Buried PM inner rotor magnetic gear evaluation

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Abstract. Inner rotor SFPMR glued on the rotor surface with material of high compressive strength but low tensile strength cannot sustain the centrifugal force in the high-speed operation, thus require retaining sleeve. Electrical motor employ the retaining sleeve to increase the rotor strength, but so far in MG, there are limited design that employ this technique. Another method to avoid PM from displaced is by buried into the rotor yoke. However, this method may result in lower torque and noise. In this paper, new MG structure is designed. The inner rotor surface mount PM of magnetic gear is rearrange as buried PM. First, the torque analysis of the MG is simulated without counting any loses. Then, gear efficiency is simulated over high speed range and compared to the original topology to identify the amount of reduction of the torque. The result agrees that the buried rotor reduced the torque output 3 times lower than the surface mount PM and disturb the torque which result in high torque ripple over 240%.

1. Introduction
The topic of magnetic gears (MG) is of interest since the 19\textsuperscript{th} century with the earliest designs follows the conventional mechanical gears in which the gear teeth is replaced with permanent magnet (PM) [1,2]. However, these designs unable to create interest among the machine designer due to its low torque densities. The PM materials available at the time samarium–cobalt which has low remanance. As Neodymium magnets invented in 1980 by General Motors and Sumitomo Special Metals, MG designer began to equip this new material into MG [3–5]. In 2001, [5] introduced novel topology of MG named as the coaxial magnetic gear (CMG) whose principle of operation was based on the magnetic modulation produced by two PM rotors via the ferromagnetic pieces [6–8]. CMG has a higher torque density because the surface mount permanent magnet rotor (SMPMR) contribute simultaneously to the torque transmission. CMG was able to produce torque density up to 100KNm/m\textsuperscript{3}. Based on this principle, many improved CMG topologies were published and manufactured [9–14]. Figure 1 shows the structure of coaxial magnetic gear [15]. $\Omega_1$, $\Omega_2$ and $\Omega_3$ represent the rotational velocity of modulated magnetic flux.
Figure 1. Structure of coaxial magnetic gear

The ferromagnetic pole piece modulates the magnetic field in the air gap such that each rotor sees the corresponding pole number on the opposite rotor allowing for pole alignment and the gearing effect to be established. With the pole piece fixed and the inner and outer magnetic pole rotors allowed to rotate, the gear ratio, $G_r$, is express as follows [10].

$$G_r = \frac{p_l}{p_h} = \frac{n_p - p_h}{p_h} = -\frac{w_h}{w_l}$$

where $G_r$ is the gear ratio, $p_l$ is the outer rotor pole pair, $p_h$ is the inner rotor pole pair, $n_p$ is the number of pole piece, $w_h$ is the rotational speed of the inner rotor and $w_l$ is the rotational speed of the outer rotor. The negative sign indicates that the rotational direction is opposite to each other.

The speed of inner rotor is always higher than the outer rotor to satisfy the power transfer between two rotors.

$$P = w_h \tau_h = w_l \tau_l$$

where $\tau_h$ and $\tau_l$ is the torque at the inner rotor and outer rotor respectively.

The rotational force at the inner rotor come from the external source either from another electrical motor or combustion engine. The range of high speed obtained from electrical motor is around 20,000 rpm [16] used in compressors and aerospace application [17] while in combustion engine is below 10,000 rpm [18].

Inner rotor SFPMR glued on the rotor surface with material of high compressive strength but low tensile strength cannot sustain the centrifugal force in the high-speed operation, thus require retaining sleeve. Electrical motor employ the retaining sleeve to increase the rotor strength, but so far in MG, there are limited design that employ this technique [19][20]. Another method to avoid PM from displaced is by buried into the rotor yoke [21,22]. However, this method may result in lower torque and noise.

In this paper, new MG structure is designed. The inner rotor SFPMR of magnetic gear is rearrange as buried PM. First, the torque analysis of the MG is simulated without counting any loses. Then, gear efficiency is simulated over high speed range and compared to the original topology to identify the amount of reduction of the torque. The result agrees that the buried rotor reduced the torque output and disturb the torque which result in high torque ripple.
2. Magnetic gear design and simulation setting

2.1. Magnetic Gear structure
Figures 2 and 3 shows the structure of MG for the simulation. The inner rotor of buried MG has rectangular slot to place the PM adjacent to each other. The inner yoke holds together by the extended shaft in axial direction shown in Figure 4 as side view. The dimension of the MG is tabulated in Table 1. The pole pair of inner rotor, outer rotor and number of pole piece are 6, 14 and 20. The gear ratio for of this MG are 7/3 ~ 2.33.

![Figure 2. Structure of inner rotor buried PM MG](image)

![Figure 3. Structure of SFPMR MG](image)

![Figure 4. Side view of buried PM inner rotor structure and shaft](image)

2.2. Simulation setting
The magnet use in the simulation are NdFeB magnets. Rotor yoke and pole piece uses NSSMC 35H210. Finite element software is JMAG Designer 16.0. Transient analysis is selected to simulate the MG in dynamic condition. The first simulation analyses the torque when no loss is counted, at 700 rpm outer rotor speed and 300 rpm inner rotor speed. The second simulation analyse the gear efficiency degradation as the rotational speed increases counting eddy current losses. The rotation setting is shown in Table 2. The direction of the inner rotor is anti-clockwise, while outer rotor clockwise. Figure 5 (a) and 5 (b) shows the torque waveform for the at no loss condition. Figure 6 (a) and 6 (b) shows the gear efficiency at different speed pair when eddy current is counted on the PM. Table 3 and Table 4 summarize the result in both simulation studies.
Table 1. Magnetic gear specification

| Magnetic Gear       | Buried PM | SFPMR |
|---------------------|-----------|-------|
| MG radius           | 90mm      | 90mm  |
| Inner pole pair radius | 68.5mm   | 68.5mm|
| Shaft               | 34mm      | 34mm  |
| Axial length        | 30mm      | 30mm  |
| Inner magnet arc    | 30°       | 30°   |
| Pole piece arc      | 9°        | 9°    |
| Outer magnet arc    | 12.857°   | 12.857°|
| Inner yoke PM slot area | 152.5mm² | -     |
| Inner PM width      | -         | 5mm   |
| Outer PM width      | 5mm       | 5mm   |
| Inner air gap width | 1mm       | 1mm   |
| Outer air gap width | 0.5mm     | 0.5mm |
| PM weight (kg)      | 0.965     | 1.021 |

Table 2. Speed setting for dynamic condition

| Speed pair | Rotor                  | Speed (rpm) |
|------------|------------------------|-------------|
| Case A     | Outer rotor            | 300         |
|            | Inner rotor            | 700         |
| Case B     | Outer rotor            | 900         |
|            | Inner rotor            | 2100        |
| Case C     | Outer rotor            | 1500        |
|            | Inner rotor            | 3500        |
| Case D     | Outer rotor            | 2100        |
|            | Inner rotor            | 4900        |

3. Results
The direction of the inner rotor is anti-clockwise, while outer rotor clockwise. Figure 5 (a) and 5 (b) shows the torque waveform for the at no loss condition. Figure 6 shows the gear efficiency at different speed pair when eddy current is counted on the PM. Table 3 and Table 4 summarize the result in both simulation studies.

From the torque analysis result, the average outer torque, torque density and power density in SMPMR is nearly 3 times higher than the buried PM. The magnetic loss is high if the PM is buried because of additional reluctance it needed to overcome before the flux could reach the air gap. Torque ripple at the buried PM is very high which may result the outer rotor possibly will not rotate in the real application. The harmonic occurs due to improper magnetic coupling in buried PM has generated enormous torque ripple. In gear efficiency analysis, the gear efficiency degradation in buried PM is faster compares to SMPMR. The problems identified in the torque analysis are multiplied as the speed increases.
Figure 5. Torque waveform at the 700 rpm inner rotor speed and 300 rpm outer rotor speed without loss

Table 3. Summary for torque analysis

| Parameters                            | SMPMR | Buried PM |
|---------------------------------------|-------|-----------|
| Inner torque integral average (N.m)   | 32.97 | 11.23     |
| Outer torque integral average (N.m)   | 76.95 | 26.16     |
| Inner torque ripple (%)               | 22.17 | 46.36     |
| Outer torque ripple (%)               | 5.57  | 244.95    |
| Torque/PM ratio (T/kN.m/m^3)          | 569.03| 204.48    |
| Torque density (T/kN.m/m^3)           | 108.46| 36.87     |
| Power density (kW/m^3)                | 7951  | 2703      |

*Air gap volume counted in this calculation
Table 4. Summary for gear efficiency analysis

| Magnetic Gear | Cases | A   | B   | C   | D   |
|---------------|-------|-----|-----|-----|-----|
| Buried PM     |       | 97.48 | 92.57 | 88.43 | 84.83 |
| SMPMR         |       | 98.64 | 96.50 | 94.29 | 94.43 |

4. Conclusion
In this paper, magnetic gear having buried PM at the inner rotor performance were evaluated. The buried rotor was introduced to increase the strength of inner rotor surface mount PM that will be displaced during high speed application. The result confirm that the buried PM has several drawbacks such as low torque density and high torque ripple. The flux path in SMPMR to the air gap had to overcome additional reluctance and harmonic. It can be concluded that buried PM presented in this paper may not be a wise choice to improve surface mount PM strength in magnetic gear.

5. References

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