Research on Hall Sensor Fault Diagnosis and Compensation Method to Improve Motor Control Reliability

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In this paper, we study the fault detection algorithm and the fault compensation method in case of hall sensor fault of BLDC motor. In the case of a BLDC motor operating at high speed, the fault of the hall sensor is a very important factor that reduces the reliability of the control. If hall sensor fault occurs, ripple occurs in torque and current output value of BLDC motor. In addition, a phenomenon such as rapid braking of the motor may occur. Therefore, this paper assumes the fault of one or two hall sensors, and studies hall sensor fault detection algorithm and hall sensor fault compensation method. The peak-to-peak interval of the hall sensor signal is stored and the peak-to-peak interval is checked in real time to detect the fault immediately after the hall sensor fault. Unlike existing algorithms, it has higher reliability than existing fault detection algorithms, because it detects faults in real time. When a fault is detected, a signal of a normally operating hall sensor is input to the hall sensor fault compensation circuit. The output of the compensation circuit is a signal whose phase is delayed. The phase difference of each hall sensor signals is 120°. Therefore, the gain of the compensation circuit is appropriately selected to generate a signal for compensating for the fault of the hall sensor. Model and simulate motors, control circuits, and faulty hall sensors using MATLAB Simulink.

Keywords : blushless motor, fault compensation algorithm, fault diagnosis algorithm, hall sensor fault

1. Introduction

BLDC Motor replaces commutator and brush structure of DC motor with semiconductor switch. Therefore, the structure is simple, and it is widely used in industrial fields, because of high torque, high output density, and high efficiency [1, 2]. The phase of the current is applied depends on the position of the BLDC motor rotor. Therefore, it is necessary to know the position of the rotor precisely for the accurate phase commutation of the BLDC motor [3]. BLDC motors typically use three hall sensors to sense the rotor position. The hall sensor detects position of the permanent magnet in the rotor and generates an output signal. The three hall sensor signals are combined to divide the BLDC motor into six sections

to apply current. This is called a six-step drive. In a permanent magnet synchronous motor drive system operating at high speed, a fault of a position sensor such as a hall sensor is an important factor that decrease the reliability of the control system. However, hall sensor has frequent faults according to the use environment and has a disadvantage that an error signal can be generated due to the influence of an external magnetic field. If the magnetic field sensing capability is decrease in a high temperature operating environment or an error signal is generated due to sudden leakage magnetic flux due to the magnetic saturation of the iron core, the motor cannot change the phase at the correct position [4]. If the hall sensor fails to generate signal, the phase commutation does not occur in the correct section, and the output characteristics of the motor cannot be maintained at a constant value. Also, when the protection control is applied, if the value of all hall sensors is 0 or 1 due to the fault of the hall sensor, sudden braking occurs and a fatal problem occurs. Therefore, algorithms for diagnosis and compensating for fault of hall sensors are under study. In

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the original hall sensor fault detection and compensation method, if all hall sensor signals output the same value, it is determined that the fault is occurred, and then the sensorless operation or the motor is stopped [5, 6]. However, the original fault detection method detects a fault after a hall sensor fault occurs and after a certain time. Therefore, in this paper, we use a technique to diagnosis the fault of hall sensor in real time by sampling peak-to-peak interval of hall sensor signal and detecting peak-to-peak interval in real time to detect fault in real time. When a hall sensor fault is detected, a normally operating hall sensor signal is input to the logic circuit and the phase delay circuit to compensate for the signal of the faulty hall sensor. Therefore, it has higher reliability than the original hall sensor fault compensation algorithm. Contents of this paper has been published as a master's thesis of the author. Contents of this paper has been presented at the ICICT2017 and IcAUMS2018 conference and published as a master's thesis of the author [7].

2. Influence of Hall Sensor Fault

2.1. Six-step drive of BLDC motor

The hall sensor is a device capable of measuring the intensity of a magnetic field using a hall effect generated in a semiconductor. As shown in Fig. 1, when a current flows through the hall element and a magnetic flux B is applied to the element surface in a direction perpendicular to the current, a voltage is generated in a direction perpendicular to the current and the magnetic flux. R_H is the hall constant.

$$V_H = \frac{R_H}{d} I_H B \qquad (1)$$

The position and polarity of the permanent magnet can be detected by measuring the voltage of the hall element. Therefore, it can be used to detect the rotor position of the
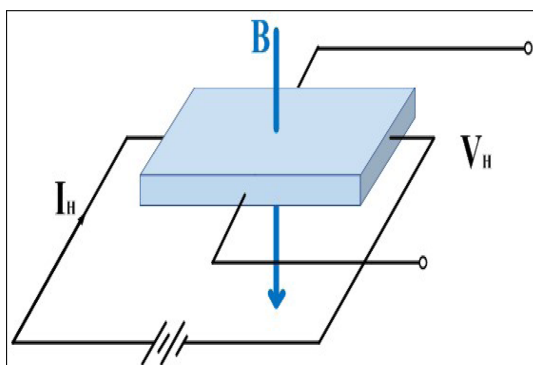

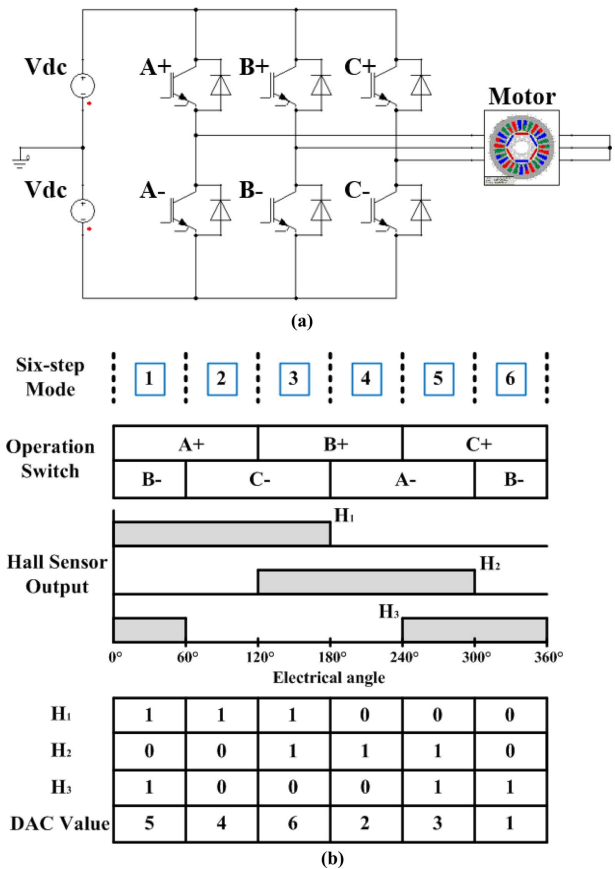**Fig. 1.** (Color online) Hall sensor fault diagnosis algorithm (a) Original algorithm, (b) Proposed algorithm.

Fig. 2. (Color online) Six-step drive (a) Control circuit, (b) Commutation sequence.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
H_1	1	1	1	0	0	0
H_2	0	0	1	1	1	0
H_3	1	0	0	0	1	1
DAC Value	5	4	6	2	3	1

BLDC motor. Normally, three hall sensors are arranged at intervals of electrical angle of 120 degrees. The electric angle of the BLDC motor is divided into six sections by combining the output values of the three hall sensors. Fig. 2(a) is a driving circuit diagram of a BLDC motor. Fig. 2(b) is a phase commutation sequence in six sections of the BLDC motor. DAC Value is obtained by combining 3 hall sensor signals by binary method. According to the DAC Value, determine the six-step mode that is currently required for the continuous rotation of the rotor in the six sections and determine the two phases to be excited. When driving a BLDC motor, only two of the three-phase windings are excited at all times, and the other phase is not excited. This driving method is referred to as a two-phase excitation method. At this time, each switching element is commutated by 120°, which is called a 120° driving method. In addition, the commutation sequence in six sections of the BLDC motor and the 120° drive method are referred to as a six-step drive.

2.2. Influence of hall sensor fault
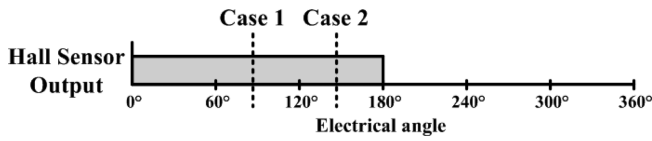
When hall sensor fault occurs, hall sensor keeps the
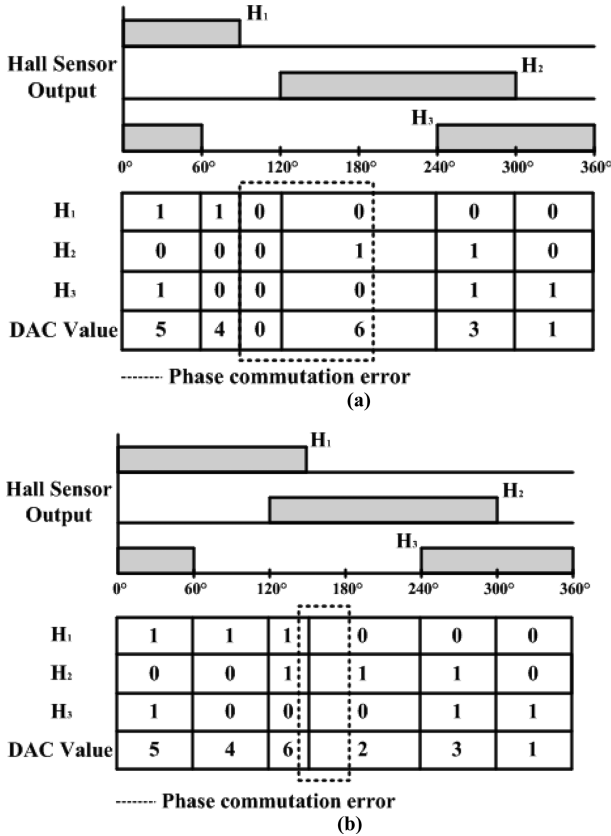
Fig. 3. Hall sensor fault signal.

Fig. 4. Hall sensor output in case of hall sensor fault (a) Case 1, (b) Case 2.

existing output or outputs low signal. There are two situations when the output value of 3 hall sensors is 0 due to hall sensor fault. Fig. 3 is the situation of two cases when the output value of 3 hall sensors is 0 when hall sensor is fault. H1 hall sensor signals output the same values as H3 at 0~60° and H2 at 120°~180°. Case 1 is when hall sensor fault occurs between 60° and 120°. Case 2 is when the hall sensor fault occurs between 120 and 180°. Fig. 4(a) is hall sensor output signal of case 1. In phase commutation error section of Case 1, DAC value of hall sensor output value is 0. The DAC value is 0 when the motor is stopped or the hall sensor is faulty. Therefore, the BLDC control algorithm has a protection control that stops the motor when the DAC value becomes 0 while the motor is running. For BLDC motors operating at high speed, sudden motor braking is very dangerous. Fig. 4(b) is hall sensor output signal of Case 2. Unlike Case 1,

DAC Value does not output 0 or 1, but does not cause an exact phase commutation. The efficiency of the output and torque of the motor is reduced by the ratio of the phase commutation error. In addition, reverse torque of the motor may occur.

3. Hall Sensor Fault Diagnosis and Compensation Algorithm

3.1. Hall sensor fault diagnosis algorithm

The original hall sensor fault detection algorithm detects the fault of the hall sensor when the output values of all three hall sensors become 0 or 1. Therefore, it is difficult to detect the fault instantly when hall sensor fault occurs.
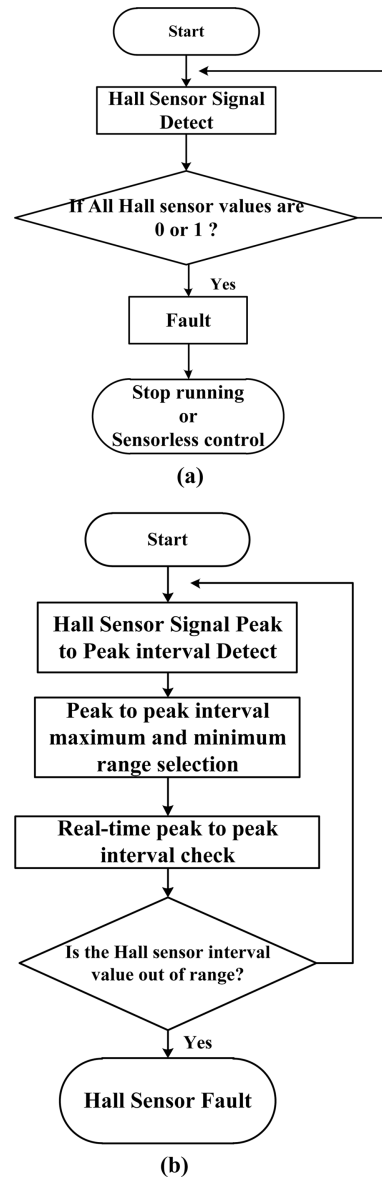

Fig. 5. Hall sensor fault diagnosis algorithm (a) Original algorithm, (b) Proposed algorithm.

In addition, since the error is detected by the combination value of the three hall sensors, it is impossible to judge which hall sensor of the three hall sensors has faulted. Therefore, it is only possible to switch to sensorless control or to stop the motor by compensating for the fault. Fig. 5 is original hall sensor fault detection algorithm and hall sensor fault detection algorithm proposed in this paper. The proposed algorithm stores the maximum and minimum values of the peak-to-peak interval of a normal hall sensor, and then detects the fault by comparing the peak-to-peak interval of the hall sensor in real time with the stored value. The proposed algorithm stores the maximum and minimum values of the peak-to-peak interval of a normal hall sensor, and then detects the fault by comparing the peak-to-peak interval of the hall sensor in real time with the stored value. Therefore, after the fault detection, the fault compensation method is diversified and the reliability is improved because it detects the fault faster than the original algorithm. The algorithm can also be applied without additional sensors or external circuit.

3.2. Hall sensor fault compensation algorithm

Figure 6(a) is a circuit that compensates the faulty H1 hall sensor by using two hall sensors H2 and H3 which operate normally when one H1 hall sensor fault. (3) is the logic gate expression of Fig. 6(a).

$$T = \overline{H_2 + H_3} = H_2H_3 + \overline{H_2}\overline{H_3} \qquad (2)$$
$$F = \overline{T + H_3} = \overline{H_2}$$

The signal output through the logic circuit is phase-shifted by 60° using the phase shift circuit to compensate the faulted H1 hall sensor. The circuit used for phase shifting is an all-pass filter. (3) is the gain and delayed phase of the all-pass filter.

A_v is the circuit gain, f_0 is the peaking frequency, $\varnothing$ is the delayed phase angle, R is the circuit resistance, C is the circuit capacitor, and f is the circuit frequency. As shown in the formula, the amplitude of the output does not change, but the phase angle is adjusted by changing the RC value.

$$A_v = 1$$
$$f_0 = \frac{1}{2\pi RC} \qquad (3)$$
$$\varnothing = -2\arctan\frac{f}{f_0}$$

Figure 6(a) is a circuit that compensates two faulted hall sensors by using one hall sensor that operates normally when two hall sensors faulted. (4) is a mathematical expression of the Fig. 6(b) circuit.

$$\overline{H_1}(\theta + 60°) = H_3$$
$$\overline{H_2}(\theta + 60°) = H_1 \qquad (4)$$
$$\overline{H_3}(\theta + 60°) = H_2$$

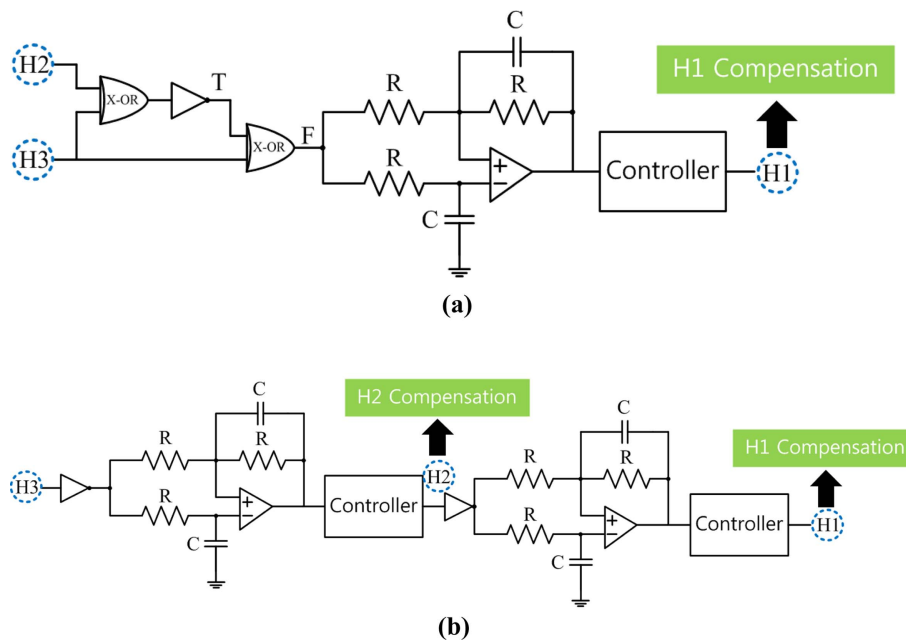## 4. Simulation

4.1. Simulation environment

Fig. 6. (Color online) Faulted hall sensor compensation block diagram (a) Fault of one hall sensor, (b) Fault of two hall sensor.
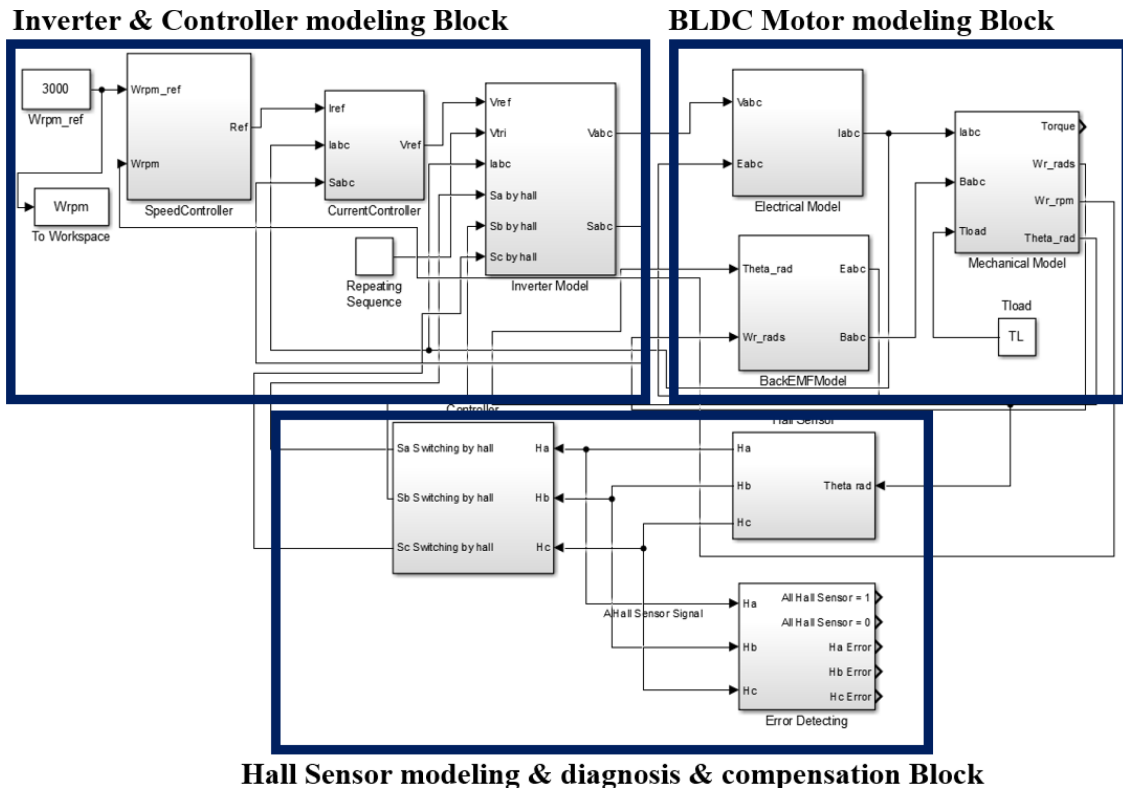
Fig. 7. (Color online) Simulation block diagram with simulink.

Simulation is performed by modeling BLDC motor, control circuit, hall sensor, hall sensor fault detection and compensation algorithm using Simulink. Fig. 7 is a schematic diagram of the simulation.

4.2. Hall sensor fault diagnosis simulation

Figure 8 shows the simulation results of the fault detection algorithm proposed in this paper and the original fault detection algorithm. The hall sensor has faulted at 0.5 [s]. Fig. 8(b) shows that the proposed algorithm
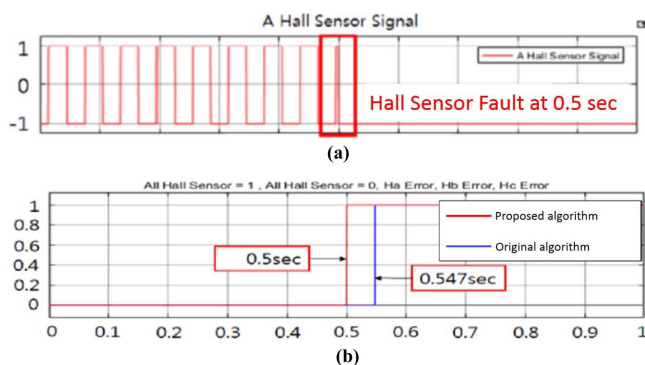

Fig. 8. (Color online) Fault diagnosis algorithm simulation (a) Faulted hall sensor signal, (b) Fault diagnosis time comparison.

detects faults faster than the original algorithm by 0.047 [s]. In the case of a BLDC motor operating at high speed, the time of 0.047 [s] can be extremely fatal because the signal of the hall sensor changes in units of several microseconds.

4.3. Hall sensor fault diagnosis and compensation simulation

Figure 9 shows the results of fault diagnosis and compensation simulation. If an H1 hall sensor fault occurs at 0.8 [s], an error detection signal is generated. Then, the faulty hall sensor is compensated through the logic combination of H2 and H3 hall sensors and the phase shift circuit. If the H2 hall sensor faulted at 1.2 [s], a fault detection signal is generated and the H3 hall sensor that is normally driven compensates for the faulty hall sensors A and B. Simulation results show that the 3-phase current of the BLDC motor has some error but returns quickly to the normal state.

5. Conclusion

In this paper, we have studied fault diagnosis and fault compensation method in hall sensor fault of BLDC motor. Modeling of BLDC motor and control circuit through
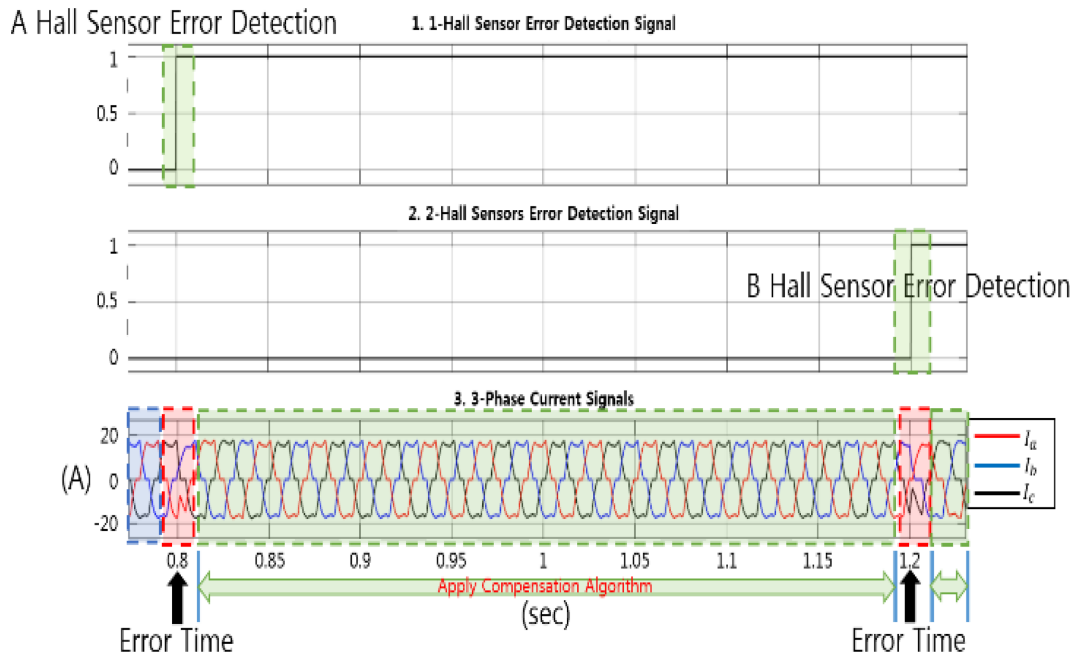
Fig. 9. (Color online) Hall sensor fault diagnosis and compensation simulation.

MATLAB Simulink, fault detection and compensation simulation of hall sensor were carried out. In addition, we prove the superiority of the proposed algorithm in comparison with the original hall sensor fault diagnosis algorithm. In the proposed method, the peak to peak interval of the hall sensor output value is stored when the three hall sensors operate normally, and the output value of the hall sensor signal is compared with the stored value in real time. It is possible to detect a fault immediately when a fault occurs by comparing the stored value with the hall sensor output value in real time. In addition, since it is possible to distinguish a faulty hall sensor, it is possible to perform control switching that cannot be implemented in the original fault detection method. Therefore, in this paper, we propose a method of driving the motor using only hall sensor that operates normally when hall sensor fault occurs. The method using only the normal hall sensor is more reliable than the conventional sensorless control, and it is considered to be easier to cope with afterwards.

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