A Novel Pseudo-Direct-Drive Permanent-Magnet Machine with Less Magnet

Xin Yin, Pierre-Daniel Pfister* and Youtong Fang

Abstract—Magnetic gears (MGs), an alternative to conventional mechanical gearboxes, have been extensively studied in the last decade. By combining the MG and the conventional permanent-magnet (PM) machine into one frame, different MG-integrated PM machines with a high torque density are obtained, among which the pseudo-direct-drive PM machine (PDD) features both a good torque capability and a high power factor with an acceptable structural complexity. However, the stator PM array in the conventional PDD obstructs the magnetic path and reduces the excitation torque due to the coils. Another problem is the large amount of PMs which increases the overall cost. In this paper, we propose a novel topology which has a reduced PM amount with an improved torque density. The working principles of the proposed PDD are analyzed theoretically and its performance is validated by time-stepping finite-element method (TS-FEM). A comparison study with the conventional topology is conducted to show its merits.

1. INTRODUCTION

In low-speed high-torque applications, mechanical gearboxes are widely used to reduce the rotating speed and boost the output torque. Since the torque transmission is based on the engagement of gear teeth, undesired side effects are inevitable such as friction losses, acoustic noise and vibration, lubrication requirement, and regular maintenance. In addition, the mechanical gearbox is vulnerable to overload, which reduces the reliability of the entire system. To solve these problems, the idea to use magnetic coupling instead of mechanical contact in gears emerged. The study on magnetic gears (MGs) revived since 2001 after the publication of Atallah and Howe, in which a coaxial topology of MG was proposed [1]. With high-performance rare-earth permanent magnets (PMs), the coaxial MG is capable to obtain a torque density which is comparable with mechanical gearboxes [2]. Although the radial MGs are extensively studied, the torque density of MGs can be further increased by using other flux orientations [3].

Compared with its predecessors, the coaxial MG not only has a superior torque capability, but also can be integrated with a conventional PM brushless machine due to its coaxial topology [4]. Numerous publications can be found on this topic, in which three integrated topologies are mainly adopted, viz. the magnetic-gearered machine (MGM) [5], the pseudo-direct-drive machine (PDD) [6], and the flux-modulated machine (FMM) [7]. Since there is only one layer of PM array and two air gaps in a FMM, the structure is simpler than the other two topologies. However, its torque capability is shown to be much lower. In addition, its low power factor is also a problem [8]. Although the MGM makes full use of the inner space of the MG which results in a very high torque capability, its structure with three air gaps is difficult to fabricate. In addition, the inner-stator configuration is not beneficial for heat dissipation. The PDD, which artfully fixes one layer of PM array on the inner surface of the stator, is more feasible for fabrication and meanwhile remains a high torque density. The external-stator structure is preferable from a thermal perspective. The slot area is also larger compared with a MGM. That is the reason

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why the PDD is the more attractive to industrial application and has already entered the market. The PDD in [6] is reported to have a torque density exceeding 60 Nm/L which is significantly higher than a normal PM machine. We choose this topology as our benchmark and it will be studied in detail in the following sections.

This paper aims to reduce the PM amount of PDD while improving its torque capability, and is arranged as below: Working principles of the PDD and its constraints are discussed in Section 2 with the superposition principle. A novel topology of PDD is introduced in Section 3 with reduced PM amount. In Section 4, a comparison study between the proposed PDD and the conventional PDD is conducted based on the time-stepping finite-element method (TS-FEM) considering saturation effect.

2. WORKING PRINCIPLES OF PDD

Due to the integration of a MG, the topology of a PDD (Fig. 1(a)) is more complex compared with that of a conventional PM machine, comprising an external stator with current windings, a stator PM array mounted on the inner surface of the stator lamination, a high-speed PM rotor (transmitter) in the center, and a ring rotor consisting of ferromagnetic flux-modulating pole pieces between the two PM arrays. The PDD can be regarded as an elegant combination of two components, i.e. a PM machine comprised of the stator and the transmitter, and a MG comprised of the stator PM array, the ring rotor and the transmitter. The transmitter is shared by both components. In stable operation, the transmitter experiences the torques exerted by both the stator windings and the MG, with the net torque being zero. In other words, the transmitter bridges the PM machine and the MG. The two components are coupled both mechanically and magnetically. On the one hand, the back iron of the stator PM array of the MG is provided by the stator tooth tips of the PM machine. On the other hand, the magnetic flux generated by the coils of the PM machine has to penetrate the whole structure of the MG.

The characteristics of the MG part is first investigated by leaving the coils open-circuit. In the absence of the stator PM array, the radial magnetic flux density distribution in the air gap adjacent to the stator PM array due the transmitter PM array is [9]

$$B_r(\theta) = F_r(\theta) \Lambda(\theta)$$

where $\Lambda(\theta)$ is the permeance function and $F_r(\theta)$ is the magnetic potential function of the transmitter PM array, which can be expanded as a Fourier series:

$$F_r(\theta) = \sum_{m=1,3,5,...}^{\infty} f_m \cos (mpu (\theta - \omega_t t - \theta_{t0}))$$

Figure 1. Schematic diagram of (a) conventional PDD and (b) Proposed PDD.
where \( p_t \) is the pole-pair number of transmitter PM array, \( \omega_t \) and \( \theta_{t0} \) are the angular rotating speed and the initial angular position of the transmitter, respectively, and \( f_k \) is the Fourier coefficient. Due to the modulating effect of the ring rotor, \( A(\theta) \) can be expressed as

\[
A(\theta) = \lambda_0 + \sum_{j=1,3,5,...}^{\infty} \lambda_j \cos (jn_r (\theta - \omega_r t - \theta_{r0}))
\]

(3)

where \( n_r \) is the number of pole pieces in the ring rotor, \( \omega_r \) and \( \theta_{r0} \) are the angular rotating speed and the initial angular position of the ring rotor, respectively, \( \lambda_0 \) is the average value of the permeance and \( \lambda_j \) is the Fourier coefficient. In order to use the space harmonic with the highest amplitude, the pole-pair number of the stator PM array is chosen to be \([1]\)

\[
p_s = n_r - p_t.
\]

(4)

Because the stator PM array is fixed, the relationship between the rotating speeds of the transmitter and the ring rotor is given by

\[
\omega_r = \frac{\omega_t}{G_r}
\]

(5)

where the gear ratio is

\[
G_r = \frac{n_r}{p_t}.
\]

(6)

Ignoring the power losses, the torque relationship is given by

\[
T_r = -G_r T_t
\]

(7)

where \( T_r \) and \( T_t \) are torques of the ring rotor and the transmitter due to the MG, respectively. Because \( n_r \) is much larger than \( p_t \), a reduction in speed and an increase in torque is obtained. In normal operation, there is no load connected to the transmitter, so at constant speed the net torque on the transmitter is zero. This net torque is the sum of the torque due to the MG (denoted by \( T_t \)) and the excitation torque due to the coil (denoted by \( T_{ex} \)).

Ignoring the saturation effect of steel, according to the superposition principle, the maximum output torque of a PDD is expressed as

\[
T_{omax} = \text{Min}(T_{MG}, G_r T_{ex})
\]

(8)

where \( T_{MG} \) is the stall torque of the MG. We can see that the output torque of a PDD is limited by either the torque capability of the MG or that of the PM machine. Usually they are contradictory in the PDD design. In order to get the optimal output torque, the match between the two is of vital importance \([10,11]\). The utilization factor is hence defined as

\[
U = \frac{G_r T_{ex}}{T_{MG}}.
\]

(9)

If \( U > 1 \), it means the torque capability of the PM machine is not fully used, otherwise the capability of the MG is underused. In an optimal design, \( U \) should be close to unity to make full use of both components. Similar to a conventional PM machine, \( T_{ex} \) is proportional to the line current density and to the magnetic flux density produced by the transmitter \([12]\]

\[
T_{ex} \propto A_m B_{mg1} \cos \psi
\]

(10)

where \( A_m \) is the peak value of the stator line current density, \( B_{mg1} \) is the peak value of the fundamental magnetic flux density produced by the transmitter in the air gap, and \( \psi \) is the angle between the phase current and back-EMF. Thus the second term in the parenthesis in (8) can be further derived as

\[
T_{ex} G_r \propto G_r A_m B_{mg1} \cos \psi
\]

(11)

Due to the introduction of \( G_r \), the torque of the PM machine is greatly amplified.
3. A NOVEL PDD WITH LESS MAGNETS

A major problem which reduces the output torque of a PDD is the relative long magnetic path. Due to the existence of the stator PM array and the ring rotor, the effective air-gap length \( g_e \) is much larger than that of a conventional PM machine which is usually less than 1 mm. Consequently, \( B_{mg1} \) in (11) is significantly reduced. To solve the problem of low excitation torque arisen from the existence of the stator PM array whose permeability is close to the permeance of air, researchers have proposed some improved topologies. In [13], the stator PM array is completely removed and the PDD is actually reduced to a FMM. As is mentioned in Section 1, the torque density becomes much lower. To improve the torque capability, another version was proposed [11]. The stator PMs are in the stator slots rather than on the stator inner surface, resulting a shorter magnetic path. However, the pole-pair number of the stator PMs has to be the same as the number of stator teeth. Consequently, the gear ratio \( G_r \) is less flexible and cannot go too high due to the restriction of the tooth number. For example, the gear ratio in [11] is only 3.4 which does not give a good torque capability according to (11). In addition, the PMs in the stator slots do not have a back iron which is thick enough to close the magnetic circuit, which significantly reduces the torque transmission capability of the MG (\( T_{MG} \)).

Although \( T_{ex} \) can be boosted by increasing the electric loading, copper losses will become larger and thermal condition deteriorates. As a result, the coils will be overheated and the surface-mounted stator PM array will be vulnerable to irreversible demagnetization. To address these problems, we propose a novel topology of PDD as is shown in Fig. 1(b). Compared with the conventional topology in Fig. 1(a), half of the stator PMs are replaced by ferromagnetic segments, resulting a split-tooth structure just like that of a Vernier PM machine [14]. The remaining stator PMs are inset in the space between the split teeth which is beneficial from mechanical point of view. It should be noted that all the stator PMs are radially magnetized in the same direction. In the prototype, the radially-magnetized PMs can be realized using techniques such as segmentation. The idea behind this is to increase \( T_{ex} \) by improving the magnetic path between the coils and the transmitter. In this way, we address the problem of the large effective air-gap length of conventional PDD.

4. COMPARISON STUDY

In order to verify the effectiveness of the proposed topology, a comparison study with the conventional PDD is conducted using the TS-FEM. This paper chose the structure in [6] as a benchmark since the structure has already been well designed and experimentally tested to obtain a high torque density exceeding 60 Nm/L. This paper adopts the same pole-pair combination, stator dimension, winding configuration, and materials as [6]. The gear ratio is 11.5. Three-phase sinusoidal current is fed into stator windings. The commonly-used zero-\( d \)-axis current (\( i_d = 0 \)) control strategy is adopted and thus the input current is in phase with the no-load back-EMF, viz. \( \cos \psi = 1 \) in (11). The thicknesses of the two PM arrays and the ring rotor of both machines, and the arc-span ratio of the proposed PDD are optimized respectively to get a higher output torque. Since the thickness of the ring rotor should not be too small in order to maintain sufficient mechanical strength, the lower limit of the ring-rotor thickness is set to be 9 mm. The highest root-mean-square (RMS) current density of the slots are restricted to be 2 A/mm\(^2\) for thermal safety. The arc-span ratio of the stator PMs is defined as

\[
\alpha = \frac{\beta_1}{\beta_2}
\]

where \( \beta_1 \) and \( \beta_2 \) are the angles of the PM arc span and the pole pitch, respectively (Fig. 1(b)). The variation of \( T_r \) with the transmitter position when the ring rotor is fixed is shown in Fig. 2(a). We can see that \( T_{MG} \) increases with \( \alpha \) due to the increasing stator PM. It should also be noted that due to the split-tooth structure, the peak position of \( T_{MG} \) of the proposed PDD is different from that of the conventional structure. On the other hand, the iron split teeth becomes smaller with a larger \( \alpha \), resulting in a reduction in \( T_{ex} \). The torque-current curves with the linear steel is shown in Fig. 2(b). \( T_{MG} \) with different \( \alpha \) is denoted by horizontal dashed lines. It shows that as \( \alpha \) increases, \( U \) becomes smaller, the restricting factor of \( T_{omax} \) in (8) changes from \( T_{MG} \) to \( T_{ex} \). The optimized results (Table 1) show that \( U \) of the conventional PDD is smaller than the proposed topologies, which agrees with the analysis in Section 3. On the other hand, \( U \) of the improved PDD can be changed flexibly by varying the
arc-span ratio $\alpha$. From Fig. 2(b), we see that the design with $\alpha = 0.6$ and $\alpha = 0.7$ can reach a similar maximum torque $T_{omax}$ below 2 A/mm$^2$. Although the design with $\alpha = 0.7$ exhibits a higher $T_{MG}$ than that with $\alpha = 0.6$, the latter has a higher $T_{ex}$ under the same excitation current. Moreover, the design with $\alpha = 0.6$ is less influenced by the saturation effect (discussed in Section 4.3.1). Consequently, we choose $\alpha = 0.6$ as our final design. The specifications of the two machines are given in Table 1.

4.1. Characteristics of the MG Part

The characteristics without the current excitation are first compared. The distribution and spectrum of the magnetic flux density generated by the transmitter PM array in the air gap adjacent to the stator PM array is shown in Fig. 3. From Fig. 3(a), the amplitude of the magnetic flux density of the proposed topology is significantly higher than the conventional one because of the improved magnetic path. From Fig. 3(b), we can see that in both conventional and proposed PDDs, a space harmonic with the pole-pair number of 21 which is the same as that of the stator PM array appears due to the existence of the ring rotor. This agrees with the theory discussed in Section 2. Because of the split-tooth structure, there are more harmonic components in the proposed PDD compared with the conventional one. In the proposed structure, the magnetic flux generated by the transmitter PM array is modulated not only by the 23 ferromagnetic pole pieces in the ring rotor, but also by the 21 slit teeth in the stator, resulting in the additional dominant harmonics with the pole-pair number of 19, and 23. These additional harmonics might introduce undesired distortion in the EMF waveform and increase the torque pulsation. Rotating the transmitter with the ring rotor fixed, the torque variation on the ring rotor is shown in Fig. 2(a). The MG stall torque of the proposed PDD ($\alpha = 0.6$) is 16.4% lower than that of the conventional PDD.

4.2. Characteristics of the PM-Machine Part

Ignoring the stator PM array, we get a PM machine with the split-tooth structure and the additional ring rotor. The schematic diagram together with its flux distribution are shown in Fig. 4(a). It can be seen that the split teeth between the stator PMs do conduct the magnetic flux and thus the average permeance viz. $\lambda_0$ in (3), of the proposed PDD is larger than that of the conventional one. The excitation torque $T_{ex}$ due to the coils on the transmitter is shown in Fig. 4(b), from which we see that the $T_{ex}$ of the proposed PDD is higher than that of the conventional one. However, due to the split-tooth structure, the torque ripple is also larger. The back-EMF waveforms are shown in Fig. 5. The back-EMF amplitude of the proposed PDD is 29.7% higher than the conventional one as a result of the improved magnetic path. The back-EMF waveform of the proposed PDD is slightly less sinusoidal compared to the conventional one.
Table 1. Specifications of the two PDDs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Winding pole-pair number</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Pole-pair number of transmitter PM array</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Pole-pair number of stator PM array</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Pole-piece number of ring rotor</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Overall outer radius</td>
<td>89</td>
<td>mm</td>
</tr>
<tr>
<td>Active axial length</td>
<td>75</td>
<td>mm</td>
</tr>
<tr>
<td>Outer radius of the stator PM array</td>
<td>64</td>
<td>mm</td>
</tr>
<tr>
<td>Slot opening</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of both air gaps</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Shaft radius</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Remanence of the PMs</td>
<td>1.25</td>
<td>T</td>
</tr>
<tr>
<td>Relative permeability of the PMs</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>Relative permeability of iron</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>Working frequency</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Rotating speed of the transmitter</td>
<td>1500</td>
<td>rpm</td>
</tr>
<tr>
<td>Rotating speed of the ring rotor</td>
<td>130.4</td>
<td>rpm</td>
</tr>
<tr>
<td><strong>Conventional topology</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of the stator PM array</td>
<td>4.5</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of the ring rotor</td>
<td>9</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of the transmitter PM array</td>
<td>16.1</td>
<td>mm</td>
</tr>
<tr>
<td><strong>Proposed topology</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of the stator PM array</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of the ring rotor</td>
<td>9</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of the transmitter PM array</td>
<td>13.9</td>
<td>mm</td>
</tr>
<tr>
<td>Arc-span ratio ρ</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Magnetic flux density due to the transmitter PM array in the air gap adjacent to the stator PM array, (a) distribution, and (b) spectrum.
4.3. On-load Characteristics

4.3.1. Saturation effects

In previous sections, the non-saturated iron is used in order to use the superposition principle so that the MG part and the machine part can be analyzed separately. Only in this way can $U$ be clearly defined and give more insight into the torque characteristics of PDD. Using linear materials also enables a optimization process with a reasonable computation cost and time consumption for the preliminary design. Nevertheless, it is important to evaluate the effects of saturation on the final results. We simulate both the conventional PDD and the improved PDD with the saturated steel 1010 with a relative permeability of 700 in the linear region and a saturated point at 2 T. Noting that the excitation RMS current density of the proposed PDD is increased to 2 A/mm$^2$ to compensate the saturation effect. It shows that although the torque capability of both structures decreases due to saturation, the proposed topology maintains a higher torque capability than the conventional one (Table 2).

4.3.2. Torque Characteristics

The comparison of the two structures is shown in Table 2. The torque density of the proposed PDD is 9.8% higher than the conventional one. Considering the reduction in PM amount, the torque per unit PM volume is increased by 35%.
Table 2. Comparison of the two structures considering saturation.

<table>
<thead>
<tr>
<th>PDD</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS Current density (A/mm²)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>120.1</td>
<td>131.9</td>
</tr>
<tr>
<td>Torque density (Nm/L)</td>
<td>64.35</td>
<td>70.67</td>
</tr>
<tr>
<td>Torque per unit PM (Nm/L)</td>
<td>269.63</td>
<td>363.98</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>2.1%</td>
<td>3.3%</td>
</tr>
<tr>
<td>PF</td>
<td>0.83</td>
<td>0.82</td>
</tr>
</tbody>
</table>

4.3.3. Power Factor

One of the advantages of PDD and MGM compared with the FMM is their high power factor. Assuming that the winding resistance is negligible, under the $i_d = 0$ control strategy, the power factor (PF) is approximated as

$$\cos \varphi = \frac{1}{\sqrt{1 + \left( \frac{X_q I_q}{E_1} \right)^2}}$$

(13)

where $X_q$ is the $q$-axis reactance, $I_q$ is the RMS value of $q$-axis current, and $E_1$ is the RMS value of the fundamental component of the back-EMF. The PF is determined by $X_q I_q / E_1$. On the one hand, the proposed PDD has a relatively large $X_q$ which will reduce the PF. On the other hand, the back-EMF $E_1$ is also larger, resulting an increase in the PF. The comparison of PF of the two structures are also shown in Table 2. We can see that both structures maintain a high power factor.

5. CONCLUSION

By decomposing the PDD into a MG and a PM machine, theoretical analyses indicate that its torque capability is restricted by the capability of either the MG part or the PM-machine part. A novel PDD is proposed which uses a split-tooth stator. The function of the split teeth is threefold. First, less PMs are used and the cost is reduced. Second, the split teeth help to conduct the magnetic flux. Consequently, the effective air gap of the PM-machine part is shortened and the excitation torque due to the coils increased. Third, the stator PMs are inset in the split teeth rather than surface-mounted, which helps to increase the mechanical robustness. The simulation results based on the TS-FEM show that the PM amount is reduced by 18.6% while the torque density is increased by 9.8%. The high power factor of the conventional PDD is maintained.

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