New Fault Impedance Modeling For Inter-Turn Fault Analysis of IPM motor

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Abstract — We proposed new fault impedance modeling, which varies with the rotating speed, at an inter-turn fault of IPM motor. The fault impedance is required to calculate the circulating current that causes magnetic distortion. Thus, this paper proposes a method for estimation of the circulating current taking into account the voltage at the shorted turn and the rotating speed. Using this method, a finite element method (FEM)-based model of an interior permanent magnet (IPM) type BLDC motor was developed to analyze inter-turn faults. The analysis data were verified experimentally.

I. INTRODUCTION

Interior permanent magnets (IPM) motors operating as brushless DC (BLDC) drives have been widely used and their application extended to many safety-critical systems because of their robustness and high performance [1].

In such systems, a failure related to the stator winding insulation and core is an important factor to be considered. In particular, inter-turn faults in a symmetrical three-phase machine result in large circulating current that subsequently generates excessive heat at the shorted turns. The heat, which is proportional to the square of the circulating current, can result in complete failure and shutdown of the motor unless the fault is detected early and evasive action is taken [2]. Distorted transient current caused by inter-turn faults must to be analyzed in terms of the magnetic distribution in stator and torque characteristics to improve the fault tolerance in high-reliability applications, where continuation of operation with degraded performance is much more desirable than complete shutdown of the motor [3]. To this effect, many studies concerning inter-turn faults are conducted using only the fault fraction including fault resistance [2]. The impedance is assumed to be purely resistive. However, the fault resistance (R_f) must be considered along with the reactance component, because the voltage at the fault turn has an alternating component caused by the permanent magnet and input current. Therefore, this paper proposes fault impedance (Z_f) modeling considering the variation in reactance with rotating speed and the fault resistance (R_f). In addition, the circulating current at the inter-turn fault is calculated using the proposed fault impedance (Z_f). The circulating current can be calculated using the proposed fault impedance modeling. In addition, the model can help analyze the magnetic nonlinearity at the inter-turn fault.

II. FAULT IMPEDANCE

An inter-turn fault can occur within a coil, between two coils of the same phase, or between two different phases. A schematic of a three-phase winding with an inter-turn fault in the *A*-phase winding is shown in Fig.1, where *as1* and *as2* represent the healthy and shorted turns, respectively, and i_f represents the circulating current at the shorted turns. In addition, the schematic provided in Fig.1 implies that regardless of the number of coils in a single-phase winding, a series winding motor with turn faults can be interpreted as a motor with four windings, which are mutually coupled with each other. As per the assumptions made, the stator line-neutral voltages and the developed torque of an IPM motor with an inter-turn fault on the *A*-phase winding can be represented in abc-variables by the following equation (1).

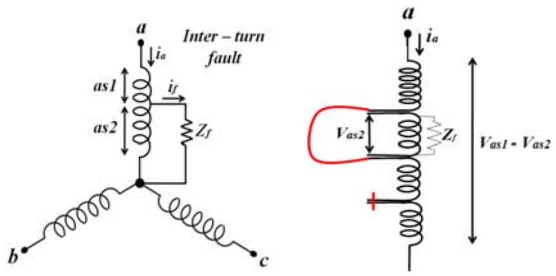


Fig.1 Schematic of fault

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

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

In addition, the symbol μ, referred to as "fault fraction" is defined as the ratio of the number of the shorted turns to the number of turns per phase. The inter-turns fault increased rapidly at the rated speed because the heat generated is proportional to the square of the circulating current. Thus, the circulating current is an important factor in inter-turn faults because of the variations in the torque characteristics due to magnetic interruption which the opposite magnetic field by the circulating current make distort main flux. In addition, a short circuit current of this magnitude will cause a breakdown of the adjacent winding insulation. The winding configuration with an inter-turn fault in a phase is illustrated in Fig.2. In this case, the stator winding has a short circuit, indicated by the thicker line. The short circuit current flows opposite the phase current. Figure 3 shows the distribution of magnetic flux density and the equip-potential line of the IPM type BLDC motor without and with a turn fault. As shown in Fig.3, the magnetic flux is distorted by the circulating current, which directly influences the torque characteristics. Moreover, it was confirmed that magnetic saturation in the stator and rotor core is changed and becomes unbalanced as the fault fraction increases.

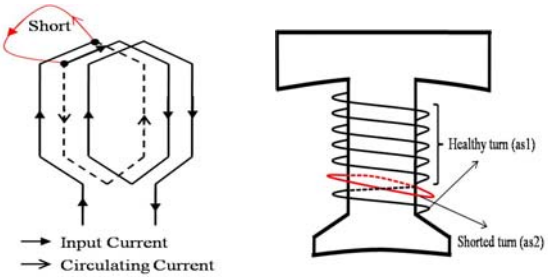


Fig.2 Winding configuration with the inter-turn fault

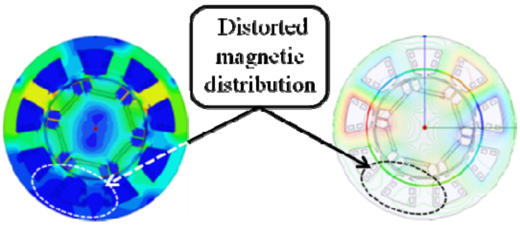


Fig.3 Distribution of magnetic flux density and the equipotential line (fault fraction=12.5%)

Thus, to sum up, this paper proposed a method for calculating the circulating current using the values of the voltage at the shorted turn (v_{as2}) and fault impedance (Z_f). Many studies did not consider reactance (X_f), which varies with the rotating speed. However, the reactance used for calculating the circulating current depends on the rotating frequency (f_{rot}) and inductance of the shorted turn (L_f). This is because the flux of the permanent magnet induces an AC voltage. The impedance vector is presented in Fig.4.

Equation (2) describes the circulating current model [2]; it does not consider the reactance. Therefore, the circulating current can be calculated using equation (3), in which v_{as2} increases in proportion with the fault fraction. In addition, as shown in equation (4), the impedance of the shorted turn is expressed as the vector sum of the fault resistance and fault reactance.

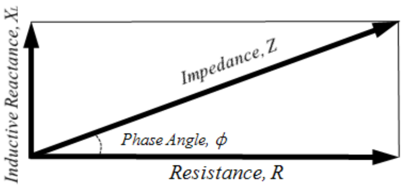


Fig.4 Impedance vector

$$|i_f| = \frac{|v'_{as}|}{\left|\frac{R_f}{\mu_{se}} + R_s + j\varpi_e\left[L_{ls} + \mu_{se}(L_1 - 3L_2)\right]\right|} \tag{2}$$

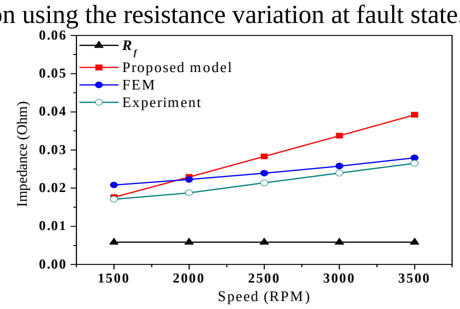
$$i_f = \frac{v_{as2}}{Z_f} \tag{3}$$

$$Z_f = \sqrt{R_f^2 + X_f^2} \tag{4}$$

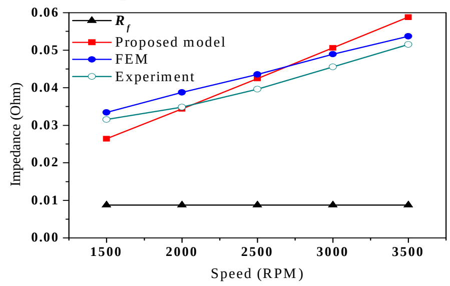
Here $v_{as2} = \mu \cdot v_a$, $R_f = \mu \cdot R_s$, and $X_f = 2 \cdot \pi \cdot f_{rot} \cdot \mu \cdot L_s$

III. Results and Discussion

The proposed fault impedance model can help calculate the circulating current using parameters of the healthy state and fault fraction. Figure 5 compares the calculated impedance obtained by the equation (4) with the FEM result, the experimental results. The fault resistance (R_f) must be considered along with the reactance component, because the voltage at the fault turn has an alternating component caused by the permanent magnet and input current. The experiment was performed to measure the fault phase voltage (v_{as2}) and circulating current (i_f). Thus, the fault impedance can be calculated as $Z_f = v_{as2}/i_f$. Figure 6 shows the result of the measurements of v_{as2} and i_f when the fault fraction is 8.33[%]; rotating speed, 3500 [RPM]; voltage peak, 21.2[V]; and circulating current peak, 85[A]. So, the fault impedance modeling can apply to fault detection using the resistance variation at fault state.



(a) Impedance (Fault fraction = 8.33%)



(b) Impedance (Fault fraction = 12.5%)

Fig.5 Impedance comparison of results

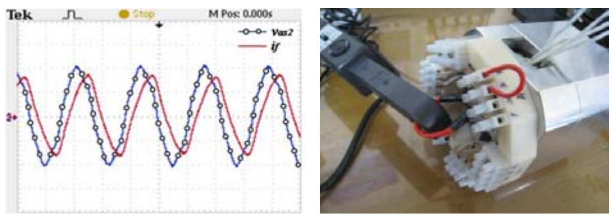


Fig.6 Experiment result and measurement (Fault fraction=8.33%)

This work was supported by the development program of local science park funded by the ULSAN Metropolitan City and the MEST (Ministry of Education, Science and Technology)

IV. References

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