Comparison of Dynamic Responses For IPM and SPM Motors by Considering Mechanical and Magnetic Coupling

Tae-Jong Kim, Sang-Moon Hwang, Kyung-Tae Kim, Weui-Bong Jung, and Chul-U Kim

Abstract—The permanent magnet motor is often the most important element in high performance rotor applications and also a frequent source of vibration and acoustic noise. Because of manufacturing imprecision such as mass unbalance, shaft bow and bearing tolerances, rotor eccentricity extensively exists in all kinds of electric machines. This paper investigates magnetic unbalanced forces for IPM and SPM motors which are widely used in a washing machine due to high average torque and dynamic responses of a rotor motor system when rotor eccentricity exists. For the magnetic field analysis, a finite element method is used to account for the magnetic saturation and rotor eccentricity. An IPM motor, mostly chosen to realize high speed operation, shows a worse effect on magnetic unbalanced forces and dynamic responses compared with SPM motor due to magnetic saturation when the eccentricity exists.

Index Terms—Dynamic responses, interior permanent magnet motor, magnetic unbalanced force, rotor eccentricity.

I. INTRODUCTION

In a permanent magnet brushless DC (BLDC) motor, vibration results primarily from the forces induced by rotating magnetic fields created by the permanent magnets. Unbalanced forces are highly dependent upon the geometry between the rotor and the stator. Theoretically, unbalanced forces do not exist in perfectly manufactured symmetric motors. Due to the manufacturing imprecision such as unbalanced mass, shaft bow and bearing tolerances, rotor eccentricity is inevitably introduced mechanically. For interior permanent magnet (IPM) motors, the rotor whirl induced by mechanical origins causes the variation of the airgap, which adversely affects magnetic saturation of the rotor iron. With the variation of airgap, magnetic unbalanced forces acting on rotor surface are increased due to magnetic saturation, which again adversely affect the whirl of the rotor-motor system.

The investigation of magnetic force and vibration for a rotor-motor system has been addressed by a number of investigators. Reichet et al. suggested the finite element method, the volume integral of the force density and the surface integral of Maxwell stress tensor in one single relative position of the movable versus the fixed [1]. Jang and Lieu expressed the driving frequencies of magnetic force as a function of pole, teeth and phase for surface-mounted permanent magnet (SPM) motor [2]. Kim and Lieu modeled the magnetic field associated with rotor eccentricity by a perturbation of the corresponding Maxwell’s equations and boundary condition [3].

This paper presents magnetic force analysis of IPM and SPM motors with radial rotor eccentricity using finite element method. In order to investigate the dynamic responses, the rotor-motor system is modeled using finite element transfer matrix (FE-TM) and the whirl responses for IPM and SPM motors are determined for comparison.

II. METHOD OF ANALYSIS

Fig. 1 shows 4-pole and 24-slot IPM and SPM motors that are popularly used in a washing machine. To realize high speed operation, IPM motors are widely used to prevent separation of permanent magnets from the rotating rotor. Unlike SPM motors, magnetic saturation occurs at the rotor iron due to its geometry for IPM motors. Table I lists the detailed information for the IPM motor and the SPM motor has the same specification except for different magnet configuration. To include effects of magnetic saturation, the FEM was used for magnetic field analysis for motors with rotor eccentricity ANSYS, a FEM solver for magnetic fields, was used to calculate the magnetic field and the magnetic flux density. Since $\mu_{irn} \gg \mu_{air}$, the magnetic force acting on iron surface can be determined using Maxwell stress tensor:

$$f_r = \sigma_{rr}^{air} - \sigma_{rr}^{iron} \approx \frac{1}{2\mu_{air}} (B_r^2 - B_\theta^2)$$

$$f_\theta = \sigma_{r\theta}^{air} - \sigma_{r\theta}^{iron} \approx \frac{1}{\mu_{air}} B_r B_\theta$$

Fig. 1. Prototype BLDC motors to be analyzed.
TABLE I
DESIGN PARAMETERS OF THE SPM MOTORS

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Value</th>
<th>(Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator radius</td>
<td>35</td>
<td>(mm)</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>8.0</td>
<td>(mm)</td>
</tr>
<tr>
<td>Airgap length</td>
<td>0.6</td>
<td>(mm)</td>
</tr>
<tr>
<td>Slot opening angle</td>
<td>5</td>
<td>(degree)</td>
</tr>
<tr>
<td>Magnet remanence</td>
<td>0.4</td>
<td>(T)</td>
</tr>
<tr>
<td>Relative permeance</td>
<td>1.061</td>
<td></td>
</tr>
</tbody>
</table>

where \( f_r \) and \( f_\theta \) denote the radial and the tangential traction. Radial unbalanced magnetic forces acting on the rotor center can be determined by integrating radial force density along the rotor surface, as in (3).

\[
F_r = \int_0^{2\pi} f_r \cdot r d\theta. \tag{3}
\]

The radial distance between the stator and rotor axes is defined as the eccentricity of the rotor and is denoted by (4).

\[
\epsilon = e \cdot g \tag{4}
\]

where \( e \) is the eccentricity ratio and \( g \) is the nominal airgap length. For the analysis, a full model is required to analyze the motor with rotor eccentricity. The total number of nodes and elements are 60 402 and 49 080 respectively.

A rotor-bearing system to be analyzed consists of a rotor with 7 finite segments and 2 roller bearings, shown in Fig. 2. Dynamic behavior of the rotor system is influenced by mass unbalance forces, reaction forces of roller bearings, and magnetic unbalanced forces. The assembled element system equation of motion for the element \( j \) with nodes \( i \) and \( i+1 \) can be expressed in the \( XYZ \) coordinates as;

\[
[M_j]\{q_i(t)\} + [C_j]\{q_i(t)\} + [K_j]\{q_i(t)\} = \{F_i(t)\} \tag{5}
\]

where \([M_j],[C_j],[K_j]\) are the mass, damping and stiffness matrices of the element \( j \), and \( \{F_i(t)\} = \{R f_i(t)\}L f_{i+1}(t)\}^T \) is the generalized force vector acting on nodes \( i \) and \( i+1 \). Superscripts \( R \) and \( L \) represent right- and left-side elements, respectively, of the \( j \)th node.

Fig. 2. Rotor-motor system configuration.

III. RESULTS AND DISCUSSION

In order to understand the operating characteristics of an IPM motors, it is important to appreciate that burying the permanent magnet inside the rotor introduces iron saturation into the rotor magnetic circuit which is not present in SPM motors. Figs. 3 and 4 show the radial flux density distribution for IPM and SPM motors without and with the eccentricity ratio of 0.5. With the rotor eccentricity, it can be seen that the radial flux density is stronger in the narrow airgap region for IPM and SPM motors. Variation of radial flux density can be explained by variation of airgap permeance function. For the SPM motor, variation of airgap permeance function is introduced by rotor eccentricity only. For the IPM motor, however, variation of the airgap permeance function is also introduced by the difference of magnetic saturation at the edges of iron pole pieces, as well as the rotor eccentricity. Fig. 5 shows the radial force density distribution for IPM and SPM motors without and with rotor eccentricity at the instant when the rotor eccentricity angle is 0°. For IPM motors, the iron edges at pole transitions are particularly vulnerable to magnetic saturation as the rotor eccentricity is increased. For a given rotor eccentricity, the saturation of these iron segments has a bigger influence on the difference of radial force density between narrow and wide airgap region, resulting in increased
unbalanced magnetic force. Fig. 6 shows the maximum magnitude of magnetic unbalanced forces with respect to the eccentricity ratio. For the SPM motor, they increase approximately linearly due to the relatively small airgap in the motor. For the IPM motor, however, they significantly and nonlinearly increase due to severe magnetic saturation as the eccentricity increases. For analysis of dynamic responses, magnetic forces can be expressed as the function of rotor eccentricity and rotating speed and they can be obtained using MATLAB program.

\[
F_x = F_1x\varepsilon \cos(\omega t + \phi) + F_2x\varepsilon^2 \cos(\omega t + \phi) \quad (6)
\]

\[
F_y = F_1y\varepsilon \sin(\omega t + \phi) + F_2y\varepsilon^2 \sin(\omega t + \phi). \quad (7)
\]

For SPM motors, it should be noted that \(F_2x\) and \(F_2y\) vanish due to linear nature of magnetic circuit.

Dynamic response or whirl response of the coupled system can be determined by considering the unbalanced magnetic forces as function of time and position in a rotor-motor system. The FE-TM was applied to illustrate magnetically coupled effects in rotor dynamics. The data for rotor motor system is given in [4]. Fig. 7 shows comparison of transient whirl responses of converging characteristic for IPM and SPM motors. Fig. 8 shows orbit plot along the rotor axis for the two cases. It can be seen that the whirl magnitude for IPM motor is increased by 52 percent compared to that for SPM motor, due to magnetic saturation.

IV. CONCLUSION

An IPM motor is sometimes a design alternative for high speed applications to prevent separation of permanent magnets. However, it introduces uneven magnetic field distribution due to magnetic saturation especially when the rotor eccentricity exists. When rotor eccentricity exists, magnitude of unbalanced forces for IPM motor is significantly increased compared to that of SPM motors due to magnetic saturation. Magnetic unbalanced forces for the IPM motor are also nonlinearly increased as the eccentricity increased. An IPM motor shows a worse effect on dynamic responses compared with SPM motor, resulting in severe motor vibration.

REFERENCES