

Proposal of Sensorless Control Method for Small Brushless DC Motor

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ABSTRACT

On-car motor quantities and applications have tended to increase in recent years. This is increasing the total size and weight of motors per vehicle, and operating environments are also becoming more severe, including mounting inside the engine room, resulting in an increasing trend towards replacement with compact, lightweight brushless DC motors that have better durability under harsh environments. However, as phase current and rotor position sensors are generally needed to control brushless DC motors, the cost tends to rise and reducing cost is an issue. An algorithm was therefore constructed with the aim of reducing cost while maintaining brushless DC motor performance and reliability. This algorithm estimates both the phase current and the rotor position, without using phase current or rotor position sensors, by using the DC current sensor for fail detection that was originally present in the controller, and the motor drive voltage information. The newly constructed method provided prospects for reducing brushless DC motor cost.

1. Introduction

Recently, attention is being given to safety and environmental measures in addition to the basic automobile performance dynamics of running, turning and stopping, and functions are being enhanced through the introduction of electronic control to various systems. Typical drive actuators converted to electronic control include motors, and with application increases come demands for compact size, high performance, high reliability, low cost, and low power consumption. Motor usage originally expanded from DC motors with brushes, but the switchover to brushless DC (BLDC) motors is accelerating from the standpoints of enhancing performance and reliability and reducing power consumption. However, although the motor unit of a BLDC motor is less expensive than that of a DC motor, there is the issue of overall cost increase due to factors such as the addition of the rotor position and phase current sensors required for motor control, and increasingly complex drive circuits and control logic.

This study aimed to make BLDC motor cost competitive with that of DC motors. To achieve this, the authors focused on the fact that the two sensors required for motor control are the main factors increasing the cost, and proposed a sensorless control method that targets power-use motors that mainly rotate in a single direction,

and which are often used in cars.

Much research has been done on sensorless control methods that involve rotor position estimation⁽¹⁾⁻⁽⁴⁾. However, there is little research on methods that simultaneously estimate both the phase current and the rotor position⁽⁵⁾. The cited study used past estimation values in areas where phase current estimation is a challenge, and applied these values to simplified vector control without a speed controller or a current controller, limiting such motor control performance as responsiveness. Therefore, this study proposes a sensorless control algorithm that simultaneously estimates the phase current and the rotor position, and can also be applied to generally used vector control.

The hardware comprises the conventional BLDC motor control system minus the two sensors and their respective interface circuits.

Regarding phase current estimation, intermittent phase current information is obtained from the DC current sensor for fail detection, in accordance with the FET switching pattern obtained by performing pulse-width modulation (PWM) on the motor drive voltage. Focusing on the symmetry of the FET switching pattern, phase current estimation is performed at the timing appropriate for rotor position estimation by detecting the DC current.

On the other hand, rotor position estimation uses the motor drive voltage and the phase current, which have an

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Table 1 Motor classification by use

	Power use		Servo use	
Control	Torque control		Speed control; Position control	
Specific examples	Household electrical appliance; Factory automation	Car application	Household electrical appliance; Factory automation	Car application
	Vacuum cleaner; Washing machine	Oil pump; Water pump; Fan	Robot	Variable lift system

input-output relationship relative to the motor. A motor model that is not dependent on the rotor position and rotational speed is configured within the CPU used for motor control, with the voltage applied to the motor used as the input, and the model phase current obtained as the output. The rotor position is estimated by comparing the model phase current with the phase current estimated from the DC current that has been detected according to the FET switching pattern, and extracting the rotor position and rotational speed information.

2. Current Situation and Issues for Compact BLDC Motors

Table 1 shows BLDC motor classification.

BLDC motor applications are broadly divided into power use and servo use, and a significant difference

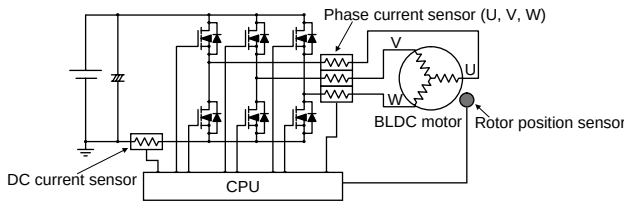


Fig. 1 BLDC motor drive electric circuit

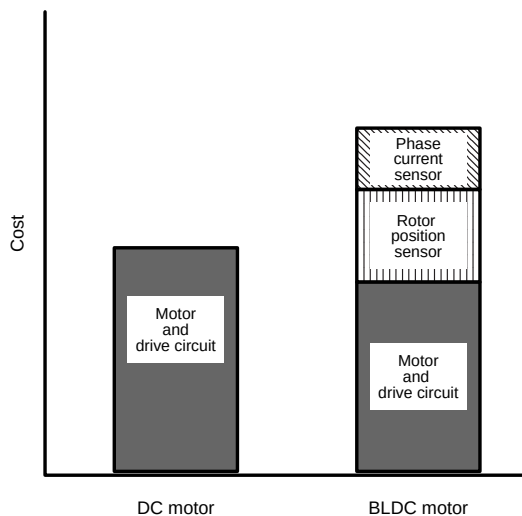


Fig. 2 DC motor and BLDC motor costs

between the two is the different motor control methods used. This study targeted power-use motors that mainly rotate in a single direction, and which are often used in cars.

Figure 1 shows a typical BLDC motor drive circuit. The circuit comprises a smoothing capacitor, FET bridge, a DC current sensor for fail detection located between the smoothing capacitor and FET bridge, a CPU, and the two types of sensors conventionally required for BLDC motor driving: a phase current sensor (U, V, W), and a rotor position sensor mounted on the motor rotor.

Figure 2 compares the costs of a typical DC motor and BLDC motor. This shows that BLDC motors tend to be more expensive than DC motors, and that the factors increasing the cost are the phase current and rotor position sensors. Therefore, of the three types of sensors, this study simultaneously eliminated the phase current and rotor position sensors that are the factors increasing the cost.

3. Control Algorithm

The following control methods used to eliminate the phase current and rotor position sensors, accurately estimate the phase current and rotor position, and achieve the target performances are described below.

- (1) Phase current estimation algorithm
- (2) Rotor position estimation algorithm
- (3) Coordination between rotor position estimation and phase current estimation

3.1. Phase Current Estimation Algorithm

The conventional phase current estimation method detects and uses the phase current information at the timing according to the FET switching pattern using a DC current sensor. The phase current information for each phase is not the same timing, which made it challenging to accurately estimate phase current. In addition, rotor position estimation requires phase current information that matches the command voltage update timing, but the phase current information obtained by the conventional phase current estimation method does not match the command voltage update timing, and is instead the information at the timing according to the FET switching pattern. This made it challenging to accurately estimate the rotor position.

Therefore, focusing on the symmetry of the FET switching pattern, an algorithm is proposed that accurately estimates the phase current at the command voltage update timing by detecting the DC current.

Figure 3 shows the proposed phase current estimation algorithm. The controller outputs the command voltage according to the command torque and the phase current. The command voltage is compared with the carrier wave and converted to the FET switching pattern by the PWM modulator. The phase current is generated and the motor

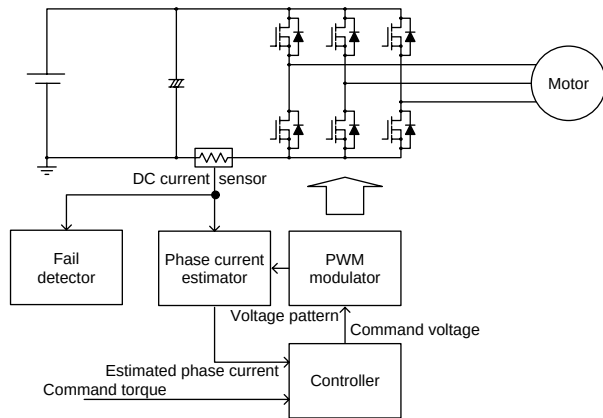


Fig. 3 Block diagram of phase current estimation system

Table 2 Relationship between basic voltage vector and detected current (I_{dc})

Voltage vector	Phase U	Phase V	Phase W	Detected current (I_{dc})
V0-	Low	Low	Low	0
Vu+	High	Low	Low	I_u
Vv+	Low	High	Low	I_v
Vw-	High	High	Low	$-I_w$
Vw+	Low	Low	High	I_w
Vv-	High	Low	High	$-I_v$
Vu-	Low	High	High	$-I_u$
V0+	High	High	High	0

is driven by switching the FET in accordance with this pattern. On the other hand, an intermittent phase current flows to the DC current sensor for fail detection in accordance with the FET switching pattern. Therefore, the phase current can be estimated by obtaining the DC current from the DC current sensor detection in accordance with the FET switching pattern.

The FET switching pattern is determined by the ON/OFF combination (8 patterns) of the 6 FET in the motor drive circuit. Figure 4 shows each FET operation pattern. Upper FET ON is indicated by orange, and lower FET ON is indicated by blue. The zero voltage vectors (V0-, V0+) and voltage vectors offset by a 60 deg phase from each other (Vu+, Vu-, Vv+, Vv-, Vw+, Vw-) can be generated according to the FET ON/OFF combinations. Table 2 describes the relationship between each voltage vector and

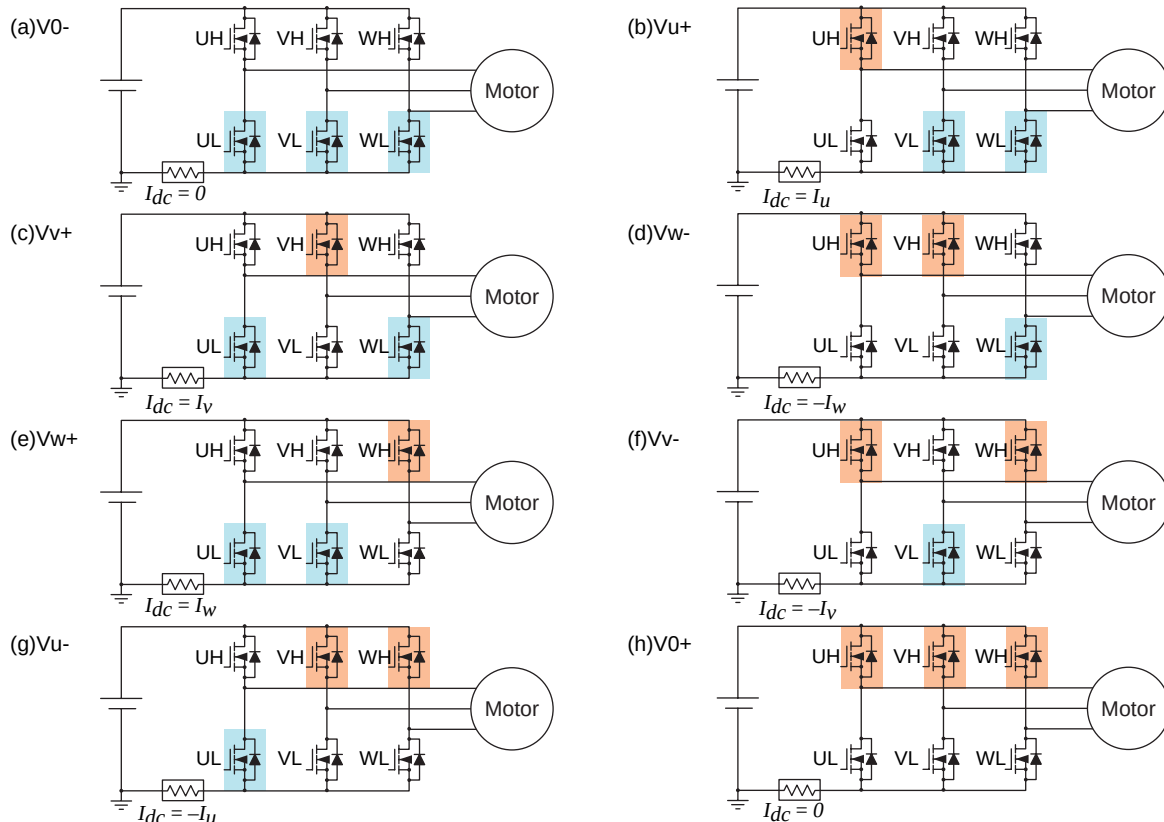


Fig. 4 Relationship between basic voltage vector and detected current

the phase currents that can be detected by the DC current sensor.

Figure 5 shows the FET switching pattern obtained by performing PWM on the command voltages using a triangular carrier wave. The command voltages are generated according to the FET switching pattern within one carrier wave cycle. When the command voltages (V_u^* , V_v^* , V_w^*) are larger than the carrier wave, the respective upper FET turn ON (orange). Conversely, when the command voltages are smaller than the carrier wave, the respective lower FET turn ON (blue). Using the voltage vectors shown in Fig. 4, the FET switching patterns per carrier wave cycle are V_0^- , V_u^+ , V_w^- , V_0^+ , V_w^- , V_u^+ and V_0^- .

Figure 6 shows the relationship between the FET switching pattern and the phase current information that can be detected by the DC current sensor. As shown in Table 2, when the voltage pattern is V_u^+ , the U phase

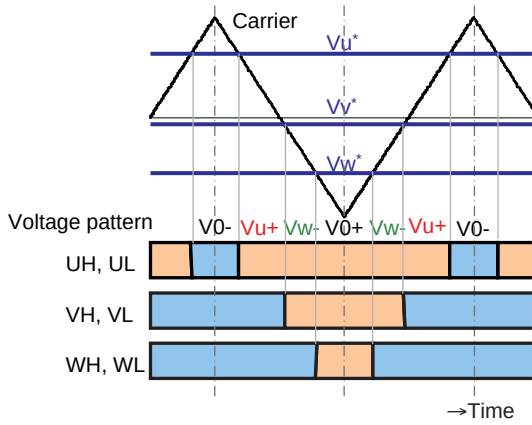


Fig. 5 Relationship between command voltage and voltage pattern

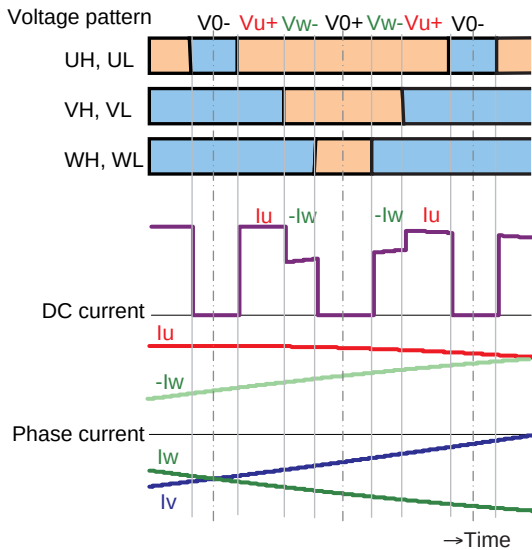


Fig. 6 Relationship between voltage pattern and phase current

current (I_u) can be detected, and when the voltage pattern is V_w^- , the value with the W phase current (I_w) polarity inverted can be detected. The phase current information for two phases can be detected during one cycle from the carrier wave peak to the next peak, and the remaining phase currents can then also be estimated using the principle that the sum of the phase currents of the three BLDC motor phases is zero.

However, the estimated phase currents are not the phase current information aligned with the command voltage update timing, and the timing of the phase current information for each phase also differs. This makes it challenging to accurately estimate the phase current.

Therefore, Fig. 7 below shows an average calculation method that uses the symmetry of the carrier wave peaks as a means of reducing the phase current estimation error. This shows that the FET switching pattern per carrier wave cycle is V_0^- , V_u^+ , V_w^- , V_0^+ , V_w^- , V_u^+ and V_0^- , and that the pattern is symmetrical relative to the carrier wave trough ($T_{c[m-1]}$). Focusing on the symmetry of the FET switching timing, the phase current values at the trough of the carrier wave (■ marks in the figure) are estimated by obtaining the U phase currents (I_{u1} , I_{u2}) and W phase currents (I_{w1} , I_{w2}) at two symmetrical timings relative to the carrier wave trough (● marks in the figure), and averaging those values (I_u , I_w). The remaining V phase current (I_v) is then calculated using the estimated U phase current (I_u), the estimated W phase current (I_w),

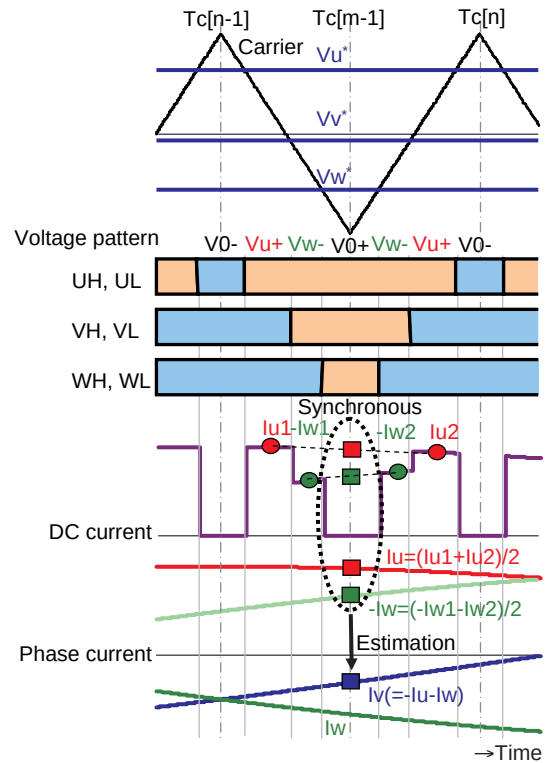


Fig. 7 Measures for reducing phase current estimation error

and the fact that the sum of the three phase currents is zero. All three estimated phase current values are the values at the same timing of the carrier wave trough. In addition, the command voltage update timing is generally synchronized with the carrier wave peak, so the estimated values at the trough timing are suitable as the phase current information used for rotor position estimation.

As shown in Fig. 8, it is challenging to estimate the phase currents when the command voltages are approximately equal ($V_u^* \approx V_v^* \approx V_w^*$). In this case, the only voltage pattern that enables phase current detection during one carrier wave cycle is V_u+ , so only the U phase currents (I_{u1} , I_{u2}) can be obtained, and only the U phase current value (I_u) can be estimated at the carrier wave trough. Phase current estimation values for a minimum of two phases are required to estimate the phase currents for all three phases, which makes it challenging to estimate

the phase currents for all three phases.

To avoid this situation, the minimum necessary voltage is superimposed onto the command voltages so that the command voltage level is different for each phase, thus enabling estimation of all three phase currents. Since rotor position estimation requires the command voltage information, the superimposed voltages should be quantitatively understood. Figure 9 shows the voltage superimposed to avoid areas where estimation is challenging. Gray areas indicate areas where the command voltages for two phases are approximately the same level, making it challenging to estimate the phase currents for three phases. In Fig. 9(a), the command voltage (V^*) is a gray area, making it challenging to estimate the phase currents for three phases. Therefore, as shown in Fig. 9(b), voltages ($V^*h[m]$, $V^*h[m+1]$) with the same level but different vectors to avoid the gray area are

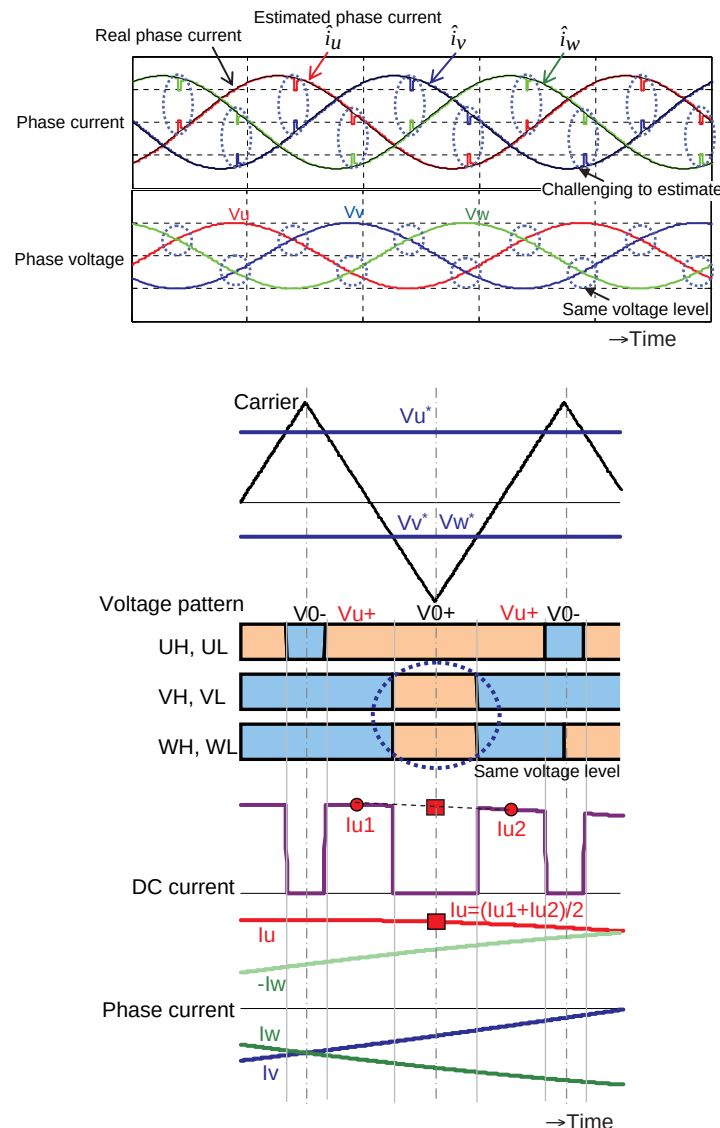


Fig. 8 Challenging cases in phase current estimation

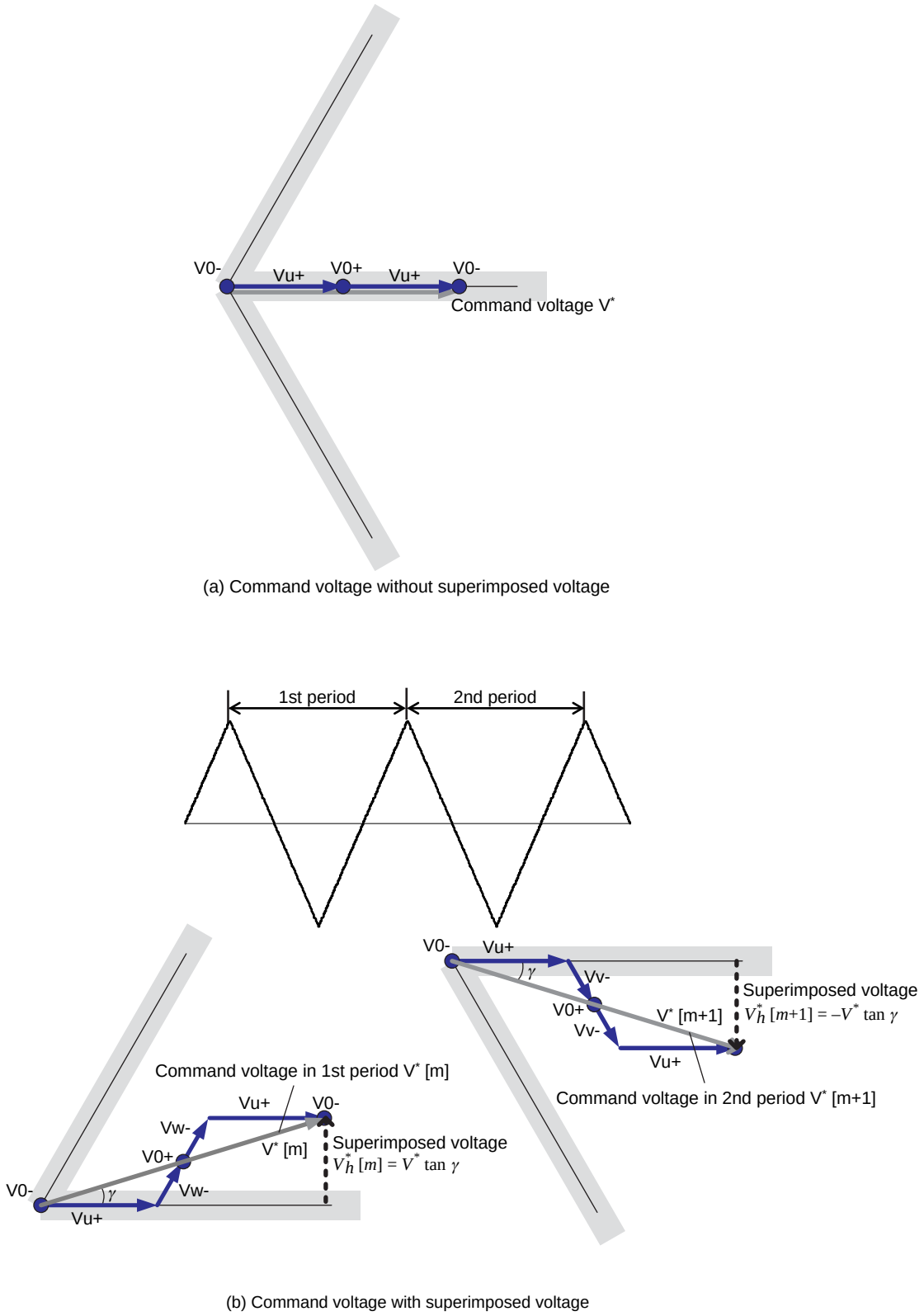


Fig. 9 Relationship between command voltage and superimposed voltage

superimposed onto the command voltage (V^*) in two consecutive carrier wave cycles (first cycle and second cycle). The command voltage with superimposed voltage ($V^*[m]$, $V^*[m+1]$) has a phase difference γ relative to the original command voltage (V^*). Equation (1) shows the superimposed command voltage. The phase currents for all three phases can be estimated by using the values of the command voltage with the superimposed voltages ($V^*[m]$, $V^*[m+1]$) for rotor position estimation.

$$V_h^* = \pm V^* \tan \gamma \quad (1)$$

3.2. Rotor Position Estimation Algorithm

For power use, startup control in which a rotational magnetic field unrelated to the rotor position is generated is used to drive the motor up to a rotational speed at which the electromotive force (EMF) information can be detected. When the rotational speed range is reached at which the EMF information can be detected, the motor is controlled in accordance with the rotor position estimated using the EMF information. Figure 10 shows the proposed rotor position estimation algorithm that uses EMF.

The model installed in parallel with the actual motor does not include EMF correlated with the rotor position, and comprises only resistance and inductance. EMF information is included in the command voltages applied to the real motor, and this information is also input to the model. Rotor position information is therefore included in the current deviation calculated from the model phase current output from the model and the real motor phase current. As a result, the estimated rotor position error is calculated from the current deviation, and the rotor position and rotational speed are estimated using phase-locked loop control (PLL) to minimize the estimated rotor position error.

The automatic current regulator (ACR) uses the estimated phase current and rotor position to calculate the command voltage and perform motor control in accordance with the command torque.

3.3. Coordination between Rotor Position Estimation and Phase Current Estimation

Figure 11 shows the coordination between rotor position estimation and phase current estimation. As previously mentioned, the command voltage and phase current values are required for rotor position estimation. In addition, the command voltages ($V^*[n-1]$, $V^*[n]$) are generated by the combination of voltage vectors during the cycle from one carrier wave peak to the next, so the phase current used for rotor position estimation should also be obtained in accordance with the carrier wave. The phase current estimation method used in this study enables estimation of the motor phase currents ($I_u[m-1]$, $I_u[m]$, $I_w[m-1]$, $I_w[m]$) at the carrier wave trough. The command voltages ($V^*[m]$) between adjacent carrier wave troughs, which are the phase current estimation timing, are the average values of $V^*[n-1]$ and $V^*[n]$. Rotor position estimation is performed using the values of the phase currents ($I_u[m-1]$, $I_w[m-1]$) estimated at the carrier wave trough, the phase currents ($I_u[m]$, $I_w[m]$) estimated at the next trough, and the command voltages ($V^*[m]$) during this period.

The phase current and rotor position can be accurately estimated simultaneously by performing phase current estimation at the timing of the carrier wave trough, which is suitable for rotor position estimation, and at the same time correcting the command voltages used for rotor position estimation in accordance with the phase current estimation timing.

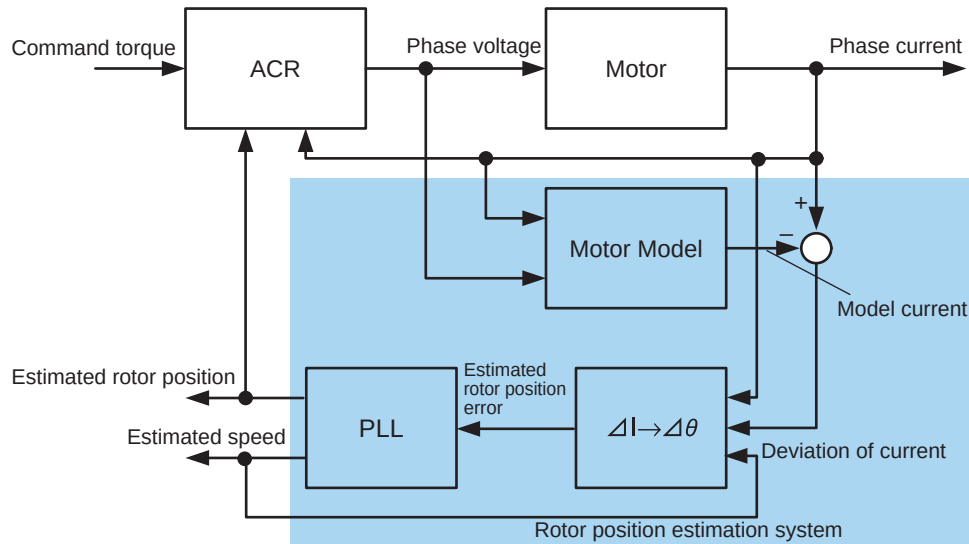


Fig. 10 Block diagram of rotor position estimation system

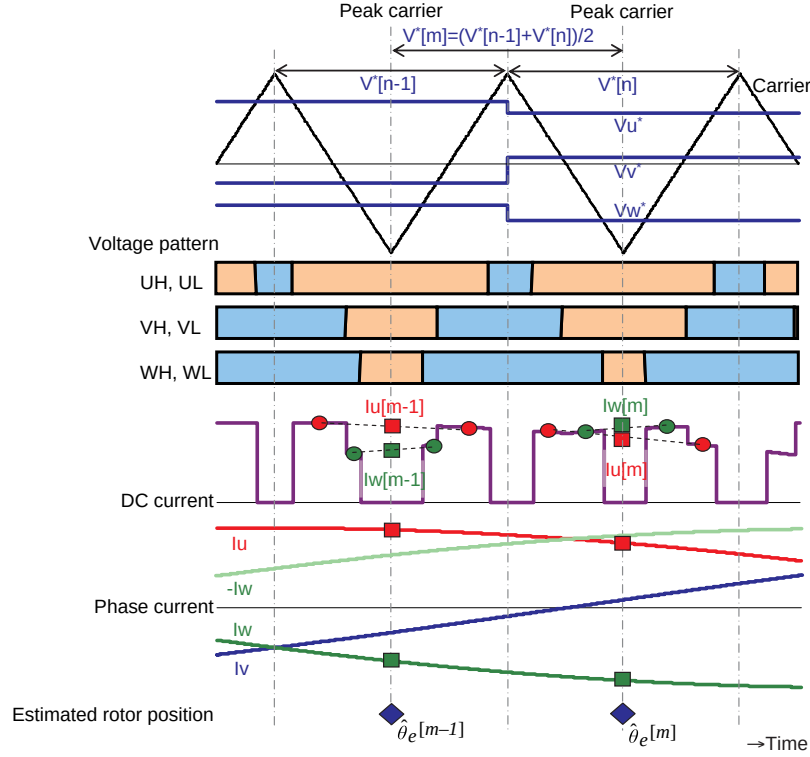


Fig. 11 Coordination between rotor position estimation and phase current estimation

4. Simulation Analysis

4.1. Analysis Methods

The feasibility of the proposed rotor position estimation and phase current estimation was verified by simulation analysis. MATLAB was applied as the analysis simulator. In the simulation analysis, the motor was a 100 W interior permanent magnet synchronous motor (IPMSM), the maximum motor phase current was 10 Arms, the supply voltage was 12 V, and the generally used vector control was used as the control method. In addition, the switching elements were assumed to be in the ideal state (switching time = 0 s).

4.2. Rotor Position Estimation Characteristics and Phase Current Estimation Characteristics

Figures 12 and 13 show the estimated rotor position error and estimated phase current error in each rotational speed range. These errors indicate the maximum value when the motor phase current is analyzed from 0 to the maximum motor current. It was found that estimation for both the phase current and the rotor position can be performed within the range that does not hinder practical application. In addition, the estimation error increases at a rotational speed of around 500 rpm. For power use, startup control in which a rotational magnetic field unrelated to the rotor position is generated is used to drive the motor up to a rotational speed at which the electromotive force (EMF) information can be detected.

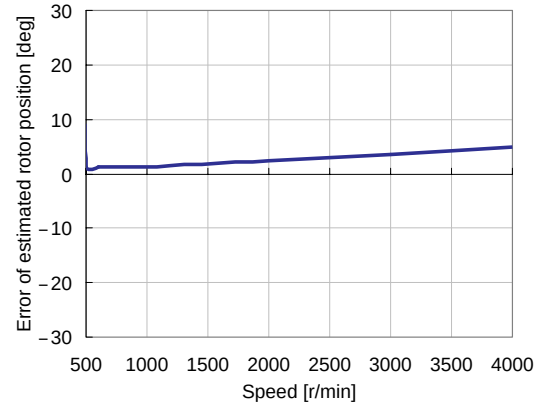


Fig. 12 Simulation results of estimated rotor position

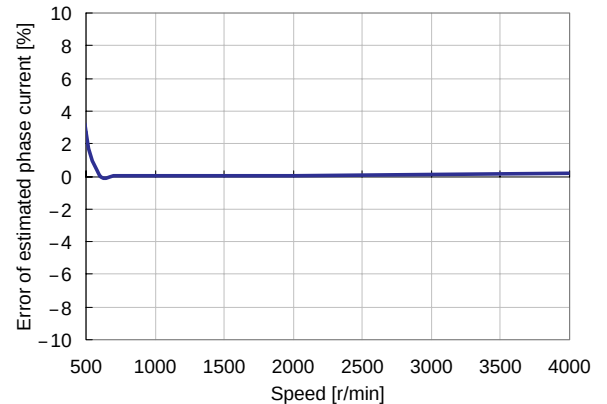


Fig. 13 Simulation results of estimated phase current

Therefore, by setting the startup control range exceeding 500 rpm, this does not hinder practical application for power use.

5. Evaluation Using a Real Motor

The feasibility of the proposed rotor position estimation and phase current estimation was verified by evaluation using a real motor. Like the simulation analysis, the motor was a 100 W IPMSM, the supply voltage was 12 V, and vector control was used as the control method.

Figure 14 shows the estimated and real rotor position at a rotational speed of 1000 rpm. The real rotor position was measured using a generally used resolver sensor. The results show that the rotor position was accurately estimated.

Figure 15 shows the estimated and real phase current at a rotational speed of 1000 rpm. The real phase current was measured using a Hall effect current sensor. The sine wave is slightly deformed due to the effects of the

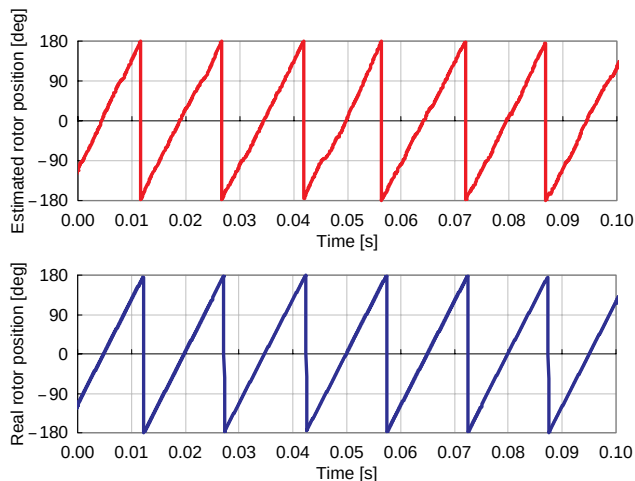


Fig. 14 Results of estimated rotor position

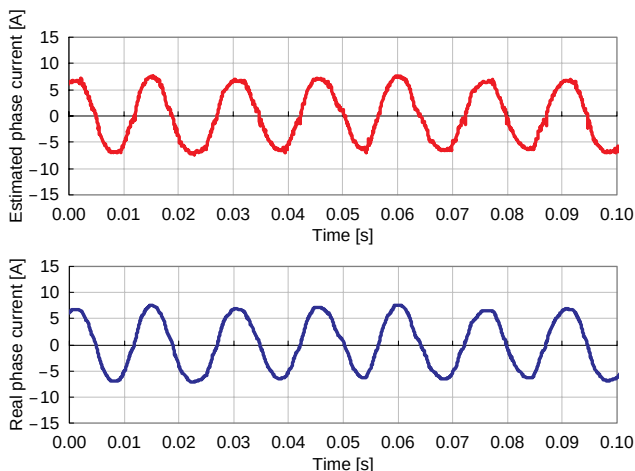


Fig. 15 Results of estimated phase current

superimposed voltage used to avoid areas in which phase current estimation is challenging, but these results show that the phase current was also estimated at a level that does not hinder practical application.

6. Conclusion

This study constructed a sensorless control algorithm with the aim of reducing cost by enabling sensorless control of BLDC motors. This algorithm simultaneously estimates the rotor position and phase current without using the rotor position and phase current sensors generally considered necessary for BLDC motors.

Phase current estimation focused on the symmetry of the FET switching pattern, and a method was presented for estimating the phase current at the timing suitable for rotor position estimation, by detecting the DC current.

For rotor position estimation, a motor model was constructed that does not depend on the rotor position and rotational speed, and a method was presented for estimating the rotor position by comparing the model phase current and the phase current value of a real motor estimated using phase current estimation.

Regarding coordination between rotor position estimation and phase current estimation, a method was presented for estimating the phase current and rotor position simultaneously by estimating the phase current at the timing of the carrier wave trough, and at the same time correcting the command voltage used for rotor position estimation in accordance with the phase current estimation timing.

The feasibility of the proposed algorithm was verified by simulation and evaluation using a real motor, and the results confirmed that the algorithm accurately estimates both the phase current and rotor position.

The proposed algorithm can be applied to generally used vector control, and is effective for on-car power-use BLDC motors. This proposed a sensorless control method for power-use BLDC motors, and established prospects for reducing the cost of brushless DC motors.

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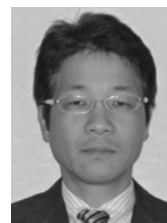
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