Detection of the Fault Type under Eccentricity and Inter-Turn Fault using Fault Frequency of Stator Input Current in IPM-type BLDC motor

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***Abstract*—This paper deals with the frequency pattern in order to detect the fault types under stator inter-turn fault (SITF) and dynamic eccentricity fault (DEF) in an interior permanent magnet (IPM)-type brushless DC (BLDC) motor by monitoring the stator current. For classifying fault types, we have analyzed the additional side-band frequencies of the stator current. Each type of the fault generates the different additional frequencies.**

***Index Terms*—Fault detection, frequency pattern, stator inter-turn fault, dynamic eccentricity, IPM-type BLDC motor.**

I. Introduction

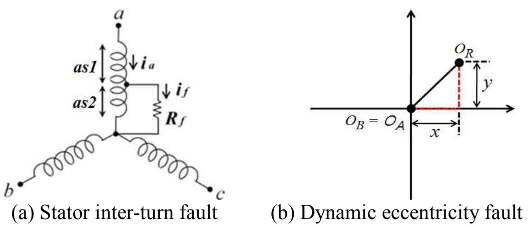
Obviously, the lifetime and reliability of an interior permanent magnet (IPM) type brushless DC (BLDC) motor are sharply decreased by mechanical and electrical faults. In addition, these problems not only lead to distortion of the input current but also become a main cause for faults in driving motor [1]. The generation of stator inter-turn fault (SITF), a type of electrical fault, and dynamic eccentricity fault (DEF), a type of mechanical fault, lead to increase in the unbalanced magnetic field and torque pulsation owing to the simultaneous distortions in the air gap flux density and the stator input current [2, 3]. From the viewpoint of fault detection and fault diagnosis, the determination of the fault frequency pattern according to the fault types is essential for obtaining an efficient fault response.

Therefore, in this study, we have determined the frequency pattern to obtain the efficient fault response under DEF and SITF by the stator current analysis that is a very useful method for monitoring the conditions of electrical machines [4].

II. Analysis the Patterns of fault Frequencies

We have analyzed the frequency pattern by the stator current spectrum analysis to determine the fault frequency of the stator current. In a permanent magnet synchronous motor, supplied frequency is used as fundamental frequency (f_f) [3]. However, in IPM-type BLDC motor, f_f can be obtained as

$$f_f = \frac{RPM}{60[Hz]} \times P . \tag{1}$$



(a) Stator inter-turn fault (b) Dynamic eccentricity fault
Fig. 1. Schematic representation of DEF and SIFT

A. Stator inter-turn fault (SITF) frequency pattern

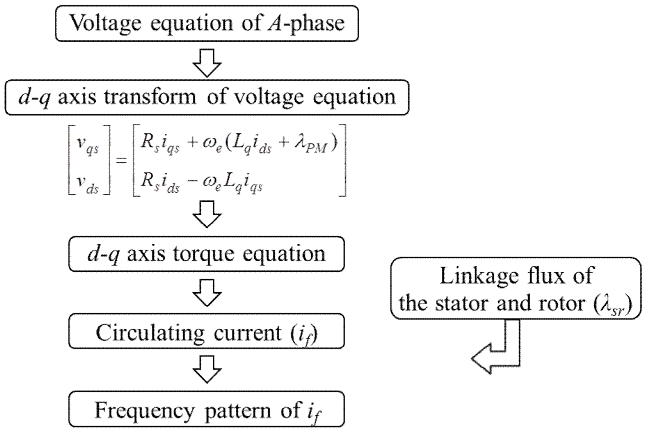


Diagram 1: Process to calculate the pattern of i_f

Fig. 1 (a) shows a schematic of the three-phase windings with SITF in the A-phase. In here, *as1* is the residual healthy windings, *as2* is the faulty windings, i_a is the stator input current, $\boldsymbol{i_f}$ is fault current, R_f is the resistance of fault windings.

SITF leads to not only the distortion of the stator current but also the generation of the circulating current [2]. Basically, the circulating current is caused by the flux generated by the PM. For this reason, the linkage flux between the stator and the rotor directly affects the circulating current. As a result, additional harmonic components are generated, which, in turn, affect the stator current. In this section, we have determined the additional side-band frequencies of the stator current through the analysis of the circulating current under SITF condition as shown in Diagram. 1.

We have used the voltage equation of A-phase under SITF condition which has been calculated in [4], to calculate the circulating current (i_f) and can be represented as in (2) [4].

$$v_{as} = \frac{R_f}{u} i_f + \{R_s i_f + [L_{ls} + u L_{am}(\theta_r)] \frac{di_f}{dt} + u\omega_e \frac{dL_{am}(\theta_r)}{d\theta_r} i_f\} . \tag{2}$$

where v_{as} is the A-phase voltage, R_f is the external resistance between the shorted windings, i_f is the circulating current, μ is the turn-fault fraction ratio [4], L_{ls} and L_{am} are the leakage inductances, and ω_e is the electrical rotating velocity.

The torque of the IPM-type BLDC motor can be calculated using the d-q axis transform as in (3), and therefore, i_f can be calculated using by this torque equation as in (4).

$$T_e = \frac{3}{2}\frac{P}{2}[\lambda_{PM} i_{qs} + (L_d - L_q) i_{ds} i_{qs}\,. \quad (3)$$

$$i_f = \frac{R_S + \dfrac{C_1}{C_2 + i_{ds1}} + w_e(L_d \cdot i_{ds1} + \lambda_{PM}) + (-R_S \cdot i_{ds1} + w_e \cdot L_q \cdot \dfrac{C_1}{C_2 + i_{ds1}})}{(R_S + \dfrac{R_f}{u}) + w_e(L_{ls} + u(L_1 - 3L_2))}\,. \quad (4)$$

where C_1 and C_2 are the integer dependent on the machine parameters, L_1 is the inductance of the residual healthy windings, L_2 is the inductance of faulty windings, $L_d \cdot i_{ds1}$ is the linkage flux of the stator, λ_{PM} is the linkage flux of the rotor, and remainder parameters can be represented as coefficient.

Thus, the linkage flux between the stator and the rotor is represented as in (5), and it can be expressed as in (6) by using Fast Fourier Transform (FFT) [4].

$$\lambda_{sr} = (L_d \cdot i_{ds1}^e + \lambda_{PM})\,. \quad (5), \qquad \lambda_{sr} = \sum_{k=1}^{\infty} \lambda_{2k-1} \cos((2k-1)\omega t)\,. \quad (6)$$

Using (4)-(6), we can determine the circulating current equation to obtain the side-band frequencies can be rewritten by using FFT as

$$i_f(t) = c + k \sum_{k=0}^{\infty} I_{f_k} \cos((2k-1))\omega t \pm \varphi_{f_k})\,. \quad (7)$$

where k is an integer ($k = 0, 1, 2, 3\ldots$).

Therefore, because the harmonic components of i_f directly affect the stator current, the frequency pattern of SITF can be determined as

$$f_{SITF} = (2k-1) f_f\,. \quad (8)$$

B. Dynamic Eccentricity (DE) frequency

As shown in Fig. 1 (b), O_A is the center of the stator symmetry, O_B is the rotor rotation center, and O_R is the rotor symmetrical axis. Further, x: 0.4 mm represents the distances by which the rotor symmetrical axis is separated by the DEF.

In this section, we have calculated the magneto motive force (MMF) by taking into account the air-gap permeance to determine the frequency pattern of the stator current as shown in Diagram. 2.

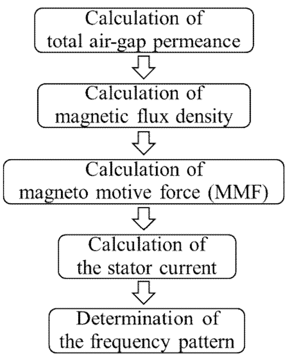


Diagram 2: Process to calculate the pattern of the DEF

Magnetic field in the air-gap includes all of the information between stator and rotor as well as harmonic components [5]. Thus, air-gap permeance under DEF condition is considered to determine the fault frequency of the stator current under DEF condition. In conclusion, we calculated the stator current by the MMF considering air-gap permeance [2].

The air-gap permeance is calculated by taking into account the effect of the stator slots, saturation, as well as the DEF [3]. Thus, the total permeance can be represented as

$$P_{Total} = \sum_{k_{SS}=0}^{\infty} \sum_{k_{SAT}=0}^{\infty} \sum_{k_{SE}=0}^{\infty} \sum_{k_{DE}=0}^{\infty} P_{k_{SS}} \cdot P_{k_{SAT}} \cdot P_{k_{DE}} \times \cos(\pm(2k_{SAT} + k_{DE})\omega t + (k_{SS} S \pm 2k_{SAT} \pm k_{DE})\theta\,\cdot \quad (9)$$

where P_{kss}, P_{kSAT}, P_{kDE} are the permeances calculated by taking into account the effect of stator slots, saturation, and dynamic eccentricity, respectively. K_{SAT}, k_{DE}, and k_{SS} are the integers.

Using (9), the magnetic flux density can be calculated as

$$B(t) = P_{Total}(t) \int \mu_0 \cdot j_S(\theta, t) d\theta\,. \quad (10)$$

where μ_0 is magnetic permeability of the air-gap, $j_S(\theta, t)$ is current density of the stator inner surface.

Using (9) and (10), the stator current can be calculated by applying FFT as in (11), and therefore, the frequency pattern of DEF is determined as in (12).

$$i_{a,DE}(t) = \sum_{k=0}^{\infty} I_{f_k} \cos((1 \pm (2k-1))\omega t \pm \varphi_{f_k})\,. \quad (11)$$

$$f_{DE} = [1 \pm (2k-1)] f_f\,. \quad (12)$$

III. RESULTS

In this study, we have simulated by using 4-pole, 6-slot IPM-type BLDC motor in 3500[rpm] under 1.1[mNm] load condition. Fig. 2 shows the stator currents under each fault conditions. The frequency patterns under the SITF condition occurred at $(2k\text{-}1)f_f$. On the other hand, the frequency patterns under the DEF condition occurred at $[1\pm(2k\text{-}1)]f_f$.

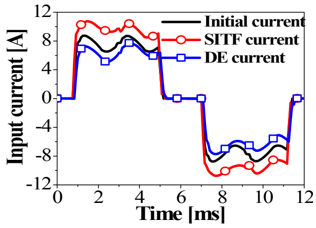
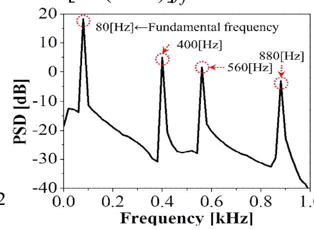
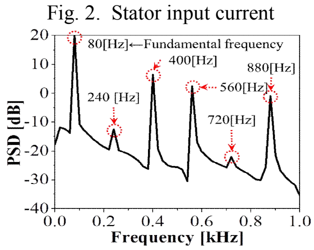


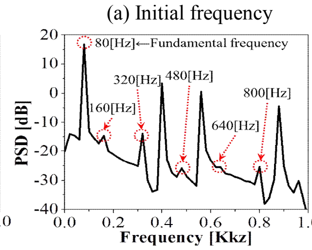
Fig. 2. Stator input current



(a) Initial frequency



(b) SITF frequency



(c) DEF frequency

Fig. 3. Compare the frequency of steady state and fault state

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