Design and Analysis of a Permanent Magnet Synchronous Motor Considering Axial Asymmetric Position of Rotor to Stator

Tapas Ku Benia, Ashok Kumar Sahani, Ashok Kumar Sahani, Arunakumar Rout
Department of Electrical Engineering, NM Institute of Engineering and Technology, Bhubaneswar, Odisha
Department of Electrical Engineering, Raajdhani Engineering College, Bhubaneswar, Odisha
Department of Electrical Engineering, Aryan Institute of Engineering and Technology, Bhubaneswar, Odisha
Department of Electrical Engineering, Capital Engineering College, Bhubaneswar, Odisha

ABSTRACT: This paper presents the design and analysis of a permanent magnet synchronous motor (PMSM) considering the axial asymmetric PM overhang for smart actuator applications such as an isokinetic exercise machine. This structure helps take advantage of the motor space effectively and makes the system small in size and light in weight. However, two drawbacks related to the performance of the motor occur when the axial asymmetric PM overhang is used: (1) an axial attractive force (AAF) is created, which can produce motor noise and vibration; (2) the torque of the motor is reduced compared with the symmetric PM overhang model. We used five steps to solve these problems. Firstly, the AAF according to the variation in axial position of the rotor to the stator was calculated and analyzed. Secondly, the torque was calculated under the same conditions to confirm that the system requirements were satisfied. The three-dimensional finite element analysis was used to determine the AAF and torque. Thirdly, the appropriate axial position of the rotor to the stator was suggested considering the analysis results and space inside the housing. Next, the commercial bearing type was chosen so that the total force acting on the bearing was below the bearing load limit to ensure motor stability. Finally, a prototype model was made and tested to confirm the accuracy of the analytical results. Through this study, by using the axial asymmetric PM overhang, the total length of the SA was reduced by 5 mm and the performance of the motor was guaranteed.

Keywords: axial asymmetric permanent magnet overhang; axial attractive force; groove ball bearing selection; isokinetic exercise machine; permanent magnet synchronous machine; smart actuator

I. INTRODUCTION

Smart actuators (SAs) composed of modules integrating an electric motor, gear reducer, and controller, which are widely developed as driving modules for robots, are used in many applications to make the compact system. In this study, we examined when SAs are used as an electrical load on an isokinetic exercise machine (IEM), and described the design and analysis of the electric motor that constitutes the SA. IEM is a machine that controls the speed of contraction within the range of motion. It is widely used in rehabilitative activities or sports rehabilitation [1]. The main components of an IEM system are shown in Figure 1a. The electric load mainly consists of a controller, electric motor, and reduction gear. Conventionally, the three main components of the electric load are replaced separately, creating the conventional electric load, as shown in Figure 1b. However, since the space for the system is limited, using a SA type electric load is useful, as shown in Figure 2. The SA module can help simplify the system structure, improve reliability, and create a compact system [2]. Researchers are interested in the permanent magnet synchronous motor (PMSM) design for SA module to achieve high efficiency and high power density, which can be designed using optimal design techniques or the PM overhang to generate more magnetic flux in the air-gap [3–16]. Most PMSMs use a PM overhang structure in the rotor to operate the Hall effect sensor for cost-saving and a simplified motor structure [4].

Figure 1. (a) Isokinetic exercise machine system and (b) conventional electric load.
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Therefore, we investigated the value of AAF according to the axial position of the rotortothestator. The torquevaluesalsoaffected bythe asymmetricPMoverhang, so we calculated the torque to ensure that the system requirement was satisfied. Both AAF and torque were determined using three-dimensional finite element analysis (3-D FEA). Afterward, the commercial bearing was selected to ensure the stability of the motor. Considering the analysis results together with the actual dimension of the motor, the appropriate axial position of the rotor to the stator was determined. Finally, the analysis results were validated by the experiment.

II. PROPOSED MODEL DESCRIPTION

Several periodically 3-D analysis models of the PM motor with different rotor core to stator core positions are shown in Figure 4, in which Dx is the distance between the mechanical centers of the rotor and stator. The motor is symmetrical when Dx = 0 mm, i.e., the symmetrical model has 5 mm of PM overhang on both sides. The concentrated winding with the 20-pole and 24-slot model is designed to have a lower end-winding length and lower copper loss. The axial length of the rotor is 10 mm longer than the stator’s axial length, i.e., 5 mm of PM overhang for each side in the axial symmetrical model. The design target is to meet the torque requirement and obtain high efficiency. Table 1 shows the output performance requirements and dimensions of the motor.

Figure 4. Periodic three-dimensional (3-D) analysis model, when Dx, which is the distance between the stator center and rotor center, is (a) 0, (b) 5, and (c) 15 mm.

Table 1. Specifications of the analysis model.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power</td>
<td>1.5</td>
<td>kW</td>
</tr>
<tr>
<td>(Continuous operation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum output power</td>
<td>1.5</td>
<td>kW</td>
</tr>
<tr>
<td>(Instantaneous operation, 30s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated speed</td>
<td>340</td>
<td>rpm</td>
</tr>
<tr>
<td>Rated torque</td>
<td>26.7</td>
<td>Nm</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>180</td>
<td>mm</td>
</tr>
<tr>
<td>Rotor inner diameter</td>
<td>90</td>
<td>mm</td>
</tr>
<tr>
<td>Length of stator</td>
<td>90</td>
<td>mm</td>
</tr>
<tr>
<td>Length of rotor</td>
<td>108</td>
<td>mm</td>
</tr>
<tr>
<td>Air gap</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Cooling type</td>
<td>Natural cooling</td>
<td></td>
</tr>
</tbody>
</table>

III. AAF ANALYSIS DUE TO ASYMMETRIC PM OVERHANG

Due to the asymmetric configuration, the 3-D FEA was used to calculate the AAF values. The magnetic field can be solved using commercial software (3D Maxwell, ANSYS, Inc., USA). The virtual work method is used to determine the axial attractive force and magnetictorque [18].

\[
W_{mag} = \frac{1}{2} Y B H / 4
\]

\[
AAF = \frac{\partial W_{mag}}{\partial z}
\]

\[
T = \frac{\partial W_{mag}}{\partial z} = F \times R_{mag}
\]
where $W_{mag}$ is the total stored magnetic energy, $B$ is the magnetic flux density, $H$ is the magnetic field, $z$ is the axial displacement, $F_\theta$ is the force in the $\theta$-direction, and $R_{rotor}$ is the radius of the outer rotor.

Figure 5 shows the periodic analysis model of the PM motor. Since the model has a fractional slot per pole configuration, which is 20-pole and 24-slot, a 1/4 periodic of the machine was modeled in 3-D FEA. The Neumann boundary condition was applied to reduce the analysis time. The model with symmetrical PM overhang has a 5 mm on both sides. The air-gap flux density distribution in both symmetric and asymmetric models is shown in Figure 6. In the case of the symmetric model, the air-gap flux density is distributed symmetrically on both sides of the overhang region. In contrast, the asymmetric model generates asymmetrical flux, which produces AAF and motor vibration.

![Figure 5. Periodically analysis model by using 3-D finite element analysis (FEA) (number of triangle elements is about 400,000): (a) symmetrical and (b) asymmetrical models.](image)

![Figure 6. Air-gap flux density distribution: (a) symmetrical model and (b) asymmetrical model.](image)
With variation in $D_x$, the value of AAF is as shown in Figure 7a. AAF is 0 N when $D_x = 0$, indicating that the motor is symmetrical. AAF increases dramatically when $D_x$ is less than 9 mm. After that point, AAF tends to be constant. The torque gradually decreases by about 11.4% when $D_x$ increases from 0 to 15 mm.

For a more visual perspective of the change in AAF and torque according to the variation in $D_x$, torque was normalized at $D_x = 0$ mm and AAF was normalized on the basis of $F_{\theta}$ at $D_x = 0$ mm, which are defined as torque percent ratio and AAF percent ratio, respectively, as shown in Figure 7b. The torque percent ratio decreases slightly as $D_x$ increases from 0 to 3 mm, and increases dramatically as $D_x$ is over 3 mm. On the contrary, the AAF percent ratio significantly increases by 20% as $D_x$ changes from 0 to 3 mm and remains at almost 50% of $F_{\theta}$ when $D_x$ is over 3 mm.

To choose the proper position of the rotor to the stator, the bearing position and space inside the housing should be considered. Combined with the analysis results, we find that 5 mm is a reasonable axial position of the rotor to the stator, as shown in Figure 8. At $D_x$ of 5 mm, the torque is 30.26 Nm, which satisfies the system requirements.

**Figure 7.** (a) The change in axial attractive force (AAF) and torque values according to the variation in $D_x$, and (b) AAF and torque percent ratio.
IV. BEARING SELECTION CONSIDERING AXIAL ATTRACTIVE FORCE

To select the correct bearing for each application, several factors need to be considered, such as allowable space, bearing load (magnitude, direction), and rotational speed. For this studied motor, both axial and radial forces act upon the bearing. In the previous section, the axial force caused by axial asymmetry of the motor was determined, which is 99.27 N. We assumed that the motor is ideally symmetrical in the radial direction; thus the radial magnetic forces eliminate each other on the bearing. Therefore, the weight of the rotor and the rotational force (tangential component of the force) that generates the motor torque are considered radial loads. Since the maximum torque is less than twice the rated torque and the main operating point is the rated torque range, the rotational force was calculated based on the rated torque. To consider the maximum load on both bearings, we used the case where the direction of gravity to the rotor coincides with the direction of rotational force. The radial load was calculated by multiplying the sum of the two loads by a load factor of 1.2 (the value for the environment with little external impact on the shaft [19]). The load acting on each bearing was calculated using the moment equilibrium equation [19,20]. We chose deep groove ball bearings in this study because they can carry both axial and radial loads and have outstanding noise and vibration characteristics. Since the inner ring rotates, the value of the rotational coefficient \( V \) is 1 in Equation (4), so the equation of equivalent load on the ball bearing is as expressed in Equation (5).

The equivalent radial load acting on the ball bearing is calculated by [20]

\[
Pr = X \cdot Fr + Y \cdot Fa \tag{4}
\]

\[
Pr = X \cdot Fr + Y \cdot Fa = 0.496 \text{kN} \tag{5}
\]

where

- \( Pr \) is the dynamic equivalent radial load N,
- \( Fr \) is the actual radial load N,
- \( Fa \) is the actual axial load N,
- \( X \) is the radial load factor,
- \( Y \) is the axial load factor,
- \( V \) is the rotational factor.

The values for \( X \) and \( Y \) are listed in the bearing table provided by the manufacturer [20]. Considering the allowable space for the bearing and the bearing load limit, we used the 6205-ZZ bearing (NTN Bearing Corporation, Japan) in this study.

V. EXPERIMENTAL VALIDATION

1.1. Resistance and Back Electromotive Force Comparison

To check whether the prototype was manufactured exactly as the designed model, the resistance and back electromotive force (backEMF) were measured using a dynamo system as shown in Figure 9. The data were acquired using the dynamo user interface and power analyzer. Table 2 presents the comparison of phase resistance and back EMF between the calculated values and experiment results for the symmetrical model. It was clearly observed that the error...
between the calculated and measured values was acceptable, at under 5%.

![Image](image1.png)

**Figure 9.** The experimental setup to measure the back electromotive force value.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Calculated Value</th>
<th>Measured Value</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase resistance</td>
<td>Ω</td>
<td>0.66</td>
<td>0.664</td>
<td>0.6</td>
</tr>
<tr>
<td>Phase back EMF constant</td>
<td>Vrms/rpm</td>
<td>0.13</td>
<td>0.12</td>
<td>4.6</td>
</tr>
</tbody>
</table>

1.2. Measurement of Axial Attractive Force

The force measurement system was setup, as illustrated in Figure 10. The load cell (BDHS–1t) was used to measure the AAF value. A coupling is used to connect the motor shaft with the hand-wheel. When the hand-wheel turns in the clockwise direction, the rotor moves along the +z-direction, and vice versa. Each 180° rotation of the hand-wheel, the rotor linearly moves 1.1 mm. Therefore, the AAF depending on the rotor position with respect to the stator core was measured.

The comparison between the calculated and experimental values is shown in Figure 11. The AAF value increases as the axial position of the rotor core to the stator core increases. Similar to the analysis results, the measured value tended to be constant when Dx exceeded 9 mm. The experiment results are consistent with the analysis results.

1.3. Isokinetic Exercise Machine Test

After the motor had been tested separately, it was assembled together with a controller and reduction gear to create the smart actuator type electric load as shown in Figure 2. Both isotonic exercise mode and isokinetic exercise mode tests were implemented to check the performance of the system, as shown in Figure 12a.

In the isotonic mode, the same force is applied in the pedal and the value of force depends on selecting a resistance between 0 to 100%, while in the isokinetic mode, the constant speed is maintained regardless of the force exerted in the pedal. Both help to increase muscle endurance and muscle strength. In addition, training in the isokinetic mode also reduces the risk of injury. The torque value was measured in the two training modes and results are shown in Figure 12b,c. The experiment results show that the isokinetic exercise machine works well in both training modes.

![Image](image2.png)

**Figure 10.** The experimental setup for the measurement of AAF.
VI. CONCLUSIONS

In this paper, the design and analysis of a PMSM were proposed considering the axial asymmetric position of the rotor to the stator for efficient use of space inside the motor. Due to the axially asymmetrical motor, the Z-thrust force appeared, which may cause motor noise and vibration, and torque was reduced. To maintain the performance of motor, we numerically and experimentally investigated the axial force and torque according to the axial position of the rotor to the stator. Considering the available space for the bearing, and the simulation results, we found that 5 mm is the axial offset position of the rotor core center to the stator core center, which means that the axial length of the motor can be decreased by up to 5 mm. At a 5 mm axial offset position of the rotor to the stator, torque was reduced by 1.7% in comparison to the symmetric overhang PM model, which still met the system requirement. The process of how to choose a bearing to maintain the stability of the motor was also presented.


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REFERENCES


[18] Ansys Corporation. “Maxwell online help”, Maxwell 18.0. Available online: h t t p s : / / w w w . s c r i b d . c o m / document/

