Position Control of Low Cost Brushless DC Motor using Hall Sensor

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Abstract— **This paper concerns the research on position control of low cost brushless DC (BLDC) motor. Usually BLDC motors are controlled by using the hall-effect sensor in a low cost application. Based on the characteristics of back electromotive force (back EMF), the rotation information of rotor can be acquired from the hall sensor. During the one electrical cycle, the motor has six trigger signals for three phases. Speed and position of the rotor can be calculated by using hall sensor signal. The motor system has 30:1 gear ratio in experiment. Then, the number of hall sensor signal per one cycle is 180. Using the dsPIC33FJMC804 CPU as controller, some experiments were performed with the prototype which is the surface-mounted permanent magnet motor. Currently it is being developed for air intake system of vehicle.**

Keywords; BLDC motor, back EMF, position control, PI controller, hall-effect sensor, air intake valve system

I. INTRODUCTION

Because brushless DC (BLDC) motors do not use brushes, they have longer operating life and noiseless operation. So, BLDC motors have been used widely in many applications that require stable operation and high performance. It has permanent magnet, so it has high ratio between torque and motor size and it is suited for applications where space and weight are critical. BLDC motor has higher speed ranges, better speed and torque than other motors. Low rotor inertia improves acceleration and deceleration times while shortening operating cycles [1].

There is two way for control of BLDC motor, sensor control and sensorless control. Although there have been numerous sensorless approaches proposed in the paper [2]-[3], BLDC motors with the hall sensor are applied to industry and home appliances. In low or medium cost applications, the hall sensors are usually utilized for rotor position, speed and switching signals of inverter transistors [4].

Now in air intake system of automobile, dual duct system has been operated by natural air pressure. But it has a problem; incorrect angle of valve opening has low output power and a lot of noise. If a large amount of air than normal is inhaled, big noise will be occurred. And if a small amount of air is taken, it will make reduced output power of engine and restricted efficiency. Therefore, the exact opening angle of intake valve is needed for system. The valve control by using motor is presented in Fig. 1. In this paper, the position control of motor for valve angle is explained. The motor control for adjusting the angle of the intake valve depending on engine speed is proceeding. As the motor control is used for the opening and closing operation, the system will be better.

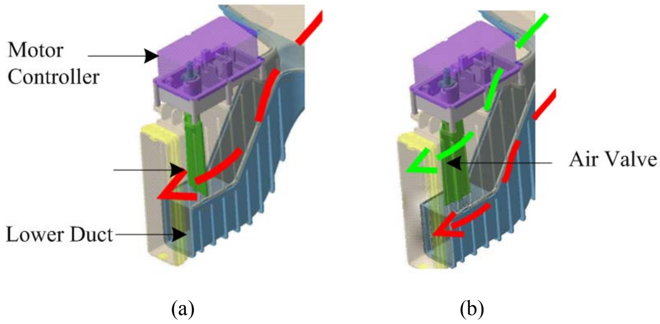

Figure 1. Air intake valve system (a) Valve close (b) Valve open

In this paper, a PI control algorithm is used for position control and described the minimal hardware requirements. The detailed descriptions of the control algorithm and sensor signal acquisition is presented.

II. BASIC PRINFIPLE

The commutation of the BLDC motor is done electrically. To know the position of rotor is very important for electrical commutation. Usually the hall sensors are placed in 120-degree intervals and the common operation of BLDC motor is achieved by six-section. The back EMF and hall sensor signal are presented in Fig. 2.

When the magnet poles of rotor come to hall sensor, the signal is generated. According to six-step in Fig. 2, the commutation sequence is performed. The motor phases are supposed to conduct for 120 electrical degrees two times per cycle [4]. The two phases are only conducted at one time. The hall sensor signal has the rising edge and the falling edge for each phase. That is, the six-trigger signals are generated per one cycle. Using these trigger signals, motor control is carried out. The switching sequence for commutation phase is given in Table I. For forward and reverse direction of rotor, switching sequence is different. A detailed operating principle by hall sensors is well explained in many papers for more detailed description [4]-[5].

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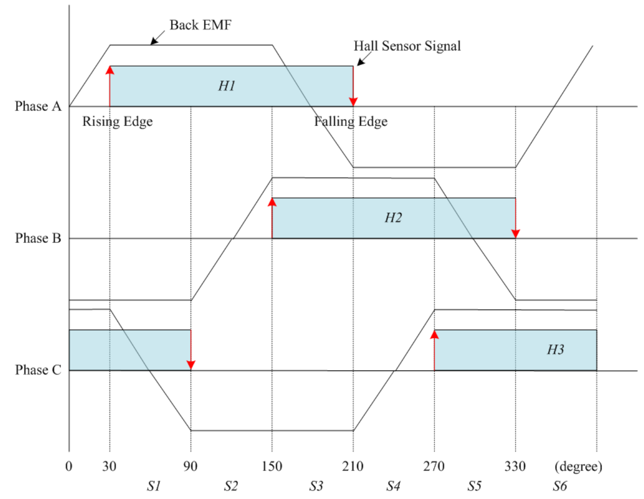


Figure 2. Back EMF and hall effect sensor signal

III. MATHEMATICAL MODELING OF BLDC

Modeling of BLDC motor is similar to three-phase synchronous machine. Since there is a permanent magnet mounted on the rotor, some dynamic characteristics are different [6]. Electrical analysis of BLDC motor is presented by Fig. 3.

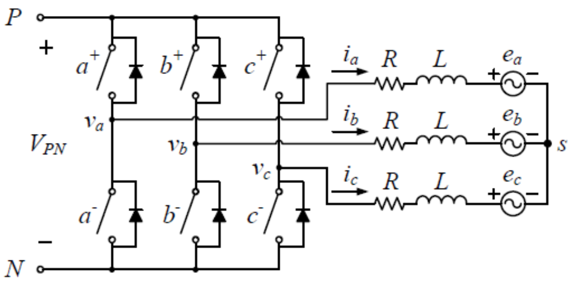


Figure 3. Electric circuit of BLDC motor

TABLE I. SWITCHING SEQUENCE

Direction	Switching Sector					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**
Forward	$a^+ b^-$	$a^+ c^-$	$b^+ c^-$	$b^+ a^-$	$c^+ a^-$	$c^+ b^-$
Reverse	$b^+ a^-$	$c^+ a^-$	$c^+ b^-$	$a^+ b^-$	$a^+ c^-$	$b^+ c^-$

The voltage equation has components of voltage and current for A, B, C phases, resistance, inductance and back EMF. The BLDC motor is operated by a three-phase voltage source that is converted from DC power supply. The model of the BLDC motor is expressed as follow:

$$V_x = Ri_x + L\frac{di_x}{dt} + e_x \tag{1}$$

Where, V_x is the input voltage, i_x is the current, R is the resistance, L is the inductance and e_x is the back EMF, respectively. The subscript x presents a, b, c phase. In upper voltage equation, inductance L is the difference between self inductance L_s and mutual inductance L_m. That is, $L=L_s - L_m$.

$$e_x = K_w + f(\theta_e - \frac{2n\pi}{3})\omega_m \tag{2}$$

The back EMF is related to a function of rotor position. K_w is back EMF constant of one phase, θ_e is the electrical rotor angle and ω_m is the rotor angular velocity. The subscript x presents a, b, c phase. If x is a, b and c phase, n is 0, 1 and 2.

Unlike the induction motor or synchronous motor control, phase variables are used directly without any transformation equation in BLDC motors. The physical properties as current, flux and back EMF has rectangular forms, so coordinate transformation is not needed.

$$P_e = e_a i_a + e_b i_b + e_c i_c \tag{3}$$

$$T_e = \frac{P_e}{\omega_m} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \tag{4}$$

Where, P_e is the output power, T_e is the torque of motor.

If motor is operated with two-phase conduction type, the torque equation is presented newly. In *S1* mode as seen in Table I, current ($i_a=I$, $i_b=-I$, $i_c=0$) and back EMF ($e_a=E$, $e_b=-E$) are expressed as follow:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} = \frac{2EI}{\omega_m} \tag{5}$$

The total output torque is a simple equation of back EMF E and current I. According to (5), to produce an electromagnetic torque, the sum of $e_a i_a$, $e_b i_b$ and $e_c i_c$ has to be constant as far as a certain speed is concerned. As shown in Fig. 2, this means rectangular phase currents with the corresponding back EMF which is required.

IV. HARDWARE

Battery supplies energy to power module and motor. The power through voltage regulator is delivered to the CPU and the gate driver. In Fig. 4, there are BLDC motor and controller module used in experiment.

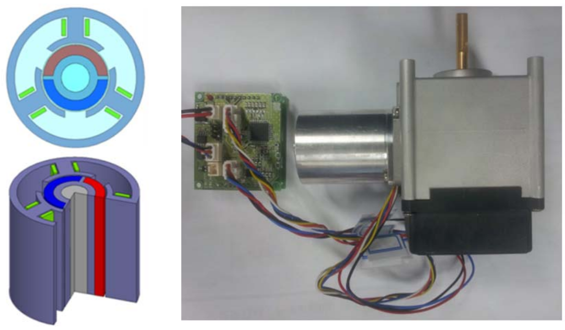


Figure 4. BLDC motor and driver

The motor is an inner rotor type with two poles. It is very small sized driver that is placed in motor case. And motor system has mechanical structure of gear ratio 30:1. The rated voltage is 12[V], rated current is 1[A] and maximum current is 5[A]. As seen in Table II, motor parameter is presented.

Motor controller is composed of power, controller and drive part. Fig. 5 is a logic diagram of BLDC motor system.

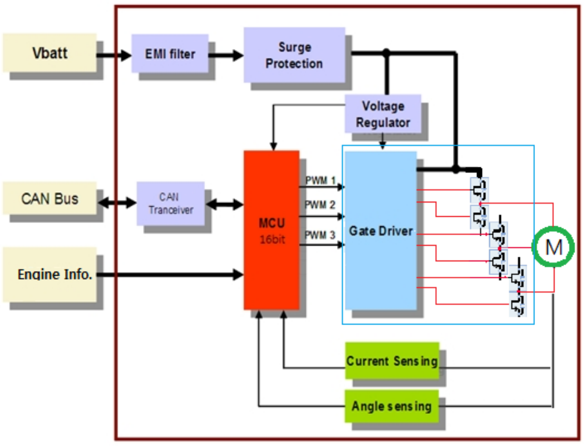


Figure 5. Logic diagram of BLDC motor

TABLE II. SPECIFICATIONS OF BLDC MOTOR

Parameter	Description
Motor Type	3ph BLDCM
Weight	226.5 g
Rated Voltage	12 V DC
Rated Speed	7380 rpm
Rated Current	0.98 A
Rated Torque	9.9 mNm
Stall Current	7.01 A
Stall Torque	79.5 mNm
Resistance	0.05 Ohm
Back EMF	580 mVrms@1000rpm

A. *Control Part*

To drive BLDC motor, the CPU generates three pulse width modulation (PWM) signals. Average DC input voltage can be changed with the duty ratio of PWM signal. Then, the current flowing to the motor will be changed depending on input voltage. That is, if switching sequence in Table I and PWM input voltage can be produced, BLDC motor will be operated. The PWM frequency used in this study is 10 kHz.

B. *Input Signal Part*

For current control, current detecting circuit is required. It checks the change of current. The signal from sensor is converted to adjusted signal for CPU. In this paper, the shunt resistor was used for inexpensive module. The resistance of 2 Watt, 0.01ohm is used and measured current is transformed to voltage with level of 0.33 volt per 1 Ampere.

For speed and position control, rotor position must be detected. There are phase detectors as resolver, encoder, and hall sensor. The resolver is excellent benefits and a simple structure, but must be applied to the resolver's stator winding for excitation signal, so hardware has the disadvantage of complexity. The absolute encoder output directly to a digital signal beam and a digital output signal is proportional to the rotational speed of the frequency changes. When the digital controller is designed it is easy to use. The hall sensor is unsuitable for the high precision control because the three phase of square wave with 120-degree is generated. But in this motor test, the hall sensor is used as low precision speed control can be required.

V. CONTROL

The BLDC motor driver has been operated by 120-degree or 180-degree turn-on method. The two-phase conduction method has 120-degree turn-on section and three-phase conduction method has 180-degree turn-on section. The three-phase conduction method has more torque ripple than 120-degree conduction. Then, the three-phase conduction method is not used generally [7]. Three hall-effect sensors are usually used to detect the commutation point at every 60 electrical degrees. In Fig. 6, control sequence is presented block diagram of current control, speed control and position control.

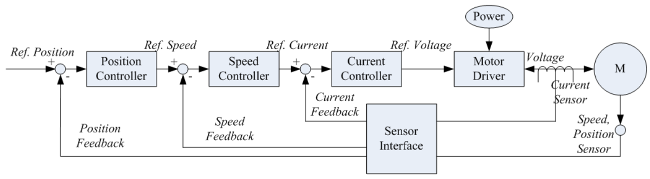


Figure 6. Control block diagram of BLDC motor

The interval time for motor speed can be calculated from the counter of the PWM interrupt. The electrical frequency is acquired from the time as seen in Fig. 7. If the frequency and rotor pole number are known, the motor rpm will be achieved.

The rpm of rotor are described in the following equation.

$$S_r = \frac{120 \times F_r}{P} \tag{6}$$

Where, S_r is the rpm and P is the pole number of rotor. F_r is the rotation frequency of rotor and presented calculated by $1/T_{int}$. The T_{int} is the time between triggers of hall sensor signal.

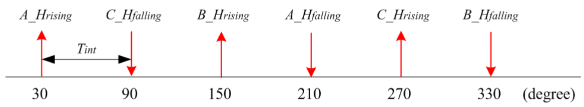


Figure 7. Triggers of hall sensor signals and time interval between triggers

The position and speed of rotor can be calculated using rising and falling edge of hall sensor signals. Thus it is generated 180 signals for one electrical cycle in case of 30:1 geared motor. If rotor has two magnetic poles, rotating angle of 2-degree is calculated from first hall sensor trigger signal to next. In addition, this angle value is enough for position control in intake system of automobile. For position control, each trigger point has counter value. That is, 0-degree of rotor is 1st point, 2-degree is 2nd point and 90-degree is last point. These points are used for position control. A closed loop control algorithm with a PI controller is presented as follows.

$$e = \theta_r^* - \theta_r \tag{7}$$

$$y = K_p e + K_i \int edt \tag{8}$$

$$\frac{y - y_0}{\Delta t} = K_p\left(\frac{e - e_0}{\Delta t}\right) + K_i e \tag{9}$$

$$y = y_0 + K_p(e - e_0) + K_i e \cdot \Delta t \tag{10}$$

In this paper, we define the position error e, previous error e_0, reference speed θ_r^* and measured speed θ_r. The y is output of the PI controller and y_0 is previous output and Δt is the sampling time. K_p and K_i are the proportional and integral gains of the PI controller respectively.

VI. EXPERIMENTAL RESULTS

The intake valve moves only between 0 and 90-degree. First, the response time was tested. From start point 0-degree to end point 90-degree, the motor driver has average value of 120ms response time for several test in Fig. 8.

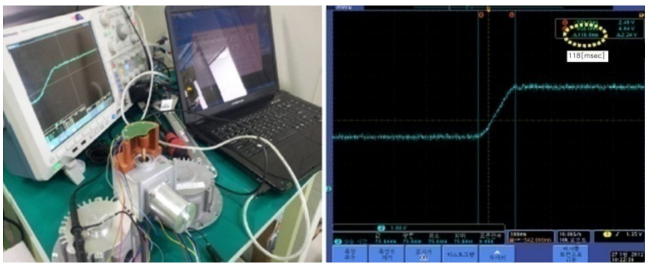
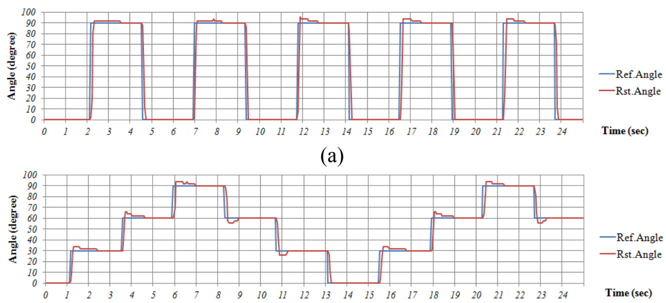


Figure 8. Measurement for response time

The second experiment is concerned with the accuracy of the position according to the reference command. The results of position control are showed in Fig. 9.



(b)

Figure 9. (a) Position contol for reference angle 0 and 90-degree (b) Position control for reference angle 0, 30, 60 and 90-degree

TABLE III presents reference angle and result angle. The system has always 2-degree angle error because of resolution of hall sensor. The experiments are processed by using angle measurement equipment as seen in Fig. 8.

TABLE III. EXPERIMENTAL DATA OF ROTOR POSITION ANGLE

Ref. Angle	Experimental Data			
	SPL #1	*SPL #2*	*SPL #3*	*SPL #4*
0°	0° (0°)	0° (0°)	0° (0°)	0°
15°	14° (-1°)	16° (+1°)	15° (0°)	15°
30°	29° (-1°)	31° (+1°)	31° (+1°)	30.3°
45°	45° (0°)	46° (+1°)	46° (+1°)	45.6°
60°	60° (0°)	61° (+1°)	61° (+1°)	60.6°
75°	76° (+1°)	77° (+2°)	76° (+1°)	76°
90°	91° (+1°)	92° (+2°)	91° (+1°)	91°

VII. CONCLUSION

This paper has presented a three-phase control technique for BLDC motor which is used in air intake valve system of automotive and described system hardware requirements. And control performance was verified by experiments.

For a low cost control of BLDC motor, hall-effect sensor was used and position information from sensor signal was acquired for motor control. Although air intake system has insignificant position error for operation, it is negligible for normal operation. Rather the response time is more important than the accurate position.

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