Finite-Element Analysis of Demagnetization of IPM-type BLDC Motor with Stator Turn Fault

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***Abstract*— This paper deals with the a dynamic demagnetization analysis of an interior permanent magnet brushless DC motor with the stator turn fault. For this transient analysis, A new analysis process based a finite element is developed. The irreversible demagnetization of an interior permanent magnet brushless DC motor is analyzed using a time-stepped voltage source inverter considering the circulating current and freewheeling current. The developed transient analysis is verified through comparison result of Ansoft Maxwell software and developed transient analysis process.**

***Index Terms*— Circuit faults, Demagnetization, Finite element method, Permanent magnet motors.**

I. Introduction

As time passes, a reliability of the motor is very important. Specially, The permanent magnet (PM) motors which frequently adopted as a power source of electric vehicles and home appliances have a great problem of reliability that the PM of the motor has the possibility of losing its magnetic property by excessively reverse magnetic field and the temperature [1]-[3]. The main factors of high external magnetic field and temperature are the excessive current from the inverter switching for starting state or rotor locked state and distorted input current due to the stator turn fault. This paper investigates the demagnetization of the interior permanent magnet (IPM) type brushless DC (BLDC) motor with stator turn fault. When the stator turn fault is generated by broken coil insulation caused by the high temperature from high current or environmental temperature and mechanical friction. The input current is distorted by electrical and magnetical imbalance and circulating current flows in shorted turns. The high-level circulating current and distorted input current heat the surrounding environment as well as the PM, which expand fault severity [4]-[5]. Particularly, irreversible demagnetization of PM motors is a big problem in safety-critical applications such as the electric vehicles, medical devices and aerospace. Therefore, analysis of irreversible demagnetization of the PM motor is necessary for the development of robust shape design.

II. Finite-Element Formulations and Transient Analysis Process

A. Turn fault model

There are many types of stator-winding-related failures. we focus on the turn-to-turn fault. A turn fault model is presented in Fig. 1. When the turn fault occurs, the number of turns in the faulty phase decreases and shorted turns is independent of the original phase. Therefore, the back electromotive force (EMF) of the faulty phase decreases and the circulating current caused by the air-gap flux density flows in the shorted turns.

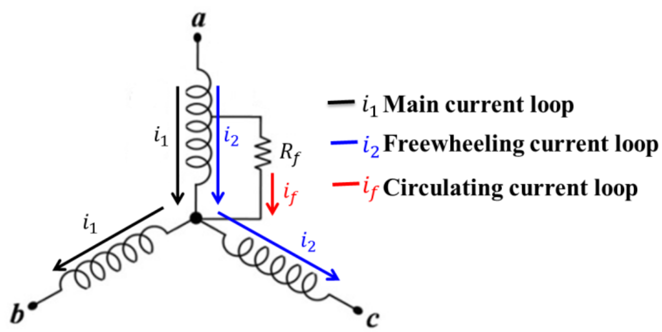


Fig. 1. Turn fault model of three-phase winding with a stator turn fault considering freewheeling mode.

B. Circuit equation

The PM BLDC motor with a stator turn fault is driven by a 120° square-wave voltage source. In the case of an ideal driver circuit, the current flows only in the two phases. However, the real circuit is not ideal. Therefore, the BLDC motor has two-phase and three-phase commutations owing to the freewheeling current. Equation (1) is the DC line voltage equation for the three-phase commutation, taking into account the circulating current flowing in the shorted turns and the freewheeling current flowing in the diode, which is expressed as follows:

$$\begin{aligned} & 2R_s i_1 + 2L_s \frac{di_1}{dt} + \frac{d\varphi_a}{dt} - \frac{d\varphi_c}{dt} = V_{dc} \\ & R_f i_f + L_f \frac{di_f}{dt} + \frac{d\varphi_f}{dt} = 0 \\ & 2R_s i_2 + 2L_s \frac{di_2}{dt} + \frac{d\varphi_a}{dt} - \frac{d\varphi_b}{dt} + V_d = 0 \end{aligned} \tag{1}$$

where R_s is the resistance of the winding in a phase, L_s is the leakage inductance of the winding in a phase, φ is the flux linkage in a phase, V_{dc} is the DC link voltage, i_1 is the main current loop, i_f is the circulating current loop, L_f is the leakage inductance of the shorted turns, R_f is the resistance of the shorted turns, i_2 is the freewheeling current loop, and V_d is the voltage drop across the freewheeling diode.

When the third equation in equation (1), which is related to the freewheeling current, is eliminated, the DC line voltage equation for the two-phase commutation can be obtained.

C. System matrix

The system matrix is constructed by combining the circuit equation and the governing equation. the system matrix of three phase commutation is presented in equation (2).

where C is the matrix related to the stator winding, F is the matrix related to the back EMF, and l_t is the axial length of the motor. When the third row in equation (2) is eliminated, the system matrix of the two-phase commutation can be obtained.

$$\begin{bmatrix} [S] & [C_1] & [C_2] & [C_f] \\ [F_1] & -\Delta t(2R_s+2L_s)/l_t & 0 & 0 \\ [F_2] & 0 & -\Delta t(2R_s+2L_s)/l_t & 0 \\ [F_f] & 0 & 0 & -\Delta t(R_f+L_f)/l_t \end{bmatrix} \begin{Bmatrix} \{A\} \\ i_1 \\ i_2 \\ i_f \end{Bmatrix}^{t+\Delta t} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ [F_1] & -\Delta t(2L_s)/l_t & 0 & 0 \\ [F_2] & 0 & -\Delta t(2L_s)/l_t & 0 \\ [F_f] & 0 & 0 & -\Delta t(L_f)/l_t \end{bmatrix} \begin{Bmatrix} \{A\} \\ i_1 \\ i_2 \\ i_f \end{Bmatrix}^{t} = \begin{Bmatrix} \{J_m\} \\ -\Delta t(V_{dc})/l_t \\ \Delta t(V_d)/l_t \\ 0 \end{Bmatrix}^{t+\Delta t} \quad (2)$$

D. Irreversible demagnetization process

The developed transient analysis process for irreversible demagnetization is shown in Fig. 2.

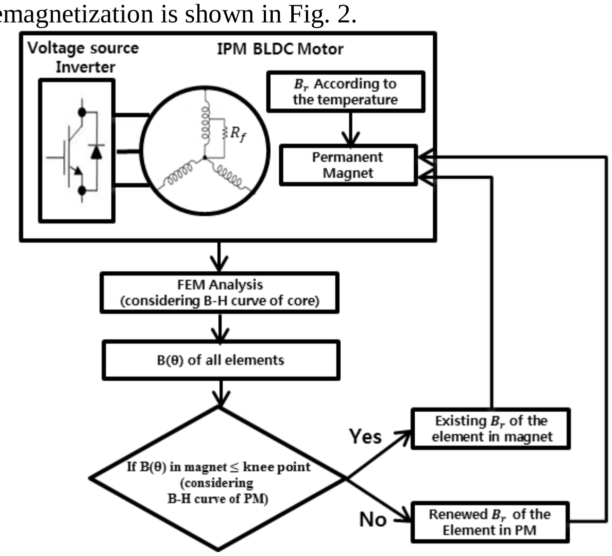
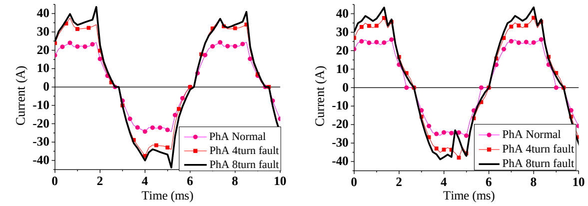


Fig. 2. Developed transient analysis process of irreversible demagnetization

III. ANALYSIS RESULT

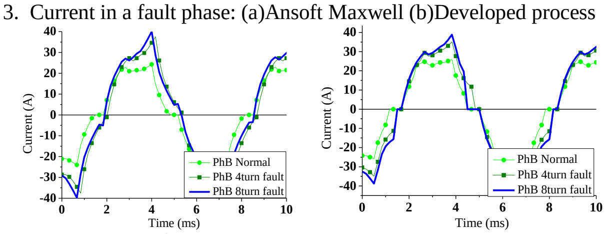
We simulate the IPM-type BLDC motor with stator turn fault according to the increase of the number of fault turns by using the Ansoft Maxwell software and developed transient analysis process. The characteristics of input current and the circulating current simulated by two soft wares are well matched as shown from Fig. 3 to Fig. 5. The currents increases and the circulating current which is reversed phase of current in a fault phase decreases depending on the number of fault turn.

We have searched a point of the demagnetization of the PM by using developed process. As a result, a point of demagnetization is that the number of fault turn is 8 and temperature of the PM is 150℃. Fig. 6 shows the flux density of all elements under 8 turn fault condition at 150℃. The magnetic property is nonsymmetrical because The increased current of three phase winding saturates the core and the high-level circulating current cancels out flux of a phase winding with shorted turns. Although the current in health phase increases, The magnitude of the current is not enough for irreversibly demagnetizing PM. However, the current in a fault phase can irreversibly demagnetize the PM of the motor. Fig. 7 shows the process of irreversible demagnetization. The motor rotates in the direction of counterclockwise. Firstly, the PM of the motor is demagnetized by magnetic field of a fault phase except for the fault phase winding of a tooth with shorted turns. After 3.4ms, next two poles are irreversibly demagnetized. When the motor is consistently driven , the all poles loses the magnetic property.



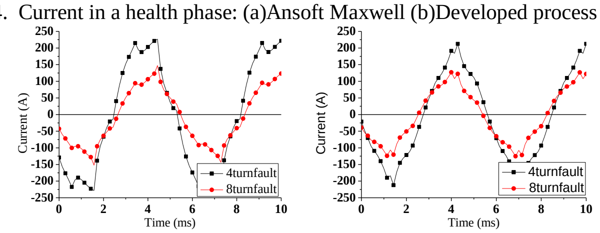
(a)Ansoft Maxwell (b)Developed process

Fig. 3. Current in a fault phase: (a)Ansoft Maxwell (b)Developed process



(a)Ansoft Maxwell (b)Developed process

Fig. 4. Current in a health phase: (a)Ansoft Maxwell (b)Developed process



(a)Ansoft Maxwell (b)Developed process

Fig. 5. Circulating current: (a)Ansoft Maxwell (b)Developed process

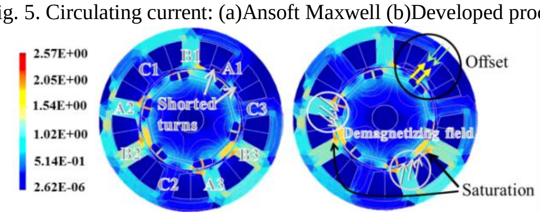
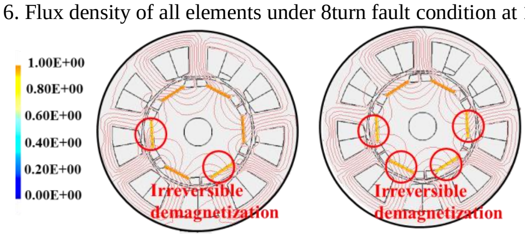


Fig. 6. Flux density of all elements under 8turn fault condition at 150℃



(a) t=7.1(ms) (b) t=10.5 (ms)

Fig. 7. Residual flux density in the PM under 8turn fault condition at 150℃

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