A Fast Diagnosis Technique of Inter-Turn Fault in BLDC motor using Impedance Algorithm

Chae-Lim Jeong and Jin Hur
Department of Electrical Engineering, University of Ulsan
102 Street Dae-hak, Nam-gu, Ulsan 680-749, Korea
jinhur@ulsan.ac.kr

***Abstract*—This paper proposes a fast diagnosis technique of inter-turn fault (ITF) using impedance algorithm. We have analyzed the varying characteristics owing to the ITF through various experiments and the finite element analysis (FEA). In addition, this technique can be applied without requiring a fast Fourier transform (FFT) and the calculation of the negative-sequence impedance. As a result, the proposed technique is simple and rapid structure. Moreover, the diagnosis technique can be real-time monitoring through the calculated impedance value by the input voltage and current.**

***Index Terms*—Real time systems, Brushless motors, Impedance, Inductance, Detection algorithms, Fault diagnosis.**

I. Introduction

The stator winding inter-turn fault (ITF) is one of the most common faults occurring in the interior permanet magnet (IPM)-type brushless DC (BLDC) motors. The ITF denotes the insulation failure between two coils in the same phase, as shown in Fig. 1. The heat generated in the short circuit is proportional to the square of the circulated current, and therefore, it causes insulation breakdown of the adjacent coil. Moreover, the propagation of the faults in a single phase could quickly lead to complete failure or shutdown of the motor. However, the ITF and complete failure of the motor do not occur at the same time. Thus, early detection of the ITF during motor operation can eliminate subsequent damage to the adjacent coils and stator core, thereby reducing repair cost and motor outage time [1].

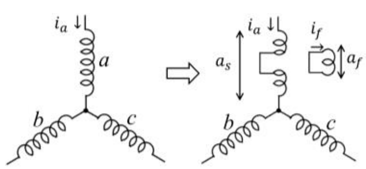

Fig. 1. ITF occurrence in single phase

We have performed an experiment and a simulation for verifying the detection technique. The IPM-type BLDC motor is used in this experiment. In the proposed technique, the winding function theory (WFT) is applied to calculate the impedance, which achieves simplicity and lower computational cost [3]. In addition, in this technique, both the calculation of the negative-sequence impedance and the application of a fast Fourier transform (FFT) to the input voltage or current are not required. Therefore, the detection of the ITF using this approach has received a wide response and is easier than the previous method.

II. Design of Fault Diagnosis Technique

In the IPM-type BLDC motor, when the phase difference between the back EMF and current occurs, the rotating speed is faster than steady state because of the field-weakening effect [2]. Thus, the rotating speed of the motor is greater than that in the steady state owing to the increase of fault fraction ratio (F_f) which can be calculated by (1). Moreover, the rotating speed of motor is correlated with frequency. Thus, when speed is faster than steady state, the period of input voltage and current is decreased according to increase of frequency. We can verify whether there is a phase difference between the steady state and the fault state through the varying speed. Therefore, we need not apply a FFT. As a result, we can simply diagnose the failure by observing the input impedance, which comprises the input voltage and current.

$$F_f = \frac{Number\ of\ shorted\ winding}{Number\ of\ total\ winding} \times 100\ . \tag{1}$$

Fig. 2 shows the block diagram of proposed fault detection technique. In order to accurate diagnosis, we have calculated database which is input impedance. Input impedance consists of resistance and reactance. Also, reactance consists of angular velocity and inductance. Inductance can be calculated using WFT. The WFT uses the winding function and turn function to the basic geometry and winding layout of machine. By these functions, it is possible to analyze performance of any faulty machine with any type of the winding distribution and the air-gap distribution around the rotor [3]-[4].

The turn function and winding function under steady state can be calculated as in (2) and (3) and are changed according to the ITF as shown in Fig. 3. Table I shows the factors of these functions.

$$t\_h = \frac{Total\ number\ of\ turns}{Number\ of\ slots\ per\ phase} = \frac{N}{3}\ . \tag{2}$$

$$T\_h = \frac{t\_h}{2} = \frac{N}{6}\ . \tag{3}$$

Through the turn function and the winding function, the self-inductance and the mutual-inductance can be calculated as,

$$L_{\mathrm{ij}} = \mu_0 \cdot r \cdot l_{st} \cdot \left[\int_0^{2\pi} g^{-1}(\theta) \mathrm{n_i}(\theta) \mathrm{N_j}(\theta) d\theta \right] \cdot \tag{4}$$

where, $\mathrm{n_i}(\theta)$ and $\mathrm{N_j}(\theta)$ are the turn function and the winding function; i, j, r and l_{st} are the phase of the turn function, the phase of the winding function, the radius of the rotor and the length of the stack, respectively; $g^{-1}(\theta)$ is the inverse air-gap

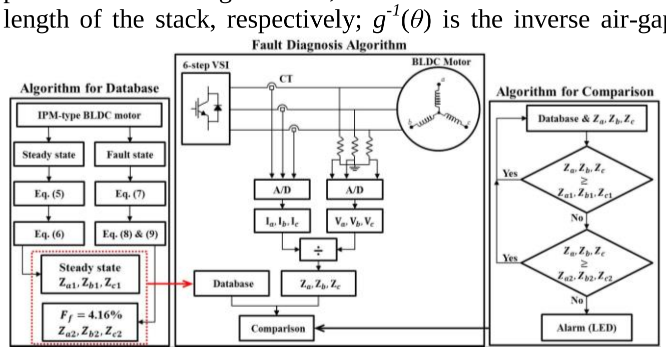

Fig. 2. Block diagram of proposed fault detection technique

function.

In the case of the IPM-type BLDC motor, it should be considered the inverse air-gap function because the air-gap is changed according to *d*-axis and *q*-axis [5].

The impedance value under the steady state and fault state can be calculated as,

$$Z_{a1} = R_a + jX_a = \sqrt{R_a^2 + (\omega_a L_a)^2}\ . \tag{5}$$

$$L_a = L_{self} + L_{mutual} = L_{aa} + L_{ab}\ ,\ \omega_a = 2\pi f_{steadystate}\ . \tag{6}$$

$$Z_{a2} = R_{as} + jX_{as} = \sqrt{R_{as}^2 + (\omega_{as} L_{as})^2}\ . \tag{7}$$

$$R_{as} = (1 - F_f / 100) R_a\ . \tag{8}$$

$$L_{as} = L_{self} + L_{mutual} = L_{aa} + L_{ab} + L_{af}\ ,\ \omega_{as} = 2\pi f_{fault\ fraction}\ . \tag{9}$$

Z_{a1} is the impedance in the steady state. When the ITF occurs in the *a*-phase, the resistance, inductance, and frequency vary. The impedance in the fault state becomes Z_{a2}. These impedance values constitute the database. Equation (10) is method of calculation about real-time impedance.

$$Z_a = \left| \frac{V_a}{I_a} \right|\ . \tag{10}$$

where, V_a and I_a are the phase voltage and current of *a*-phase.

III. Result and Analysis

Basically, when the ITF occurs, the rotating speed is reduced because of increase in the torque owing to the increase in input current. However, in the BLDC motor, the rotating speed is increased because the phase of the current becomes leading compared with the phase of the back EMF. This phenomenon is similar to the phase advance angle which is known as field-weakening effect [2]. The phase advance angle has been applied under the steady state, as shown in Fig. 4(a). However, the phase difference between the current and the back EMF is more increased under ITF condition, as shown in Fig. 4(b). Therefore, the rotating speed of the fault state is greater than the steady state. We have verified whether there are the phase difference and the increase of input current between the steady state and the fault state through the experiment and finite element analysis (FEA), as shown in Figs. 5 and 6. As a result, when the ITF occurs in the stator winding, the value of the input impedance is decreased by the variations of the input voltage and current. Fig. 7 shows the inductance value and the impedance value. This impedance value becomes the database.

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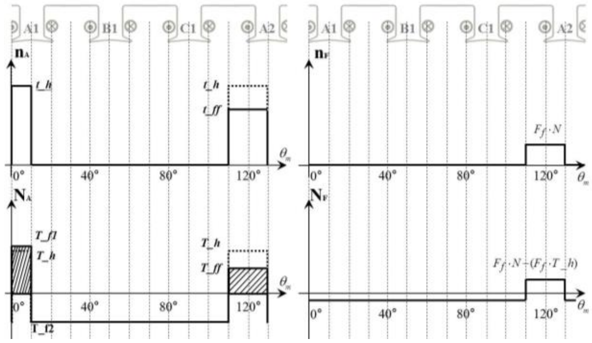
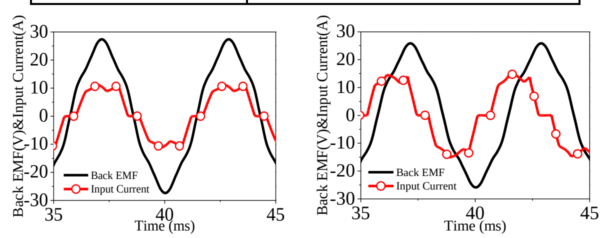


Fig. 3. Turn function and winding function of *a*-phase according to ITF

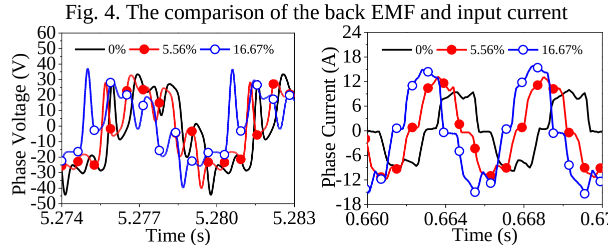
TABLE I
FACTORS OF TURN FUNCTION AND WINDING FUNCTION

Item	Definition
$t\_f = \frac{N}{3}(1-F_f)$	Turn function under ITF state
$T\_f1 = \frac{N}{3} - \frac{N}{6}(1-F_f)$	Winding function of other *a*-phase under ITF state
$T\_f2 = -\frac{N}{6}(1-F_f)$	Winding function under ITF state
$T\_ff = \frac{N}{3} - \frac{N}{6}(1-F_f) - F_f N$	Winding function of fault *a*-phase under ITF state



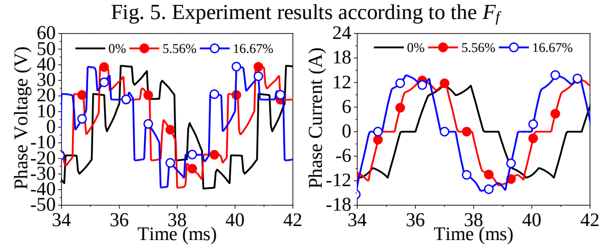
(a) The steady state (b) The fault state (F_f =5.56%)

Fig. 4. The comparison of the back EMF and input current



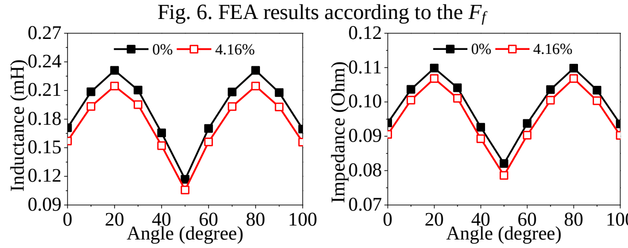
(a) The comparison of input voltage (b) The comparison of input current

Fig. 5. Experiment results according to the F_f



(a) The comparison of input voltage (b) The comparison of input current

Fig. 6. FEA results according to the F_f



(a) Inductance value (b) Impedance value

Fig. 7. Inductance and impendace according to the F_f