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Development of a highly efficient brushless dc motor utilizing both radial and axial air gaps

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This research proposes an effective structure for a brushless dc motor utilizing both radial and axial air gaps. The proposed motor generates torque in both the radial and axial air gaps, while the conventional motor generates torque only in the radial air gap. The proposed motor was optimized to minimize the electromagnetic loss of the motor to increase the effective air gap length and fill-factor of the coil while decreasing the saturation of the core at the same time. The electromagnetic loss was reduced by 35% in comparison with a conventional motor. © 2012 American Institute of Physics. [doi:10.1063/1.3676210]

I. INTRODUCTION

The efficiency of an electric motor decreases as its size decreases. The efficiency of a brushless dc (BLDC) motor of a washing machine is greater than 90%, but that of a BLDC motor of a 2.5 in. computer hard disk drive (HDD) to run a disk is less than 40%. Efficiency is one of the most important performance factors of a motor, and it is dependent on the effective air gap length, fill-factor of the coil, and core saturation.

Many researchers have investigated the structures of BLDC motors to increase efficiency. Jang et al. proposed an axial gap motor with a dual air gap and a printed circuit board winding, which eliminated the core loss.1 Yao et al. studied a radial gap motor with a high efficiency and low cogging torque by changing the shape of the teeth.2 However, previous researchers have separately utilized the radial-gaps or the axial-gaps of motors.

In this research, we propose a highly efficient BLDC motor as a hybrid motor utilizing both radial and axial air gaps. Utilizing both radial and axial gaps can increase the effective area for torque generation and the fill-factor for the coil winding. The magnetic saturation of the core is also reduced by optimizing the design variables of the core and permanent magnet (PM) to minimize the electromagnetic loss while maintaining the same level of torque.

II. BLDC MOTOR UTILIZING BOTH RADIAL AND AXIAL AIR GAPS

Figure 1(a) shows the structure and flux path of a conventional 2.5 in HDD spindle motor with 12 poles and 9 slots. The torque of a conventional motor is generated in the radial gap between the PM and the core, and the axial magnetic force, as a preload to the fluid dynamic bearings, is generated by the axial flux between the PM and the pulling plate. However, a significant amount of iron loss is consumed in the pulling plate due to the alternating magnetic field. We propose a motor with both radial and axial air gaps as shown in Fig. 1(b), to generate the torque and axial magnetic force at the same time. The radial part of the core and the PM generate torque in the radial gap, just like a conventional radial gap motor. Additionally, the axial part of the core and the permanent magnet are designed to generate torque in the axial air gap, however, it does not require any additional coils because it utilizes the same coils that are wound around the radial teeth. They also generate an axial magnetic force preload to the fluid dynamic bearings. In this way, the proposed design can increase the torque and decrease the electromagnetic loss.

Table I shows the torque and axial magnetic force calculated by using the Maxwell stress tensor method. The peak values of $B_r$, $B_0$, and $B_z$ in the radial air gap are generated between the middle of the pole and the middle of the tooth, near the end of the tooth, and near the bottom and top of the tooth, respectively. The peak values of $B_r$, $B_0$, and $B_z$ in the axial gap are generated between the middle of the pole and the middle of the tooth, near the end of the tooth, and between the middle of the pole and the middle of the tooth, respectively. The torque can be expressed as follows:

$$T = \frac{1}{\mu_0} \int r_{\text{radial}} B_r B_0 dA_{\text{radial}} + \frac{1}{\mu_0} \int r_{\text{axial}} B_z B_0 dA_{\text{axial}},$$

where $\mu_0$, $A_{\text{radial}}$, $A_{\text{axial}}$, $B_r$, $B_0$, and $B_z$ are the permeability of air, the area of the radial and axial air gaps, and the radial, tangential, and axial components of the magnetic flux density, respectively. A conventional motor generates torque only in the radial air gap. The axial air gap of the conventional motor generated a small amount of negative torque due to the electromagnetic induction effect. However, the proposed motor can generate active torque in both the radial and the axial air gaps. In a similar way, we can also calculate the axial magnetic force of the conventional and proposed motors. The axial magnetic force can be expressed as follows:

$$F = \frac{1}{\mu_0} \int B_z B_0 dA_{\text{radial}} + \frac{1}{2\mu_0} \int (B_z^2 - B_0^2 - B_r^2) dA_{\text{axial}}.$$
In this research, we developed three-dimensional finite element models of the conventional and proposed motors to validate the performance of the proposed motor. We analyzed the torque, axial magnetic force, and iron loss. Finite element models of one third of the motor were developed with a periodic boundary condition. The torque and the axial magnetic force were determined by using the Maxwell stress tensor method. The copper loss was determined by multiplying the square of the current and the winding resistance to run the motor at an operating speed of 7200 rpm. The iron loss was determined by integrating the following equation for the stator core and the pulling plate of the three-dimensional finite element model,

\[
P_{\text{core}} = k_h B_{mf}^2 + \frac{\pi^2 \sigma d^2}{6} (B_{mf})^2 + 8.67 \cdot k_e (B_{mf})^{3/2},
\]

where \(k_h, f, \sigma, d, B_{mf}, \) and \(k_e\) are the coefficients of the hysteresis loss, frequency, conductivity of the material, diameter of eddy current, peak value of the magnetic flux density, and the coefficient of excess losses, respectively. Figure 2 shows the convergences of the torques and the axial magnetic forces of the conventional and proposed models with the increase in the element number. It shows that element numbers greater than 800 000 are sufficient to guarantee convergence within a 1% error.

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\]

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A design optimization problem of the proposed motor can be formulated to minimize the electromagnetic loss with the same level of torque ripple and axial magnetic force of the conventional model as follows:

\[
\text{Minimize } P_{\text{loss}} = P_{\text{core}} + P_{\text{iron}} + P_{\text{copper}}
\]

subject to

\[
\frac{\Delta T}{T_{\text{base}}} \leq 20\% \quad \text{and} \quad \frac{F_{\text{axial}}}{F_{\text{base}}} \leq 10\%
\]

where \(P_{\text{loss}}, P_{\text{core}}, P_{\text{iron}}, P_{\text{copper}}, \) \(\Delta T, T_{\text{base}}, F_{\text{axial}}, F_{\text{base}}\) are the total electromagnetic loss, iron loss, copper loss, average torque ripple, and axial force of the motor, respectively.

### Table I. Flux densities in the air gap and torque and axial force calculated by the Maxwell stress tensor method (Conv.: conventional, Prop.: proposed).

<table>
<thead>
<tr>
<th></th>
<th>Radial air gap</th>
<th>Axial air gap</th>
<th>Radial air gap</th>
<th>Axial air gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak value of (B_r) (T)</td>
<td>0.653</td>
<td>0.070</td>
<td>0.533</td>
<td>0.152</td>
</tr>
<tr>
<td>Peak value of (B_h) (T)</td>
<td>0.170</td>
<td>0.039</td>
<td>0.136</td>
<td>0.054</td>
</tr>
<tr>
<td>Peak value of (B_z) (T)</td>
<td>0.295</td>
<td>0.311</td>
<td>0.236</td>
<td>0.282</td>
</tr>
<tr>
<td>Torque (uNm)</td>
<td>682.70</td>
<td>−0.11</td>
<td>568.86</td>
<td>96.63</td>
</tr>
<tr>
<td>Axial force (N)</td>
<td>0.307</td>
<td>0.554</td>
<td>0.255</td>
<td>0.533</td>
</tr>
</tbody>
</table>

### Table II. Specifications of the conventional and proposed motors (Rad.: radial air gap motor, Axl.: axial air gap motor).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual flux density of the PM (T)</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Inner radius of the PM (mm)</td>
<td>8.5</td>
<td>8.95</td>
<td>8.95</td>
</tr>
<tr>
<td>Outer radius of the PM (mm)</td>
<td>9.45</td>
<td>9.45</td>
<td>9.8</td>
</tr>
<tr>
<td>Height of the PM (mm)</td>
<td>3.55</td>
<td>3.1</td>
<td>0.55</td>
</tr>
<tr>
<td>Teeth width (mm)</td>
<td>1.4</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Slot opening (mm)</td>
<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Air gap (mm)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Outer radius of the radial core (mm)</td>
<td>8.25</td>
<td>8.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Number of turns (turn)</td>
<td>57</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Coil diameter (mm)</td>
<td>0.15</td>
<td>0.18</td>
<td>0.18</td>
</tr>
</tbody>
</table>

### Table III. Analysis results of the conventional and proposed motors.

<table>
<thead>
<tr>
<th></th>
<th>Conv.</th>
<th>Prop.</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average torque (uNm)</td>
<td>673.37</td>
<td>655.21</td>
<td>2.70</td>
</tr>
<tr>
<td>Torque constant (mNm/A)</td>
<td>5.61</td>
<td>5.46</td>
<td>2.70</td>
</tr>
<tr>
<td>Torque ripple (uNm)</td>
<td>45.05</td>
<td>38.83</td>
<td>13.79</td>
</tr>
<tr>
<td>Axial force (N)</td>
<td>0.92</td>
<td>0.79</td>
<td>14.66</td>
</tr>
<tr>
<td>Copper loss (mW)</td>
<td>51.84</td>
<td>36.65</td>
<td>29.30</td>
</tr>
<tr>
<td>Iron loss (core) (mW)</td>
<td>58.54</td>
<td>52.42</td>
<td>10.45</td>
</tr>
<tr>
<td>Iron loss (pulling plate) (mW)</td>
<td>26.49</td>
<td>0</td>
<td>100.00</td>
</tr>
<tr>
<td>Total electromagnetic loss (mW)</td>
<td>136.87</td>
<td>89.07</td>
<td>34.92</td>
</tr>
</tbody>
</table>
Minimize $P(X_i) = P_{\text{copper}} + P_{\text{iron}}$, subject to $T(X_i) \leq T(X_{i0})$, $0.9F_{\text{axial}}(X_{i0}) \leq F_{\text{axial}}(X_i) \leq 1.1F_{\text{axial}}(X_{i0})$, $(X_i)_{\text{lowerlimit}} \leq X_i \leq (X_i)_{\text{upperlimit}}$.

where $P(X_i)$ is an objective function of the electromagnetic loss of the HDD spindle motors. It is composed of copper, $P_{\text{copper}}$, and iron losses, $P_{\text{iron}}$. Here, $T(X_i)$ and $F_{\text{axial}}(X_i)$ are the constraints of the torque ripple and the axial magnetic force, respectively. In addition, $(X_i)$ is the $i$th design variable of the HDD spindle motor. Figure 3 shows the four design variables chosen in this research. The design optimization problem was solved by using the metamodel-based design optimization technique. To determine the optimal solution, the progressive quadratic response surface method was used as an optimization method. First, the torque constant, torque ripple, and axial magnetic force were determined by using the applied current. Second, the iron loss was determined by using Eq. (3). Third, the copper loss was determined by multiplying the square of the current and the calculated resistance. The number of coil turns of the current model was then determined by using the linear relation of the torque constant and the number of coil turns. Finally, the electromagnetic loss was calculated by summing the copper and iron losses.

III. RESULTS AND DISCUSSION

Table II shows the specifications of the conventional motor and the proposed motor, which are determined by solving the optimization problem. Table III shows the analysis results of the conventional and the proposed motors. Figure 4 shows the torque variation of the conventional and proposed motors. They show that the proposed motor has almost the same level of torque with less torque ripple. The proposed model has a larger slot area and a thicker coil diameter than the conventional model, which decreases the resistance of the coil winding, resulting in a 29.3% reduction in the copper loss. Figure 5 shows the magnetic field of the stator core of the proposed model, and it shows that the proposed model has less saturation. The iron loss generated in the pulling plate of the conventional model does not exist in the proposed motor, however, the axial part of the stator core and the PM generate the axial magnetic force. The overall electromagnetic loss in the proposed model is thus decreased by 35% compared with that of the conventional model.

IV. CONCLUSIONS

In this research, we proposed a highly efficient structure for a BLDC motor utilizing both radial and axial air gaps. The proposed structure decreased the electromagnetic loss by 35%. This result can contribute to the development of an efficient motor.

ACKNOWLEDGMENTS

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