Performance comparison of axial-flux-modulated motor with two pole-slot combinations

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Abstract: Axial-flux-modulated motors (AFMMs) with two pole-slot combinations are presented and analyzed quantitatively. They all have new topology structures, and their design rules differ from those of the traditional machine. The concentrated stator windings are designed to reduce the end length and copper losses; therefore, the efficiency of the motors can be improved. Special iron segments in the air-gap are used to modulate the magnetic field. The two proposed AFMMs have 36 stator slots and 30 stator slots, respectively, and the pole-slot combinations are 6 poles for 36 slots and 4 poles for 30 slots. This paper focuses on the comparative performance analysis of the two proposed AFMMs by using the 3D time-stepping finite element method. The flux linkage, air-gap flux density, electromotive force waveforms, output torque, core losses, and efficiency of the two proposed AFMMs have been investigated.

Key words: Axial-flux-modulated motor, low-speed, torque density, 3D time-stepping finite element method

1. Introduction

In many applications, high torque density, high power density, high efficiency, high controllability, and low-speed drive systems are significantly required, such as in motorcycles, trains, vessels, wind power generators, and electric motors [1,2]. Low-speed direct-drive gearless machines are more meritorious than their high-speed counterparts with gear boxes because the former have no associated gears and no related problems such as oil maintenance, noise issues, losses, and so on. However, conventional direct-drive machines suffer from bulkiness and low efficiency. Recently, magnetic gears, which have a highly competitive torque transmission capability, have been proposed to replace the mechanical gear. The magnetic gear can be directly combined with a conventional permanent magnet motor with the outer-rotor structure housed inside a frame [3–7]. The system torque density can be significantly improved; however, the disadvantage is that such a system has two rotating parts and its mechanical structure is complicated. Based on the operating principle of magnetic gears, many structures have been studied, such as double rotor PM machines [8], radial-flux-modulated machines (RFMMs) [9], and axial-flux-modulated machines (AFMMs) [10]. The radial-flux-modulated magnetic-gear motor presented at a conference [9] has a simple structure; it integrates a magnetic gear with a conventional outer-rotor PM motor. It has only one rotary part. The outer rotor is equipped with NdFeB magnets and has 22 pole pairs. The stator has a three-phase concentrated winding, which produces a rotating magnetic field with 3 pole pairs. Between the outer rotor and the inner stator, there are 25 pieces of stationary iron segments made of silicon steel laminations, which can be exploited for modulating the air gap fields, and the outer rotor

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can rotate at low speed efficiently. Even though the overall size of the motor is more compact than a motor and gear combination, there are two air-gaps and hence it is expensive to produce. The low-speed AFMM presented in [10] has a 3-phase concentrated winding, which can produce a rotary magnetic field with 3 pole pairs, and the outer-rotor has 22 pole pairs. Twenty-five pieces of iron segments in the air-gap are used to modulate the magnetic field. Its manufacturing and assembling process are simple when compared with those of RFMMs.

Among the RFMM and AFMM structures, the manufacturing and assembling processes of the AFMMs are simplest. They can operate with high power density at low speed and hence can be used as direct drive applications. However, the outer-rotor of the machine has 22 pole pairs, and the supply frequency is 220 Hz, which will cause large iron losses and reduce the efficiency of the motor [11–13]. In order to reduce the core losses and improve the efficiency of the low-speed AFMMs, one of the solutions is to utilize some new materials to build the stator core, such as soft magnetic compound materials [14–17] and amorphous alloys materials, but this will increase the cost of production and the manufacturing process will difficult. The other important solution is to reduce the frequency of the supply voltage, and then the slots number of the stator, pole number of the stator, and the iron segments number must be redesigned.

In this paper, AFMMs with two pole-slot combinations (6 poles for 36 slots and 4 poles for 30 slots) are proposed and designed. Both of the AFMMs have the same outer-rotor with 22 PM poles and have 14 iron segments for the 6 pole-36 slot motor and 13 iron segments for the 4 pole-30 slot motor. When stator windings are supplied with 55 Hz AC currents, rotor speed of 300 rpm will be achieved. This paper focuses on the comparative performance analysis of the two proposed AFMMs by using the 3D time-stepping finite element method (TS-FEM). The flux linkage, electromotive force (EMF) waveforms, output torque, core losses, and efficiency of the two proposed AFMMs have been investigated.

This paper consists of 4 sections. The second section introduces the construction and operation principle of the AFMMs. In the third section, a performance comparison is made between the two proposed AFMMs by using the TS-FEM, and the fourth section presents the final conclusions.

2. Operation principle and construction of the AFMMs

The operation principle of AFMMs is based on the magnetic gear (MG) effect; that is, in MGs, the low-speed multipole-pair PM fields and high-speed fewer pole-pair fields can be magnetically coupled with one another through their flux modulating ferrite poles (stationary iron segments). The relative movement between the permeance and the magnetomotive force (MMF) of PMs will make the desired flux variation. A small movement of the low-speed PMs can get a large change in the flux and the rotating flux can interact with the high-speed MMF to rotate at the same synchronous speed [3,4]. Based on this principle, the high-speed low-torque output can be transferred through a specific gear ratio to the multipole PMs on the rotor and get the low speed and high torque results correspondingly. According to the theory of magnetic gears [3,4], the gear ratio $G_r$ of the stationary iron segments and the speed of the space flux density produced by either the high-speed fields or low-speed rotor PMs is given by:

$$ G_r = (N_{iron} - P_H)/P_H $$

$$ n_L = n_H/G_r $$

where $N_{iron}$ is the number of stationary iron segments and $P_H$ is the pole pair number of the high-speed fields. $n_L$ is the rotating speed of low-speed magnetic fields (outer rotor) and $n_H$ is the rotating speed of the
high-speed magnetic fields. The pole pair number of the outer-rotor is given as \( P_L \), and then the relationship among \( N_{\text{iron}} \), \( P_H \), and \( P_L \) can be expressed as follows:

\[
N_{\text{iron}} - P_H = P_L
\]  

(3)

In AFMMs, the basic principle is the same, which means that the MMF created by PMs is modulated by the air-gap permeance and hence a desired high-speed flux variation is produced. The major difference is that the high-speed MMF is produced by the stator windings rather than by the PMs.

The 3D geometry structure of an AFMM is shown in Figure 1. The stator is located in the center of the motor, and the two outer PM-rotors are symmetrical on both sides of the stator. The coils on the two sides of the stator core are wound toroidally to shorten the length of the end windings sharing a common back iron, therefore decreasing the copper losses and improving the power density. The stator slot has good heat dissipation because of the ventilating ducts between the iron segments. Stationary iron segments are located between the stator and the outer PM rotors, and they modulate the magnetic field produced by the stator windings so that the number of pole pairs of one high-order harmonics is the same as that of the outer PM-rotors. Therefore, the positive average output torque can be produced [10].

![Figure 1. Configuration of an AFMM.](image)

In order to analyze the performance of the two proposed AFMMs, the Maxwell 3D solvers commercial software package (ANSYS Electromagnetics Suite 15.0) that uses finite element analysis (FEA) to solve electromagnetic field problems is employed to create the 3D geometric model of the AFMM. First we open a new Maxwell 3D project, and then draw all of the objects of the proposed motor using the modeling commands. Figure 2 shows the drawing process of the stator core and the stator winding. The stator core is built by cutting and subtracting the shapes of cylinders and rectangles. The independent winding is built by subtracting, uniting, splitting, moving, and rotating the rectangular and circular shapes, and then moving to embed it in the stator slot. The other objects, such as the symmetrical iron segments, PMs, and rotor yokes, are built by splitting the cylinders. Finally, it is essential to simulate the AFMMs to create the band and outer portion.

![Figure 2. Creating the 3D model of stator core and stator winding.](image)
In this paper, two pole-slot combination AFMMs are presented, and the 6 pole-36 slots motor is referred to as motor I and the 4 pole-30 slots motor is referred to as motor II.

For motor I, the pole pair number of the outer-rotor PMs $P_L$ is 11, and the number of stator pole pairs $P_H$ is 3. The number of stationary iron segments $N_{iron}$ is 14. The stator slots are designed in independent form to place the concentrated windings. According to Eq. (1), the gear ratio of the stationary iron pieces for motor I is $G_{rI} = (14 - 3)/3 = 11/3$. When the stator windings are fed with 55 Hz AC currents, then the rotating speed of the magnetic fields of stator $n_H$ is 1100 rpm, that is $n_H = (60 \times 55)/3 = 1100$ rpm, and then according to Eq. (2) the speed of the outer rotor $n_L = n_H / G_{rI} = (1100/11) \times 3 = 300$ rpm. If the supply frequency is set to 44 Hz, 33 Hz, and 22 Hz, then the speed of the outer rotor will be 240 rpm, 180 rpm, and 120 rpm, respectively. With such low rotating speeds, the motor can be used as a direct drive system without gearboxes.

For motor II, it is obvious that the structure is similar to that of motor I. The pole pair number of the outer-rotor PMs $P_L$ is also 11, but the stator has 2 pole pairs, i.e. $P_H = 2$. The number of stationary iron segments $N_{iron}$ is 13. According to Eq. (1), the gear ratio of the stationary iron pieces for motor II is $G_{rII} = (13 - 2)/2 = 11/2$. When the stator windings are fed with 55 Hz AC currents, then the rotating speed of the magnetic fields of stator $n_H$ is 1650 rpm, and then according to Eq. (2) the speed of outer rotor $n_L = n_H / G_{rII} = (1650/11) \times 2 = 300$ rpm.

The sizing of the proposed AFMMs starts with a comparison and the AFMM presented in [10]. By trial-and-error, the key design data of the two proposed motors are determined with the design specifications as listed in Table 1. In Table 1, the air-gap between stationary iron segments and stator is 0.6 mm, the same as that of the air-gap between PM and stationary iron segments. According to the comparison principles, the two motors being studied have the same outside radius and axial length, the same copper and PM materials, and the same current densities.

Table 1. Key design data of the two motors.

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Motor I</th>
<th>Motor II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rotation speed of outer rotor (rpm)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Number of outer rotor pole pairs</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Number of stationary iron segments</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Number of stator pole pairs</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Number of conductors per slot</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Rated current density of per slot (A/mm$^2$)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Remanence of PMs (T)</td>
<td>1.23</td>
<td>1.23</td>
</tr>
<tr>
<td>Total axial length (mm)</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>Outside radius of outer rotor (mm)</td>
<td>101</td>
<td>101</td>
</tr>
<tr>
<td>Inside radius of outer rotor (mm)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Outside radius of stator (mm)</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Inside radius of stator (mm)</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Thickness of PMs (mm)</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Thickness of stationary iron segments (mm)</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Thickness of stator windings (mm)</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Air-gap length (mm)</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Taking the example of motor I, the magnetic flux circuit in the axial sectional view is shown in Figure 3. The flux circuits produced by PMs and stator windings are both independent circuits, which include two air-gaps and two iron segments. In different pole positions, the magnetic flux line direction of the two magnetic circuits will be the same or different, and it has no effect for iron segments to modulate the space magnetic field.

3. Performance comparison of the proposed two AFMMs

The performance evaluation of the two proposed AFMMs is based on a 3D TS-FEM analysis using the Maxwell 3D solvers commercial software package (ANSYS Electromagnetics Suite 15.0). The 3D transient nonlinear model of the AFMMs with practical geometries of stator and rotor laminations is developed. Nonlinearity of core materials is fully taken into consideration. The credibility of 3D FEM simulation results by using the Maxwell 3D solvers commercial software package has been validated in many studies.

In [18], the output torque of a 303 kW internal permanent magnet synchronous motor was simulated by ANSOFT commercial software, and it was validated by the experimental results with 4.5% error. In [19], the magnetic Maxwell 3D analyzer of ANSOFT was used to verify the prototype motor performance and to refine the motor geometries by numerical calculation on the 3D motor configuration. In [20], an axial flux inner stator-non slot type permanent magnet motor was designed and simulated by using ANSOFT Maxwell 3D electromagnetic simulation finite element method (FEM) software. The experimental results were obtained and compared with the FEM simulation results with 4.1% error. In [21], the performances of a 3-kW, 8-pole axial flux surface magnet disk type machine with double-rotor-single-stator was analyzed by using the FEA ANSOFT Maxwell 3D software, which is extremely accurate for solving complex electromagnetic field problems.

Therefore, the built 3D TS-FEM simulation model in this paper is considered to be sufficient and can give satisfactory results. The ferromagnetic material used in the FEM simulation is the silicon steel sheet (steel_1011) that constitutes the material of the stator core, rotor core, and iron segments. Its nonlinear flux density and field strength (BH) curve is given in Figure 4. The entire magnetic field for the AFMM is necessary to compute. The mesh maps of the two AFMMs are shown in Figures 5a and 5b, respectively. Considering the great importance of the FEM results, the density of the mesh elements must be sufficient. However, a great number of elements will increase the computation time. Hence, the mesh is a choice, taking into account the necessity of accurate results and an acceptable computation time. For motor I, the number of elements is 141,654, and there are 131,986 elements for motor II. During the full-load simulation of two AFMMs, the simulation time is set to 0.1 s, and the simulation step is set to 0.0001 s. The CPU time for solving the 3D-FEA equation is 15 h, 46 min, and 23 s for motor I and 13 h, 50 min, and 37 s for motor II.
3.1. Performance simulation of locked-rotor operation for two AFMMs

In the 3D TS-FEM model of the AFMMs, the outer rotor is set to stall and the stator windings are excited with the rated sinusoidal current (180 A). Then the torque waveforms versus time of the two AFMMs can be computed as shown in Figure 6. From Figure 6, we can find that the maximum locked-rotor torque values of the two AFMMs are 111.53 Nm and 70.49 Nm, respectively, and motor I has higher torque density than motor II.

3.2. Performance simulation of no-load operation for two AFMMs

When the 3D finite element simulation models of the machines are run in no-load condition, the current excitation is set to zero and the rotor rotates at rated speed (300 rpm). Then the EMF and cogging torque of the two AFMMs can be computed, as in Figures 7a, 7b, and 8, respectively. From Figures 7a and 7b, it
is noted that the induced voltages of the two AFMMs both have sinusoidal waveforms. The amplitudes of EMF of the two AFMMs are 25 V and 30 V, respectively, and the EMF of motor II is larger than that of motor I. In Figure 8, it is noted that the average cogging torque of motor II (0.2 Nm) is smaller than that of motor I (0.45 Nm), and the cogging torque ripple of motor II is also smaller than that of motor I, because the fractional slot windings are designed for motor II. Due to the double rotor topology, the misalignment between them introduces unbalances that may increase the cogging effects. Therefore, some cogging torque reduction techniques such as the stator slot displacement technique and rotor pole skew configuration should be used, and the structure parameters of the motors should be optimally designed. Investigation of cogging torque reduction for the proposed AFMMs will be reported in a future paper.

![Figure 7. a) EMF waveforms at no-load condition of motor I (36 slots). b) EMF waveforms at no-load condition of motor II (30 slots).](image)

![Figure 8. Cogging torque waveforms of the two motors.](image)

### 3.3. Full-load simulation of two AFMMs

When the 3D finite element simulation models of the machines are run in full-load condition, the stator windings are excited with three-phase sinusoidal alternating currents (180 A) with a constant initial phase, and with 55 Hz of frequency, the rotating speed of the outer rotor will be 300 rpm. In order to ensure that the current density of the two AFMMs is the same, the coil turns of the two stator windings are different, with 10 turns for motor I and 15 turns for motor II. Then the flux linkage waveforms of the two AFMMs are as shown in Figures 9a and 9b, respectively. The flux linkages of the two AFMMs are the sine wave and three phases of the flux linkage waveforms for the two motors are balanced at the same time. On account of the excitation of various currents, the amplitude of flux linkage curves is larger than that in no-load situation.

The axial air-gap flux density diagram and the FFT results of the two motors are shown in Figures 10a, 10b, 11a, and 11b, respectively. Figures 10a and 10b show the axial component of air-gap flux density close to the stator of motor I and motor II, and we can see that the magnitude of the operational harmonics (3rd and
11th) of motor I are 0.48 T and 0.3 T, while those of motor II are 0.37 T and 0.23 T. Figures 11a and 11b show the axial component of air-gap flux density close to the PMs of motor I and motor II. It can be seen that the magnitude of the 3rd harmonic (0.2 T) and 11th harmonic (1.0 T) of motor I are larger than those of motor II (0.1 T for the 3rd harmonic, 0.79 T for the 11th harmonic). This shows that the air-gap flux density of motor I is larger than that of motor II, and the modulation effect of motor I is stronger than that of motor II in terms of the criteria of air-gap flux density for the AFMMs (0.8–1.2 T); therefore, the output torque of motor I will be larger than that of motor II.

Figure 9. a) Flux linkage waveforms at full-load condition of motor I (36 slots). b) Flux linkage waveforms at full-load condition of motor II (30 slots).

Figure 10. a) The axial air-gap flux density close to stator for motor I (36 slots). b) The axial air-gap flux density close to stator for motor II (30 slots).

The face flux density diagrams of air-gaps for the two motors are shown in Figures 12a, 12b, 13a, and 13b. When the AFMMs run at 0.02 s, the 3D plots of flux density of the two motors are shown in Figures 14a and 14b, respectively. We can find that the stators for the two motors have more saturation than the rotor yokes.

In the full-load condition, owing to the saturation of the magnetic field of the motors, the EMF waveforms of the two AFMMs are no longer the normal sinusoidal waveform; there are some harmonics in the EMF.
Figure 11. a) The axial air-gap flux density close to PMs for motor I (36 slots). b) The axial air-gap flux density close to PMs for motor II (30 slots).

Figure 12. a) The face flux density of air-gap close to stator for motor I (36 slots). b) The face flux density of air-gap close to stator for motor II (30 slots).

Figure 13. a) The face flux density of air-gap close to PMs for motor I (36 slots). b) The face flux density of air-gap close to PMs for motor II (30 slots).
waveforms. The harmonic analysis of the EMF of the two motors is shown in Figures 15a and 15b, respectively, and it can be seen that the amplitude of the fundamental wave of the two AFMMs is 42 V for motor I and 45 V for motor II, and the 3rd and the 5th harmonics of motor II are larger than those of motor I. Therefore, the EMF waveform of motor I is closer to the sine wave.

The output torque of the two AFMMs can be computed and is shown in Figure 16. The output torque for motor I is about 96.55 Nm, and for motor II it is about 65.01 Nm. Motor I produces about 33% higher

Figure 14. a) The 3D plot of flux density for motor I (36 slots) at 0.02 s. b) The 3D plot of flux density for motor II (30 slots) at 0.02 s.

Figure 15. a) Harmonic contents of EMF at full-load condition of motor I (36 slots). b) Harmonic contents of EMF at full-load condition of motor II (30 slots).
torque when compared to motor II. This is because the air-gap flux density of motor I is larger than that of motor II, and the modulation effect of motor I is stronger than that of motor II.

At the same time the relative phase angles are changed as a parameter of the torque production. The torque production by 3D TS-FEM analysis is directly based on the magnetic field density and intensity on each element. The results are considered accurate because the complicated geometry of the AFMMs and nonlinearity of the materials are fully considered. The torque production of the two AFMMs as a function of the relative position angle between the two rotational magnetic fields is shown in Figure 17 for the rated current levels (180 A). From Figure 17, we can find that the maximum torque of motor I (100 Nm) is larger than that of motor II (80 Nm).

In Figure 18, owing to the slot number of motor II (30) being smaller than that of motor I (36) and the core weight of motor II being larger, the core losses of motor II (24.74 W) are slightly larger than those of motor I (22.64 W). From all the simulation results, the performances of the two AFMMs are summarized in Table 2. The output power of the two motors is 3.03 kW for motor I and 2.04 kW for motor II, and the efficiency of both of the two AFMMs exceeds 94%. Therefore, it is noticed that motor I can achieve high torque density, high power density, and high efficiency at the same time with the same size; therefore, it has more potential to be applied in low-speed direct-drive system applications.

4. Conclusion
In this paper, low-speed AFMMs with two pole-slot combinations are presented and analyzed quantitatively. The two proposed AFMMs have 36 stator slots and 30 stator slots respectively and the pole-slot combinations are 6 poles for 36 slots (motor I) and 4 poles for 30 slots (motor II). The effects of the two pole-slot combinations for
Table 2. Performance results of the two AFMMs.

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Motor I</th>
<th>Motor II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locked-rotor maximum torque (Nm)</td>
<td>111.53</td>
<td>70.49</td>
</tr>
<tr>
<td>Output torque of full-load (Nm)</td>
<td>96.55</td>
<td>65.01</td>
</tr>
<tr>
<td>EMF of no-load (V)</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>EMF of full-load (V)</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>Average cogging torque (Nm)</td>
<td>0.45</td>
<td>-0.21</td>
</tr>
<tr>
<td>Output power (W)</td>
<td>3033.3</td>
<td>2041.1</td>
</tr>
<tr>
<td>Core loss (W)</td>
<td>22.64</td>
<td>24.74</td>
</tr>
<tr>
<td>Copper loss (W)</td>
<td>120.19</td>
<td>89.26</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95.5%</td>
<td>94.7%</td>
</tr>
</tbody>
</table>

AFMMs on flux distribution, EMF waveforms, cogging torque, air-gap flux density, output torque, core losses, and efficiency have been investigated by using 3D TS-FEM. From the simulation results, the conclusions can be obtained as follows:

1) The AFMM with 4 poles-30 slots (motor II) can achieve the higher amplitude of EMF under both no-load (30 V) and full-load operations (45 V). Its cogging torque (~0.21 Nm) and copper loss (89.26 W) are smaller than those of motor I. Therefore, motor II is a good choice in high-voltage applications.

2) For the AFMM with 6 poles-36 slots (motor I), its locked rotor torque (111.53 Nm), output torque (96.55 Nm), and output power (3033.3 W) are all larger than those of motor II. It has the higher torque density and higher power density. Although its copper loss (120.19 W) is larger than that of motor II (89.26 W), its core loss (22.64 W) is smaller than that of motor II, and finally its efficiency (95.5%) is higher than that of motor II (94.7%). Therefore, motor I has potential to be applied in high torque density, high power density, and low speed direct-drive applications.

Acknowledgment

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