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A Fault Diagnosis Method in BLDC Motor Drive Systems Using Moving Average Filter for Back Electromotive Force Signal Processing

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Abstract-- **BLDC has the advantage of obtaining good performance at a low unit price without a brush. A typical BLDC generates a field flux using a permanent magnet. However, the magnet has a disadvantage that the properties of the magnet may deteriorate when exposed to excessive stress. The deterioration of the magnet may cause an accident due to a decrease in the characteristics of the BLDC or an overcurrent and a control failure. Therefore, it is necessary to implement a failure diagnosis technique of the BLDC. In this paper, we present a fault diagnosis technique using the non-exciting phase voltage of BLDC. The control algorithm of BLDC is based on the 120-degree current flow method, so a non-excited section occurs even when driving at a phase voltage. It is possible to monitor the state of the magnet by measuring the back-electromotive force due to the bridging magnetic flux of the motor generated in the non-excitation section. In this paper, a fault diagnosis technique using a non-excited phase voltage is verified through simulation and experiment, and a signal processing technique and a diagnosis algorithm are presented to implement it.**

Index Terms--**The authors shall provide up to 4 keywords or phrases (in alphabetical order and separated by commas) to help identify the major topics of the paper.**

I. Introduction

An electric motor is a device that converts electrical energy into mechanical energy. In particular, DC motors can be easily controlled and are used in various fields. However, DC motors have disadvantages for the operating range and their lifespan is short due to wear of brushes. Therefore, a brushless DC (BLDC) motor was proposed that replaces the mechanical commutation structure of the existing DC motor and controls the excitation with semiconductor devices by sensing the polarity of the rotor with Hall sensors. BLDC motors are generally 120-degree electrically excited permanent magnet motors. BLDC is mechanically similar to permanent magnet synchronous motor (PMSM). However, unlike BLDC, PMSM is excited by sinusoidal currents. Although BLDC is disadvantageous compared to PMSM in terms of noise, vibration, and efficiency, it can be controlled with a simple system and has the advantage of not requiring expensive position sensors such as resolver or encoder. With these advantages, BLDCs are widely used in fields such as home appliances, industrial robots, unmanned aerial vehicle, and personal mobility.

A general BLDC has a rotor structure including permanent magnets [1]. However, permanent magnets can suffer irreversible demagnetization fault (IDF) due to excessive stress caused by high heat, overcurrent, or other environmental factors [2, 3]. In particular, although neodymium-based magnets have high performance [4], they have a weakness that can be demagnetized at high temperature condition. The generation of IDF in a magnet causes deterioration of the characteristics of the magnet, thereby degrading the output characteristics and efficiency of the BLDC motor. Moreover, the rapid occurrence of IDF can cause motor control failures or overcurrents, resulting in severe accidents such as device burnout and mechanical destruction. Although robustness to faults is considered in the design phase of most motors [5, 6], faults due to extreme environments and long-term use are difficult to avoid.

In order to ensure the safety of users and property from motor failures, reliability must be ensured. In particular, fault detection techniques can prevent the deterioration of the device's condition and prevent serious accidents. In addition, fault diagnosis is essential for fault-tolerant control, which enables limited operation even in fault conditions [7]. Therefore, it is necessary to detect changes in the characteristics caused by failures of BLDC motors in order to identify faults.

Various fault diagnosis techniques have been proposed for fault diagnosis of the motor [8]. The most widely used technique in the field of fault diagnosis is motor current signal analysis (MCSA) [9]. This technique mainly analyzes harmonics contained in current waveforms through fast-Fourier Transform (FFT) operations [9], [10]. The occurrence of a failure may be detected by using that a specific harmonic component that does not occur in a normal motor is generated when the failure occurs. However, this technique may be difficult to diagnose failures in which three-phase imbalance or current waveform distortion is not large [11]. In addition, since it requires a lot of computation, high-performance hardware is required, which may be disadvantageous in terms of unit price. Since BLDC is mainly applied to low-cost applications, it is difficult to employ expensive fault diagnosis systems. Moreover, most of the techniques depend on current signals are difficult to apply while the speed of the motor is changing. This is because when the speed of the motor changes, distortion of the current waveform occurs due to the transition state.

In this paper, a new method for diagnosing IDF through the non-exciting phase voltage of BLDC is presented. A typical BLDC motor adopts a 120-degree energization scheme. This implies that the motor is in a non-excited state for a predetermined period at a phase voltage during driving. In the non-excitation state, the back-electromotive force (EMF) signal of the motor may be detected at the phase voltage [12]. The state of the magnet may be estimated through the detection of the back-EMF, and a fault may be detected by comparing the back-EMF with the speed of the motor. Previously, a fault diagnosis technique has been proposed by detecting the non-exciting section of the BLDC phase voltage [13]. In this study, improved signal processing and fault determination algorithms allow fault determination without complex computation. In the next chapter, the effect of irreversible demagnetization on the back-EMF of the motor is analyzed. section 3 explains algorithms and signal processing techniques for the diagnosis of irreversible demagnetization. Finally, we validate the proposed technique through simulations and experiments.

II. CONTRIBUTION OF IDF ON BLDC PHASE VOLTAGE

A typical BLDC motor has a rotor structure including permanent magnets. By the rotating magnetic field, the stator winding generates back-EMF. Therefore, the back-EMF of the BLDC motor can be expressed as follows:

$$e = \frac{d\lambda_{PM}}{dt} = \frac{dn\varphi_{PM}}{dt} \quad (1)$$

$$e = K\varphi_{PM}\omega \quad (2)$$

where e is the back-EMF of the motor, λ_{PM} is the flux linkage by a permanent magnet, n is the number of turns of stator winding, φ_{PM} is the rotor magnetic field, t is the time, K is the constant by the motor design, and ω is the rotational speed of the rotor. e is influenced by ω, φ_{PM}, and K. When a motor of the same design operates at the same speed, the variable related to IDF is φ_{PM}.

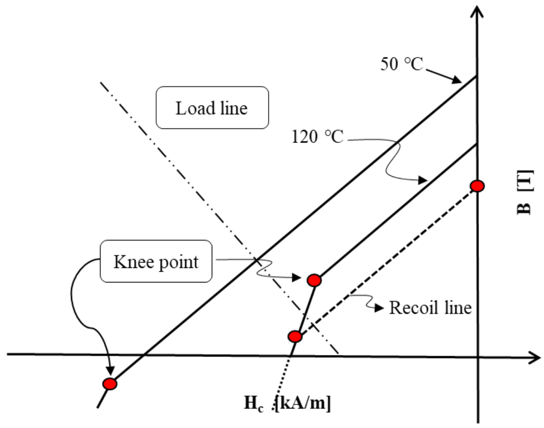
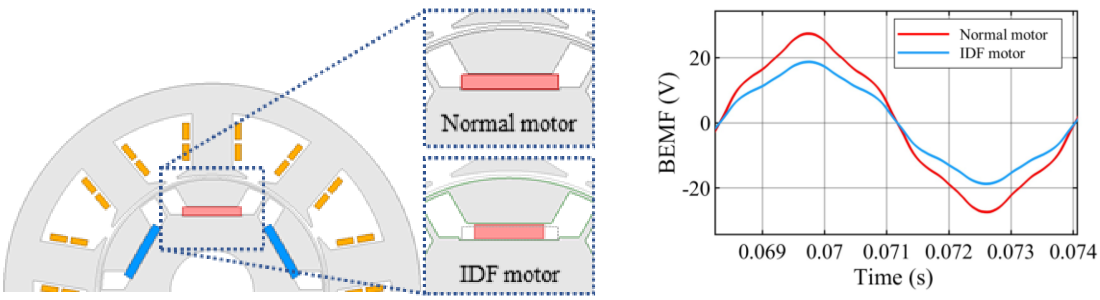


Fig. 1. Typical B-H curve regarding IDF

When IDF occurs in the motor, the φ_{PM} decreases than sthe original magnetic flux value in the permanent magnet. Fig. 1 shows the B-H curve of a typical permanent magnet. The knee point of a typical permanent magnet is located in the third quadrant of the B-H curve. However, in the case of neodymium magnets, if the temperature rises due to overheating of the motor, the B-H curve is changed, and the knee point located in the third quadrant is located in the second quadrant. When the operating point is located under the Knee point due to the movement of the load line due to the operation of the motor, the magnet forms a new B-H curve along the recoil curve, not the existing B-H curve. Thus, the residual magnetic flux density of the permanent magnet is permanently reduced, which is IDF. When the IDF occurs, the back-EMF of the motor decreases as shown in (3).

$$e' = \varphi'_{PM}\omega \quad (3)$$

e' is the reduced back-EMF by IDF, and φ'_{PM} is a reduced rotor magnetic field. To investigate the effect of IDF, the back-EMF of the normal motor and the IDF motor are simulated at the same speed. The simulation model and results are shown in Fig. 2. In order to implement the IDF motor, a magnet with reduced magnet size is inserted as shown in Fig. 2(a). As a result of the simulation, the magnitude of the back-EMF in the IDF motor decreases.



(a) (b)

Fig. 2. FEM simulation to verify the contribution of IDF. (a) Motor models for FEM, and (b) comparison of BEMF

The back-EMF of a general motor is difficult to measure while the motor is operating. However, since the BLDC motor is operated by 120-degree commutation method for driving, there is a constant non-excitation period. Therefore, fault diagnosis is possible by back-EMF measurement in the non-excited period. In the next section, a fault diagnosis technique using back-EMF measurement in a non-excited period is explained.

III. NON-EXCITED PERIOD AND SIGNAL PROCESSING ALGORITHM

In order to implement a fault diagnosis algorithm, a process of separating a non-exciting period from whole logged phase voltage waveform and signal processing is required. This section describes a technique for processing a measured phase voltage signal for fault diagnosis.

As described in section 2, the back-EMF must be determined to diagnose IDF. In this case, when the ADC is added to measure the phase voltage of the motor, the overall circuit can be represented as shown in Fig. 3. The back-EMF may be obtained from the voltage between the terminal voltage and the neutral point. When the voltage value is measured at ADC in a excited state, the inverter output voltage is measured, not the back-EMF. Therefore, in order to diagnose the state of the magnet, the phase voltage of the non-excitation state must be determined. When measuring the phase voltage, it is possible to determine the non-excited part by referring to the state of each Hall sensor as shown in Fig. 4.

A. Non-exited period extraction

In a 120-degree commutation BLDC controller, a voltage of one phase remains non-excited for a certain period during operation. In a general BLDC motor, three Hall sensors are installed, and each hall sensor is turned on/off according to each position of the rotor. The output

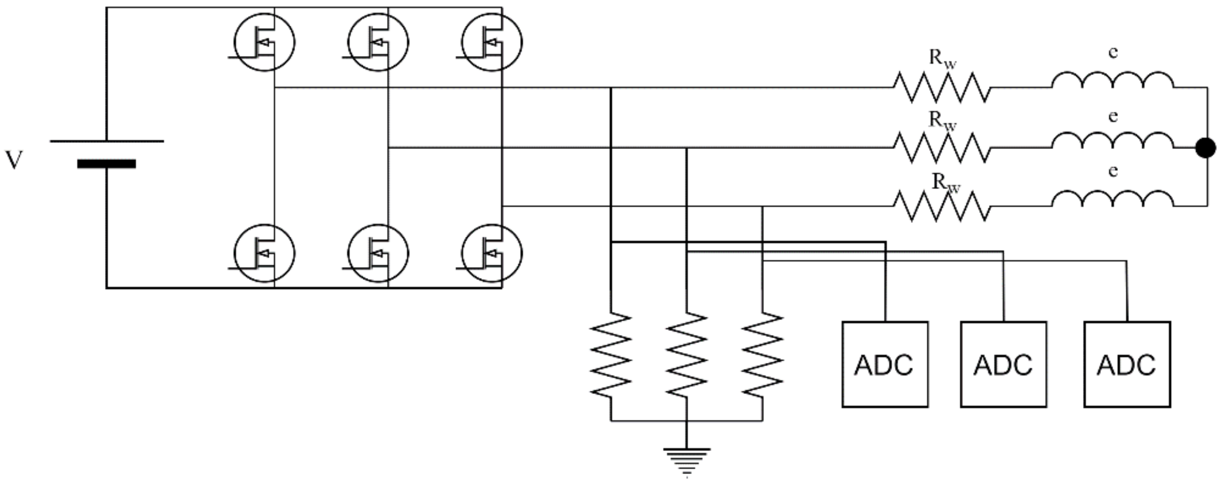


Fig. 3. Circuit of BLDC motor including ADC to detect the phase voltages.

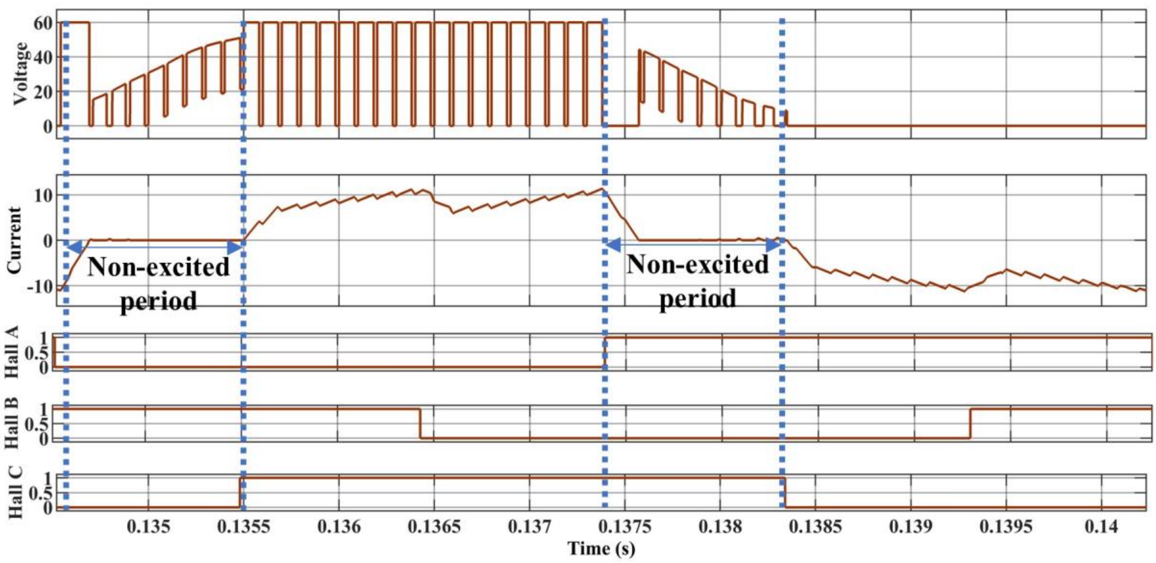


Fig. 4. Time diagram of a phase voltage, current, and Hall sensor signals.

logic state of each switching element of the inverter may be determined according to the output combination of the Hall sensor signals, and the motor can rotate. Therefore, by acquiring the combination of three Hall sensor signals and using a pre-defined one-dimensional lookup table (1-D LUT), the commutation sector can be determined through the combination of hall sensor signals. The combination of hall sensor signals for BLDC consists of six signals. In addition, there are two commutation periods per electrical angle period in one sector. The back-EMF, which is the phase voltage of the non-excited period, can be obtained by cross-product of the phase voltage data acquired through an ADC and the output of the 1-D LUT for non-excited periods extraction.

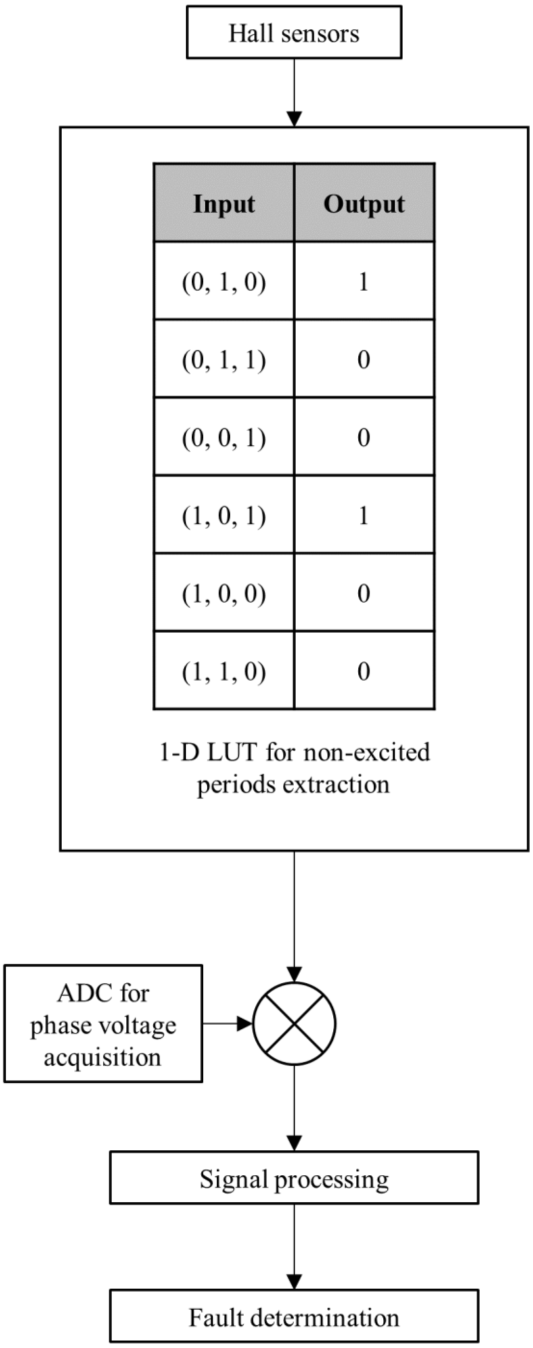


Fig. 5. Overall fault detection algorithm.

B. Filtering and Fault Determination

The driving of a general BLDC motor performs uniformity PWM switching for speed control. As shown in Fig. 4, the voltage pulse caused by the Unipolar switching on the energizing phase affects the phase voltage signal on the non-excited phase. Therefore, it is necessary to filter such noise for fault determination. In order to minimize the influence of the pulse, signal processing is performed using a low pass filter and a moving average filter. The overall algorithm, including detection of the non-excited period voltage, is shown in Fig. 5. The results of the filtering are shown in Fig. 6. Detailed filtering algorithms will be added in the future works

IV. SIMULATIONS AND EXPERIMENTS

The non-exciting phase voltage extraction and signal processing algorithm described in section 3 are verified through simulation. We implement a normal motor and an IDF motor, respectively, through finite element analysis simulation using the Ansys Maxwell program. For the finite element analysis model, the output results are compared through the phase voltage measurement and signal processing process of the BLDC motor at the time of driving using the MATLAB SIMULINK program. Fig. 7 shows the results of signal processing for the normal motor and the IDF motor. Through this result, the proposed technique is used to detect the reduction of the back-EMF due to IDF could be detected in the non-exciting period.

In this study, experiments on motors with IDFs are performed. Thus, the Hall sensor can be affected by the IDF. Therefore, a separate magnetic disk with poles equal to the number of poles of the rotor is mounted coaxially to the shaft. By sensing the polarity of this magnetic disk, regardless of the fault states of the target motor, the BLDC can be controlled.

The specification of the subject BLDC is shown in Table 1. In addition, Fig. 8 shows the test set for the experimental verification of the proposed technique. Fig. 8(a) shows a rotor into which a failure magnet is inserted to implement the IDF. In addition, Fig. 8(b) illustrates a Hall sensor board for BLDC motor control. The results of the experiment will be added in future works.

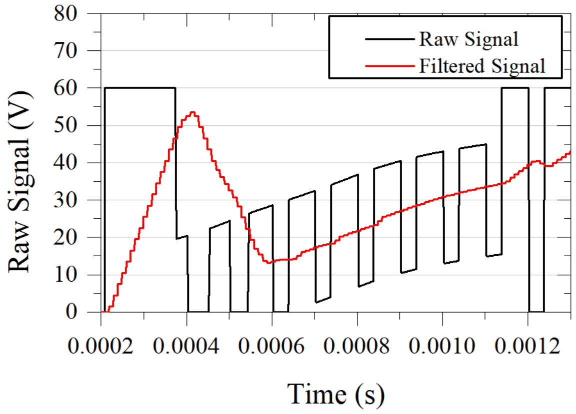


Fig. 6. Comparison of the raw and filtered signal for the non-excited phase voltage.

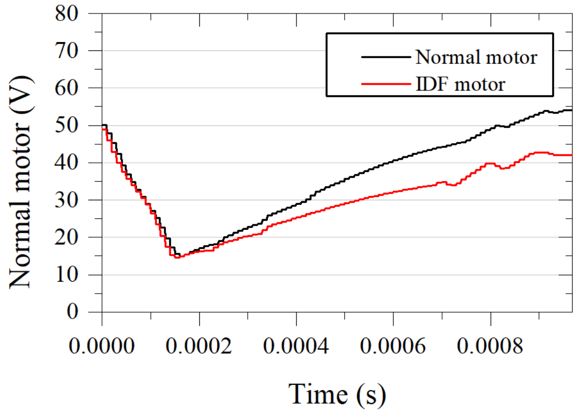
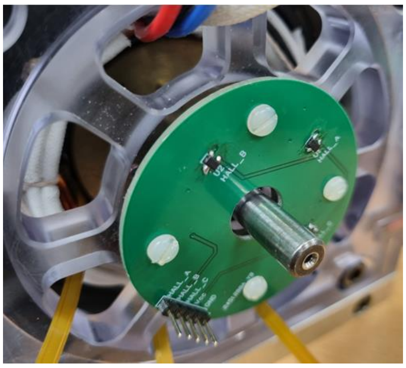


Fig. 7. Comparison of normal motor and IDF motor voltage signal in non-excited period.

TABLE I
SPECIFICATION OF THE SUBJECT MOTOR

Item	Unit	Value
Number of poles		6
Number of slots		9
Rated power	W	400
Rated current	A	10.32
DC bus voltage	V	60
Rated speed	RPM	3500
Rated torque	Nm	1.1
D-axis inductance	mH	0.92
Q-axis inductance	mH	1.35
Stator resistance	Ω	0.07

(a)



(b)

Fig. 8. Motor elements for the test setup. (a) Rotor of the target motor with IDF, and (b) Hall sensor board for BLDC control.

V. CONCLUSIONS

This paper proposes a technique for detecting IDF during operation of BLDC motor. This method detects the characteristics of the failure using non-excitation phase voltage data. This paper describes an algorithm that detects the IDF by measuring the hall sensor signals and the phase voltage signals to obtain the back EMF voltage. The proposed algorithm is validated through simulations.

This technique has the advantage of enabling fault diagnosis without complex operations such as harmonic analysis. The proposed technique can be applied to low-cost applications because expensive hardware and sensors are not required. Detailed descriptions of fault diagnosis algorithms and additional experimental results will be added to future works.

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