

Flux modulated rotating pole piece magnetic gear

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Article Info

Article history:

Received Mar 2, 2020

Revised May 1, 2020

Accepted Jun 26, 2020

Keywords:

Double rotor
Finite element
Flux density harmonic
Flux switching
Magnetic gear

ABSTRACT

In this paper, the CMG is re-condition so that the pole piece act as the outer rotor instead of surface mount PM. This magnetic coupling of the CMG is similar to the conventional CMG which uses harmonic to transfer the torque and speed from the inner rotor to the outer rotor. The working principle of the proposed CMG is derived analytically and simulated using finite element software. For this recondition, the PM at the outer section become stationary hence, retaining sleeve can be removing. The proposed MG produced 18% higher average torque than the conventional MG with drawback in torque ripple. The proposed CMG also produce higher gear ratio than the same pole pair of conventional CMG.

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1. INTRODUCTION

The mileage of electric transportation is affected by the load range and the energy storage capacity. This factor is directly dominated by the total weight of the car and the propulsion's performance, reported by Larminie [1]. Thus, focus at the drive system must be examined. The components of the drive system are the electrical propulsion (electrical motor and transmission), the converter, and the energy storage. The energy flow within the system's components is two directions. The largest portion of losses is in the electrical propulsion, 72%, on the static converter the loss is around 19%, and at the battery level the loss is around 9% as shown in Figure 1. Hence, focusing mainly on the electrical propulsion by improving its efficiency and power density will improve the overall efficiency of the EV as published in several recent studies [2–4]. With regard to the existing propulsion solution, it can be seen that over time, the operating speed has substantially increased mentioned in numerous study [5–14]. All vehicle producers are competing at levelling up the velocity of vehicle, acknowledging the enhancement of power density of the traction system, as well as EV's performance. In this relation, it must be reminded that higher speeds are not efficiently possible, since attached to the electric motor, a gear is placed in order to transfer the torque-speed to the car's traction wheels. Thus, in order to overcome this drawback, a research must be conducted. In this case, replacing mechanical gear to magnetic gear (MG) would serve as a preferable option.

Gears are used widely for speed and torque regulation in various field. It is common that the mechanical gear has a high torque to weight ratio, however, it suffers from losses in friction, noise, and heat,

not to mention vibration and reliability issues. Differently, MG suggest significant edge of low maintenance const, reduced noise and vibration, reliable and protecting from overload. Moreover, in the past two decades, MGs have received relatively little interest, possibly due to its under par torque to weight and complexity mentioned in recent studies [15–17]. With the discovery of the high energy density neodymium iron boron (NdFeB) permanent magnet (PM) material in 1980s, the research on MGs incite new passion. In 2001, K. Atallah designed a high torque density MG called as the coaxial magnetic gear (CMG), where it applies the principle of magnetic flux modulation between PM and pole piece [18, 19]. Based on the flux modulation technique, many CMG topologies were published [20–30]. CMG introduced by K. Atallah is reillustrated in Figure 2 in JMAG Application Note [31]. This magnetic gear has three important components, that is inner rotor, pole piece and outer rotor. The inner and outer rotor are mounted with permanent magnet which serve as the pole pair of the rotors.

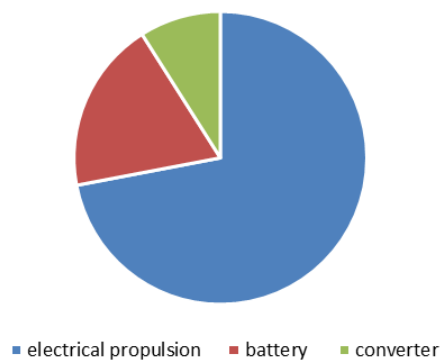


Figure 1. Losses in the drive chain component.

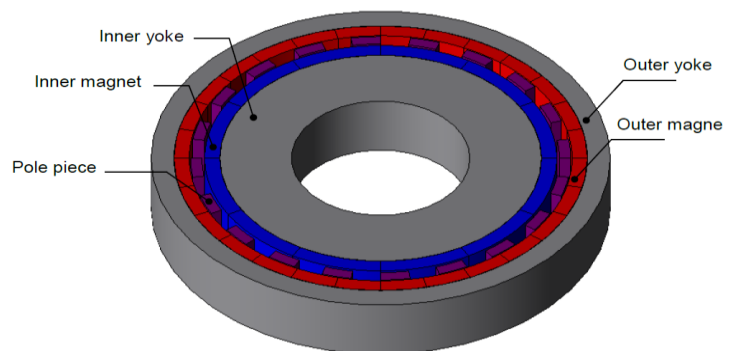


Figure 2. CMG structure.

Flux modulated type CMG consist of 2 rotors, inner and outer. Inner rotors is made of the PM pole pairs p_h and yoke, outer rotor PM pole pairs p_l with yoke and between the two rotos, there are ferromagnetic pole pieces n_s . From the inner rotor perspective, air gap magnetic flux density due to the inner rotor magnet is modulated by the pole piece, and harmonic occurs in the air gap. With the coupling of magnetic flux due to harmonic and outer rotor PM, torque is transferred. The relationship between p_h , p_l and n_s is shows in (1). The relationship between inner rotor speed w_h and outer rotor speed w_l when the pole piece is stationary is shown in (2).

$$n_s = p_h + p_l \quad (1)$$

$$w_l p_l = -w_h p_h \quad (2)$$

CMG could achieve high torque density between 50–150 kNm/m³ comparable to the mechanical gear counterpart. However, it inherits the surface mount PM problem which are not robust similar to other surface mount PM machine reported in two papers [32, 33]. In the high-speed motor utilizing surface-mounted permanent magnet, the permanent magnets glue is insuffienct to sustain force acting towards outside of the motor, due to the high-speed motion of the rotor. In order to retain the permanent magnet on the rotor surface, a retaining sleeve is usually used placed around permanent magnet surface. The complexity of the design and manufacturability when retaining sleeve is employed may increase for a machine that use two surface mount rotor such as CMG.

In this paper, the CMG is re-condition so that the pole piece act as the outer rotor instead of surface mount PM. This magnetic coupling of the CMG is similar to the conventional CMG which uses harmonic to transfer the torque and speed from the inner rotor to the outer rotor. The working principle of the proposed CMG is derived analytically and simulated using finite element software. For this recondition, the PM at the outer section become stationary hence, retaining sleeve can be removed. The proposed CMG also produce higher gear ratio than the same pole pair of conventional CMG.

2. WORKING PRINCIPLE

When each term in equation (1) is multiplied with its own harmonic speed, it can be expressed as

$$w_l p_l + w_h p_h = w_p n_p \quad (3)$$

Where w_l , w_h and w_p is the magnetic flux density harmonic speed of inner yoke surface mount PM, outer yoke surface mount PM and pole piece respectively.

In conventional CMG, w_p is set to zero, hence arrived to (2). The gear ratio can be written as

$$G_r = \frac{w_h}{w_l} = -\frac{p_l}{p_h} \quad (4)$$

The negative sign means that the rotation direction between two rotors are in opposite direction. However, if w_l is set to zero, the gear ratio can be written as (5)

$$G_r = \frac{w_h}{w_p} = \frac{n_p}{p_h} \quad (5)$$

The proposed CMG apply the condition of pole piece to be rotating while outer yoke surface PM condition is stationary. In this condition, the gear ratio is positive which indicates both rotating members are rotating in the same direction. The gear ratio when pole piece is in rotation is higher when outer yoke surface PM is in rotation, due to n_p is the sum of p_l and p_h , $n_p > p_l$. The objective of reducing the retaining sleeve is achieved now because the one of the surface mount PM now has become stationary. The magnetic field direction in the pole piece changes according to the harmonic frequency. The rotation of pole piece due to this effect can also be seen in flux-switching machine [34, 35].

3. SIMULATION OF PROPOSED CMG

3.1. Geometry and setting

The proposed CMG dimension and setting is shown in Table 1. The material used for inner yoke, stator yoke and pole piece are NSSMC 35H210 with resistivity of $5.9 \times 10^{-7} \Omega$, inner PM and outer PM, Hitachi NEOMAX 35AH at 1.2T residual, while plastic are placed between the pole piece to hold it together. Figure 3 shows the proposed CMG drawn using geometry editor of JMAG Designer version 16.

Table 1. Simulation dimension of proposed CMG

Parts	Proposed CMG
Outer rotor	Pole piece
Outer pole pair (p_l)	14
Pole piece (n_p)	20
Inner pole pair (p_h)	6
Gear ratio	10/3
Inner rotor (w_h)	1000 rpm
Outer rotor (w_p)	300 rpm
MG radius	90
Inner pole pair radius	68.5mm
Shaft	34mm
Axial length	30mm
Inner magnet arc	30°
Pole piece arc	9°
Outer magnet arc	12.857°
Inner magnet width	5mm
Outer magnet width	5mm
Inner air gap width	1mm
Outer air gap width	0.5mm

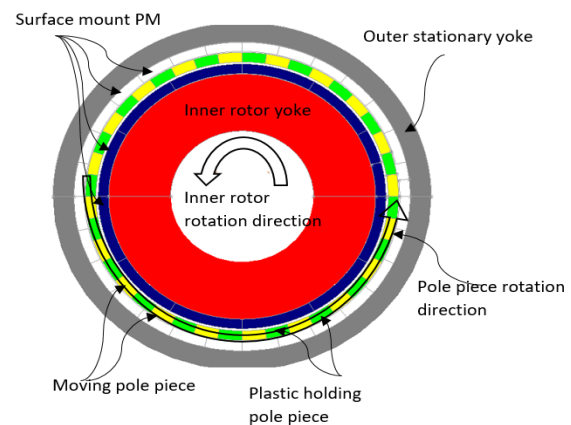


Figure 3. Proposed CMG structure

3.2. Simulation result

The torque waveform obtained when inner rotor and pole piece rotate at 1000 rpm and 300 rpm respectively is shown in Figure 4. Since the geometry is symmetrical, the simulation period is set $\frac{1}{4}$ of the full rotation. Table 2 summarized the result obtained from this simulation.

The negative torque simulated at the inner rotor indicates that an input torque is forced on the shaft of the inner rotor. Positive torque is produced at the pole piece implies that the output torque is generated and transferred from the action by the inner rotor magnetic field modulation. The torque ratio can be calculated through (6).

$$T_r = \frac{T_p}{T_i} = 3.324 \sim 10/3 = G_r \quad (6)$$

Where T_r is the torque ratio, T_p is the torque at the pole piece and T_i is the torque acting on the inner rotor. The average output torque at the pole piece is 18% larger than the equivalent conventional CMG (simulated separately). Torque density of the proposed CMG is equivalent to the conventional CMG. The only drawback observed was the torque ripple are quite large, over 30% more than the original CMG. Unlike the conventional CMG, pole piece and the plastic structure is assemble alternately. The magnetic field density is not continuously distributed as in surface mount PM; thus, torque ripple is expected to appear in the proposed CMG.

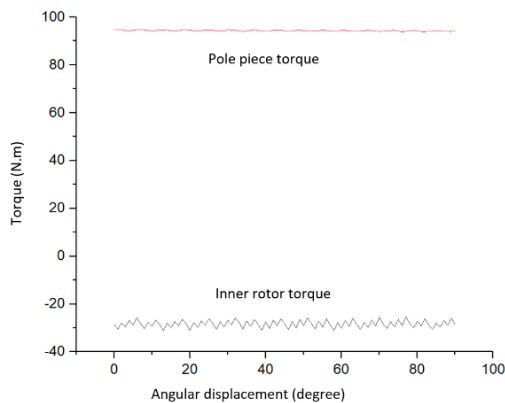


Figure 4. Torque wavefor of the proposed CMG in $\frac{1}{4}$ rotatio

Table 2. Summary of result obtained from the simulation.

Parameters	Proposed CMG
Inner rotor maximum torque (N.m)	(-)37.344
Outer rotor maximum torque (N.m)	132.190
Inner torque integral average (N.m)	(-)33.738
Outer torque integral average (N.m)	112.245
Inner torque ripple (%)	20.518
Outer torque ripple (%)	34.045
Torque density (T/kN.m/m ³)	158.199

4. CONCLUSION

In this paper, new condition of coaxial magnetic gear is proposed that switch the output of the CMG from outer yoke surface mount PM to the pole piece. This condition enables the CMG designer to remove the retaining sleeve off the surface mount PM at the stationary stator. The working principle of the proposed CMG was explained and simulated with finite element. The proposed CMG can produce higher gear ratio compares to the conventional CMG. The result shows that the integral average torque is 18% higher than its equivalent conventional CMG. Nevertheless, torque ripple is quite large, over 30% than the conventional CMG. This limitation can be overcome through the introduction of auxiliary field coil which will be introduced in later publication.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Education Malaysia, Universiti Tun Hussein Onn Malaysia (UTHM) and Universiti Teknikal Malaysia Melaka (UTeM) for the technical and financial support of this research. This work was supported by the Research Management Centre, UTHM. [Research Fund E15501]. The authors also extend our gratitude to E. I Mbadiwe, S. M. N. S. Othman and L. I. Jusoh for their contributions to the preparation of the manuscript and research ideas.

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