Diagnosis Technique using Detection Coil in BLDC motor with Inter-Turn Fault

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***Abstract*— Inter-turn faults (ITFs) cause significant changes in the electric and magnetic characteristics of the motors. In particular, the ITFs can be the cause of the serious distortions in the magnetic field of an air-gap. Therefore, this paper proposes a simple diagnosis algorithm for the detection of ITFs and developed the diagnosis circuit to apply the proposed algorithm. Using magnetic characteristic analysis under an ITF, the developed diagnosis circuit calculates by an induced voltage from the detection coil and can detect the phase/region of fault.**

***Index Terms*— inter turn fault, stator turn fault, diagnosis for turn fault, diagnosis algorithm for turn fault, detection coil.**

I. Introduction

To increase the robustness of products and to secure competiveness, the development of motors needs to focus on improving stability and reliability over previous motors. Therefore, many research fields have studied fault detection methods and fault tolerance control in brush-less direct current (BLDC) motors [1]-[2]. When a motor develops short circuit between the windings of one of its coils, known as an inter-turn fault (ITF), heat is generated by the circulating current in the shorted coil. The circulating current is induced by the magnetic linkage flux originating from the permanent magnet (PM) in the shorted turn which causes the deterioration of their output characteristics because of a distortion in the air-gap magnetic flux distribution. Many previous diagnosis methods have complex algorithms and can be cost-inefficient because of expensive equipment for analysis and measurement [3]-[4]. Therefore, this paper proposes a diagnosis algorithm for ITFs that is simpler and more efficient than the previously proposed diagnosis methods. In real-time, the proposed diagnosis algorithm can be detected by using comparison operation of induced voltage. We performed an FEM simulation using IPM-type BLDC motors applying detection coil for verification of the proposed algorithm.

The proposed algorithm can perform early detection of an ITF as well as determine the exact region of the ITF. As a result, this method can achieve rapid fault tolerance.

II. Diagnosis Algorithm for ITF

A. Machine Equation of ITF

We assumed that each phase winding consists of turns that are connected in series and that the three-phase concentrated windings are wye-connected. The "fault fraction" F_r is defined as the ratio of the number of shorted turns to the number of turns per phase because the ITF can be considered in terms of severity by the fault fraction of the shorted turn. The winding voltage of an IPM motor with an ITF in the *A*-phase winding is presented in (1). In these voltage equations, λ_a is the linkage flux of the phase coil current, λ_{ar} is the linkage flux of the PM.

$$v'_{sn} = R'_s \cdot i'_s + L'_s \cdot \frac{di'_s}{dt} + w\left(\frac{dL'_s}{d\theta} \cdot i'_s + \frac{d\lambda'_{sr}}{d\theta}\right) \tag{1}$$

$$\begin{aligned} v'_{an} &= v_{as1} + v_{as2} \\ &= \left(R_s \cdot i_a + \frac{d\lambda_a}{dt} + w\frac{d\lambda_{ar}(\theta_r)}{d\theta_r}\right) - \left(F_r \cdot R_s \cdot i_f + F_r \cdot w\frac{d\lambda_{ar}(\theta_r)}{d\theta_r}\right) \end{aligned} \tag{2}$$

where $v'_{sn} = [v_{as1}\ v_{as2}\ v_{bn}\ v_{cn}]^T$, $R'_s = diag\ [(1-F_r)R_s\ F_rR_s\ R_s\ R_s]$, $\lambda'_{sr} = [(1-F_r)\lambda_{ar}\ F_r\lambda_{ar}\ \lambda_{br}\ \lambda_{cr}]^T$, and $i'_s = [i_a\ i_a\text{-}i_f\ i_b\ i_c]^T$.

B. FEM modeling for ITF

On the basis of machine equation under the ITF state, we performed FEM-modeling for the analysis of the non-linear magnetic characteristics [5]. Fig. 1 shows the scheme of the FEM-based model under an ITF for the consideration of the magnetic saturation effect in the core and the analysis of the distribution characteristics of the motor. This model includes a shorted turn for calculation of the circulating current induced by variation of the magnetic flux that links the shorted turn.

C. Diagnosis Algorithm

In this paper, an algorithm for the diagnosis of an ITF is proposed with a detection coil that can detect the magnetic field. The electro motive force (EMF) induced in the detection coil is expressed as a function of the number of turns and flux according to the Faraday's law of induction. The induced EMF waves induced in the detection coil appear in the flux distribution of each slot in the winding. When the magnetic distribution of the air-gap is unbalanced by an ITF, the amplitude and phase of the induced voltage from the flux is changed. Therefore, the development and region of the failure is distinguished by an analysis of the measured wave. Using the appropriate space factor of coil is necessary for the application of detection coil. The detection coil of the test motor is applied to each slot.

Fig. 2 shows the configuration of the proposed algorithm utilized to diagnose the ITF. The input to the diagnosis algorithm is the induced voltage of the detection coil, and the low-pass filter (LPF) eliminates the harmonics of the input voltage and performs voltage leveling according to the limited voltage of the MCU. To perform the correct comparison operations for the induced voltages, it is important that the induced voltage of the detection coil is transformed to DC-level voltages by a half-wave rectifier. Therefore, the output of the half-wave rectifier was used as the input of the MCU.

Decision logic 1 compares the average value of all voltage with average value of each phase for diagnosis of fault phase. The decision logic 2 is the comparison operators for detection of fault region. This logic compare the mean of induced voltage in the detected fault phase with the mean of induced voltage in each slot for the diagnosis of fault region, and it can detect the fault region by reverse magnetic field.

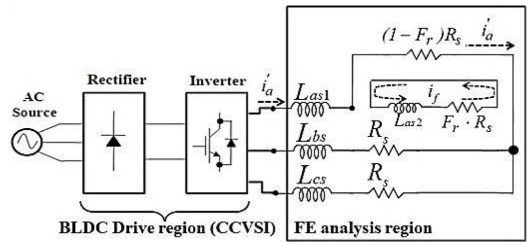


Fig.1. Scheme of FEM-based model for ITF analysis

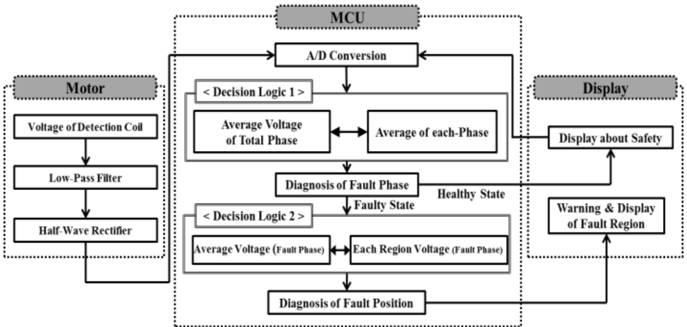
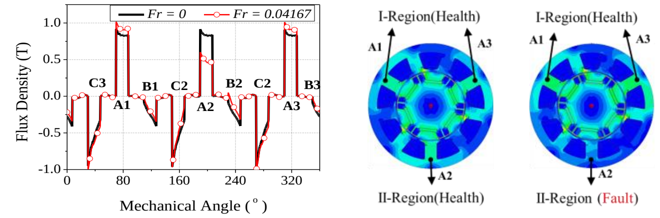


Fig. 2. ITF diagnosis algorithm using detection coil

III. Analysis Result

The distributed flux density is an important characteristic for the proposed diagnosis method using the detection coil. Fig. 5 shows the radial flux density according to the angle dimension. In the region of the included shorted turn (**II**-region), magnetic interference is generated by the magneto motive force of the circulating current. As the fault fraction increases over time, a reverse magnetic field is generated in the teeth of shorted turn (**II**-region), and flux density is decreased in the other teeth (**I**-region). The detection coil is applied to each of the 9-slots as the test motor has 3-phases and 9-slots. The input voltage of the diagnosis circuit is connected to the induced voltage of the detection coil in the FEM-simulation. The proposed algorithm can detect the fault in all slots as it uses the 2-slots at each phase, and the fault state of the remaining 1-slot is estimated by decision logic 2. In order to compare the each phase, input voltages have to consider the phase angle. The matching of the output angle is complex and inaccurate. Therefore, the proposed diagnosis circuit employs a half-wave rectifier in order to transform to the voltage to a DC value. When comparison operation was performed using a rectified voltage, fault signal was displayed in LCD, LED by the diagnosis algorithm.

The shorted winding was modeled in **A2**-region, and simulation result of **A3**-region was measured by using independence circuit for analysis of all slots in *A*-phase. Simulation result of healthy-state and faulty-state is indicated in Fig.5. Fig.5-(a) is the induced voltage of detection coil in *A*-phase connected by FEM according to motor's state. In healthy state, the magnitude and phase angle of the induced voltages are same as the phases are same. In faulty state, induced voltage in **A1, A3** are 7.25 V that was increased by saturation characteristic and induced voltage in **A2** is 2.8 V that was increased by reverse magnetic field. Fig.5-(b) shows the output voltage of rectifier which was inputted in the MCU. When an ITF occurs, rectified voltage in region of shorted turn (**A2**) was 0.2 V, rectified voltages in healthy-regions (**A1**, **A3**) were 2.58 V.



(a) Variation of distributed flux density (b) Flux density of each region

Fig. 3. Distributed magnetic flux density by the fault fraction ratio of ITF

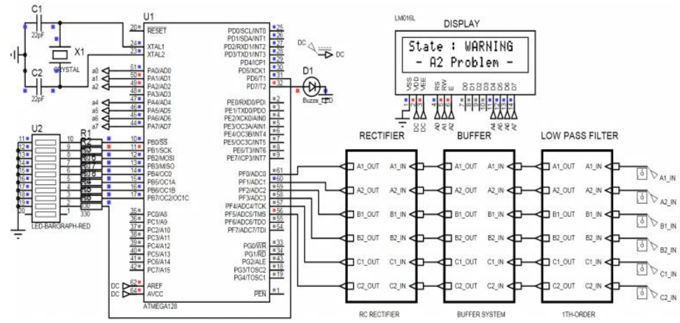
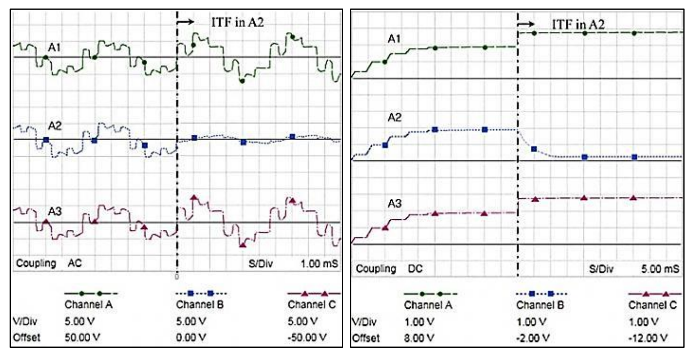


Fig. 4. Distributed magnetic flux density by the fault fraction ratio of the ITF



(a) Induced voltage of detection coil (b) Rectified voltage of detection coil

Fig. 5. Simulation result of detection circuit under healthy-state and faulty-state

IV. Conclusion

The BLDC motor is required the early-detection and fault tolerance. This paper proposed the diagnosis algorithm of ITF which is more simply and more correct method than the previous proposed diagnosis methods. In the simulation, the diagnosis circuit is developed for verification of proposed algorithm. The proposed diagnosis algorithm correctly detected position/phase of the ITF.

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