1.2$ V. Therefore, minimum detectable speed is theoretically given by 22 r/min. The authors propose the following simple starting procedure because the detectable speed is small enough.

The procedure starts by exciting two arbitrary phases for a preset time. At the time, the motor line currents are limited by the current limiter. The rotor turns to the direction corresponding to the exited phases, as is shown in Fig. 11(a).

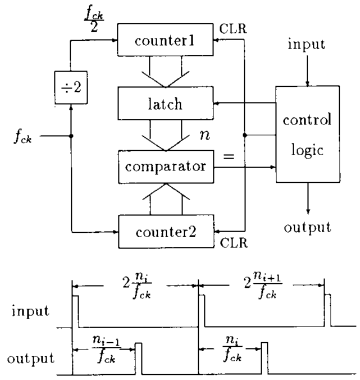


Fig. 8. Digital phase shifter.

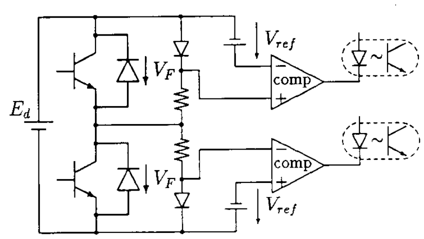
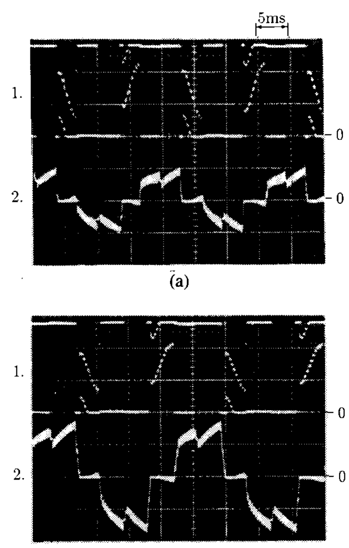


Fig. 9. Detecting circuit for conduction of free-wheeling diodes.



1. inverter phase voltage 50V/div

2. motor line current 1A/div

Fig. 10. Experimental waveforms of the sensorless drive (on load): (a) N = 1527 r/min, duty 60%; (b) N = 1314 r/min, duty 60%.

Next, the commutation signal that advances the switching pattern by 120° is given (Fig. 11(b)), and then, the open-loop commutation is immediately switched to the sensorless drive proposed in the previous section. After the next commutation, the position sensorless drive is attained (Fig. 11(c)).

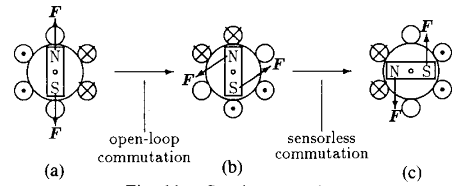


Fig. 11. Starting procedure.

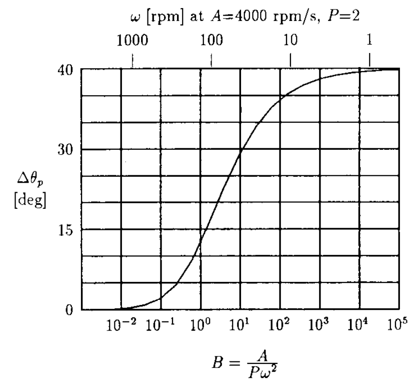


Fig. 12. Phase delay in the signal phase shifter.

Note that the phase shifter is not used in a speed range below 500 r/min. The reason is the following.

The digital phase shifter shown in Fig. 8 has no phase delay when the rotor speed is kept constant. A large amount of phase delay, however, occurs during acceleration. The following equation and Fig. 12 give the phase delay $\Delta\theta_p$ (in radians) in the digital phase shifter (see Appendix B):

$$\Delta\theta_p = \frac{\pi}{4} + \frac{3}{4B}\left(1 - \sqrt{1 + \frac{2\pi B}{3}}\right) \tag{5}$$

where

$B = \frac{A}{P\omega}$

A rotor acceleration (in radians per second squared)

P number of pole pairs

ω rotor speed (in radians per second).

Since the maximum rotor acceleration of the prototype brushless dc motor is 4000 r/min/s, ω = 100 r/min corresponds to B = 1.9, as is shown in Fig. 12. In the speed range above 500 r/min almost no phase delay is caused by acceleration.

Furthermore, there is some phase delay in the detecting circuit shown in Fig. 9. Assuming ideal trapezoidal back emf's, the phase delay $\Delta\theta_d$ is expressed by the following equation:

$$\Delta\theta_d = \frac{V_{CE} + V_F}{2k_v\omega} \cdot \frac{\pi}{6}. \tag{6}$$

Fig. 13 shows $\Delta\theta_d$ in the prototype brushless dc motor.

When the phase shifter is disabled, the commutation is performed as soon as the diode conduction is sensed. However, the leading angle is 30° at most, although the lagging angle may be greater than 30° when the phase shifter is enabled in the lower speed range.

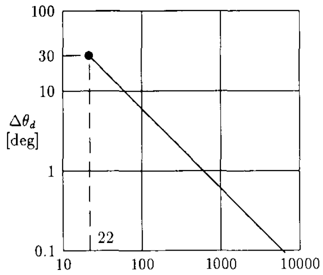
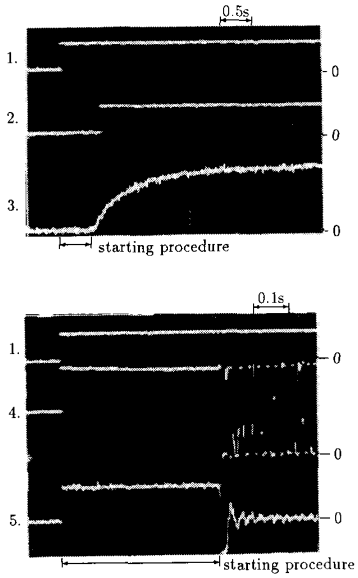


Fig. 13. Phase delay in the detecting circuit.



1. starting signal 5V/div
2. phase shifter 5V/div
   H: use, L: not use
3. rotor speed 1000rpm/div
4. inverter phase voltage 50V/div
5. motor line current 2A/div

Fig. 14. Starting characteristics ($N = 0 \rightarrow 2000$ r/min).

Fig. 14 shows a starting characteristic. The starting signal begins the starting procedure. At the end of the preset time of 0.5 s, the open-loop commutation advancing the switching pattern by 120° is done, and then, the polarity of the motor line current is altered. After the starting procedure, the alternative motor line current indicates that satisfactory sensorless commutations are performed by the proposed position-detecting method. After the preset time of 0.5 s, the excellent starting performance is attained by the proposed starting procedure.

VI. Conclusion

This paper has presented a position-sensorless brushless dc motor in which the position information is given on the basis of the conducting state of free-wheeling diodes in an open phase. The open phase current under chopper operation results from the back emf's produced in the motor windings. Therefore, this is considered to be an indirect detection of the back emf's through the free-wheeling diodes. This approach is characterized by its sophisticated position detection and makes it possible to detect the rotor position over a wide speed range from 45 to 2300 r/min compared with the conventional method that directly detects the back emf's. The capability of position sensorless drive at the low speed of 45 r/min makes a great contribution to simplify the starting procedure. The sensorless position-detecting method proposed here, however, requires the inverter to be operating in a chopping mode in order for the algorithm to work properly. Experimental results obtained from a prototype motor of rating 300 W have shown the validity of the proposed system.

Appendix A

Derivation of (1)

The loop equation through D_{a^-} and T_{b^-}, which is shown in Fig. 5, is given by

$$V_F + L\frac{di}{dt} + ri + e_a - e_b + ri + L\frac{di}{dt} + V_{CE} = 0. \quad (7)$$

Therefore, the following is the voltage drop of the motor resistance and inductance:

$$ri + L\frac{di}{dt} = -\frac{e_a - e_b}{2} - \frac{V_{CE} + V_F}{2}. \quad (8)$$

The potential of the motor neutral point v_n, which is also shown in Fig. 5, is given by

$$\begin{aligned} v_n &= V_{CE} + ri + L\frac{di}{dt} - e_b \\ &= -V_F - ri - L\frac{di}{dt} - e_a. \end{aligned} \quad (9)$$

Substitution (8) into (9) gives the following equation:

$$v_n = \frac{V_{CE} - V_F}{2} - \frac{e_a + e_b}{2}. \quad (10)$$

Since the c-phase terminal voltage v_c equals $e_c + v_n$, (1) is derived as follows:

$$v_c = e_c + v_n = e_c + \frac{V_{CE} - V_F}{2} - \frac{e_a + e_b}{2}. \quad (1)$$

Appendix B

Derivation of (5)

Assuming that the angular acceleration of the motor A is constant, the motor speed ω is expressed by the following equation.

$$\omega = \omega_0 + At. \quad (11)$$

If the position signal is detected at $t = 0$, the next signal is obtained when the rotor angle becomes 60° by electrical angle, that is

$$\frac{\pi}{3} = P\int_0^{T_0} \omega\, dt = P\left(\omega_0 T_0 + \frac{1}{2}AT_0^2\right). \qquad (12)$$

Therefore, the period T_0 is given by

$$T_0 = \frac{1}{A}\left(-\omega_0 + \sqrt{\omega_0^2 + \frac{2\pi A}{3P}}\right). \qquad (13)$$

The phase shifter outputs the signal corresponding to T_0. This output time t_c' is shown as follows:

$$t_c' = \frac{3}{2}T_0 = \frac{3}{2A}\left(-\omega_0 + \sqrt{\omega_0^2 + \frac{2\pi A}{3P}}\right). \qquad (14)$$

The phase delay of the phase shifter $\Delta\theta_p$ is given by

$$\Delta\theta_p = \theta(t_c') - \frac{\pi}{2} = P\left(\omega_0 t_c' + \frac{1}{2}At_c'^2\right)\frac{\pi}{2}. \qquad (15)$$

Substitution (14) into (15) gives (5):

$$\Delta\theta_p = \frac{\pi}{4} + \frac{3}{4}\frac{P\omega_0^2}{A}\left(1 - \sqrt{1 + \frac{2\pi}{3}\frac{A}{P\omega_0^2}}\right). \qquad (16)$$

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Satoshi Ogasawara was born in Kagawa Prefecture, Japan, on July 27, 1958. He received the B.S., M.S., and Dr.Eng. degrees in electrical engineering from the Nagaoka University of Technology, Niigata, Japan, in 1981, 1983, and 1990, respectively.

Since 1983, he has been a Research Associate at the Nagaoka University of Technology. He is engaged in research on ac motor drives.

Dr. Ogasawara is a member of the Institute of Electrical Engineers of Japan.

Hirofumi Akagi was born in Okayama Prefecture, Japan, on August 19, 1951. He received the B.S. degree from the Nagoya Institute of Technology, Nagoya, Japan, in 1974 and the M.S. and Ph.D. degrees from the Tokyo Institute of Technology, Tokyo, Japan, in 1976 and 1979, respectively, all in electrical engineering.

Since 1984, he has been an Associate Professor at Nagaoka University of Technology, Japan. He is engaged in research on ac motor drives, active power filters, and high-frequency inverters.

Dr. Akagi is a member of the Institute of Electrical Engineers of Japan.