Preliminary analysis of eddy current and iron loss in magnetic gear in electric vehicle

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ABSTRACT

The inclusion of a high energy density permanent magnet into magnetic gear improves the machine's torque density. However, it also contributes to eddy current loss, especially in a high-speed application such in electric vehicle. In this paper, the losses from eddy current and iron loss are investigated on concentric magnetic gear (CMG). Torque multiplier CMG is designed with 8/3 gear ratio for this study. Iron loss and eddy current loss are compared and discussed. Based on this study, eddy current loss contributes to almost 96% of the total loss. This finding is hoped to direct the researcher to focus more on reducing loss associated with eddy current loss.

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1. INTRODUCTION

Gears are broadly used for speed adjustment and torque transmission in various field. It is expected that the mechanical gear has a good torque density; however, it suffers from problems such as friction, noise, heat, vibration [1]. In order to overcome the drawback arising from mechanical gears, magnetic gears (MG) and magnetically geared machines have been designed and evolved as a realistic and practical alternative to the conventional mechanical gearboxes in recent times [2]. Among the latest proposed MG topologies, and one of the most compelling topology is concentric magnetic gear (CMG) [3], [4]. It consists of three main components, inner pole pair, outer pole pair and pole piece. This structure can serve as torque multiplier or speed multiplier gear [5]. Several studies were published concerning the torque density in magnetic gear through magnetization pattern and direction of rare earth permanent magnet [6]–[8]. However, the inclusion of high energy density permanent magnet in the structure would result in a high loss in eddy current [9], [10]. Furthermore, many CMG study only focus on the low-speed application which were less than 5,000 rpm. The purpose of this study is to investigate the contribution of eddy current loss and iron loss in magnetic gear. The dependencies of magnetic field density and its frequency can be seen from the iron loss and eddy current loss as shown in (1).

$$P_{iron} = K_i f B_m^n V \tag{1}$$

where P_i is the iron loss (hysteresis), K_i is the hysteresis coefficient, f is the magnetic field frequency, B_m is the maximum flux density, n is the exponent, ranges from 1.5 to 2.5, depending on material and V is the volume of the core. The eddy current loss can be expressed as (2):

$$P_{eddy} = K_e f^n B_m^n d^2 V \tag{2}$$

where P_{eddy}, K_e, f, B_m and d are the eddy current loss, eddy current loss coefficient, magnetic field frequency in s^{-1}, magnetic field density, thickness of the material and the material volume respectively [11], [12]. The understanding of the CMG loss is crucial before it can be applied as efficient torque converter. In this paper, torque multiplier CMG is designed with 8/3 gear ratio. The torque and losses are evaluated via finite element and analyzed. Iron loss and eddy current loss are compared and discussed.

2. RESEARCH METHOD

In this section, the working principle of CMG is briefly explained. Then, the proposed structure of the CMG is introduced. Finally, the simulation configuration is described.

2.1. Working principle of CMG

CMG utilized the flux modulation principle to transfer torque from the inner rotor to the outer rotor. In Figure 1, it is shown that the inner yoke is attached with pairs of surface-mount permanent magnet which we called as inner pole pair, p_i. When it rotates, magnetic field density changes according to the rotor frequency around it. However, when ferromagnetic pieces are introduced outside of the inner rotor, it creates magnetic field density space harmonics. The governing equation of the highest magnitude of space harmonic flux density is (3):

$$\Omega_h = \frac{p_i}{p_i - n_s} \Omega_r \tag{3}$$

where Ω_h is the space harmonic frequency, p is the number of pair, n_s is the ferromagnetic pole piece and Ω_r is the rotor frequency. Then, the outer pole pair with surface mounted permanent magnet (PM) is introduced at the outer side of the pole piece. The outer rotor will rotate according to space harmonic frequency created earlier. The number of pole pair at the outer rotor can be expressed as (4):

$$p_o = |p_i - n_s| \tag{4}$$

where p_o is the outer rotor pole pair. The gear ratio can be written as (5):

$$G_{rs} = -\frac{p_i}{p_o} \tag{5}$$

where G_r is the gear ratio for speed multiplier is. The minus sign indicates that the rotational direction between the two rotors is opposite to each other. The gear ratio for torque multiplier can be written as (6):

$$G_{rt} = -\frac{p_o}{p_i} \tag{6}$$

In torque multiplier, the inner rotor is attached to the prime mover while the outer rotor act as the output.

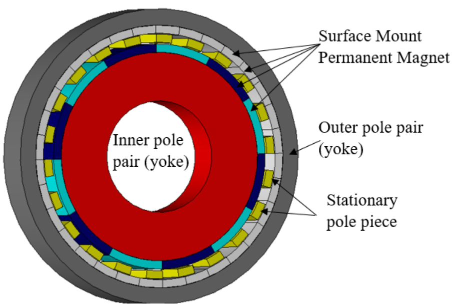

Figure 1. Structure of CMG used in the analysis

2.2. Structure of CMG

The range of single-step mechanical gear ratio commonly available in the market used in combustion engine, washing machine and agriculture sector are between 1 to 4 [13]–[15]. In this paper, gear ratio 3.33 or 8/3 is chosen, which act as torque multiplier. Based on (4), the inner pole pair, outer pole pair and ferromagnetic pole piece are calculated and tabulated together with the dimension of CMG in Table 1. The structure of CMG with gear ratio 8/3 is illustrated in Figure 1.

Table 1. Pole numbers and dimensions of CMG

Description	Parameters	Values
Pole numbers	Inner pole pair (p_i)	6
	Outer pole pair (p_o)	16
	Pole piece (n_p)	22
Dimension (mm)	Overall diameter	180
	Stack length	30
	Inner rotor radius	68.5
	Outer rotor radius	90
	Inner air gap	0.5
	Outer air gap	1
	Magnet width	5

2.3. Simulation configuration

In order to evaluate the torque, losses and efficiency, finite element software, JMAG Designer 16.0 is used in 2D transient mode. The rotational speed for the inner rotor is set for 800 rpm in forwards direction while the outer rotor is set for 300 rpm backward direction. The duration of the simulation for data collection is ¼ of a full rotation. The materials used in this simulation are shown in Table 2.

As mentioned, torque values taken at inner and outer rotor is in transient mode. Hence, integral average will be used to calculate the efficiency. Unlike motor or generator, CMG convert torque and speed into another torque and speed at set ratio. The efficiency of CMG can be expressed as (7):

$$\eta = \frac{\tau_o \omega_o}{\tau_i \omega_i} \tag{7}$$

where η is the CMG efficiency, τ_o and τ_i is the average torque at the inner rotor and outer rotor, ω_i and ω_o is the rotational speed of the inner rotor and outer rotor. Eddy current loss produced by the PM and iron loss produced by the magnetic material can be extracted directly from the simulation [16]. The evaluation steps can be simplified as in Figure 2.

Table 2. Material used in the simulation

Parts	Material	Remark
Pole Piece	NSSMC 35H210	Resistivity: 5.9e-07 ohm.m
Inner yoke		
Outer yoke		
Inner PM	NEOMAX-35AH	Resistivity: 1.44e-06 ohm.m
Outer PM		

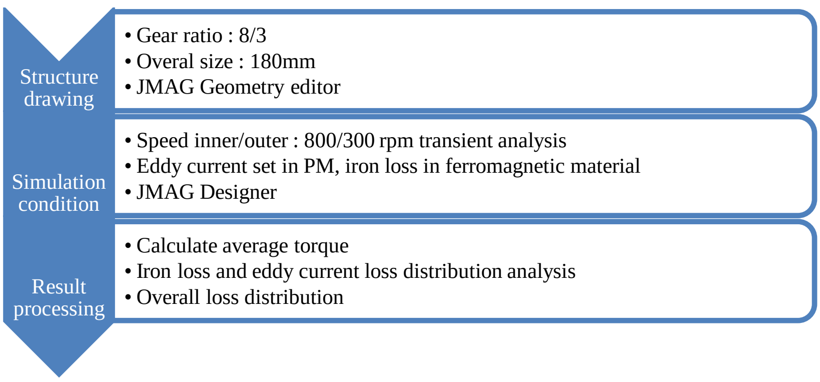

Figure 2. Magnetic gear loss evaluation steps

3. RESULTS AND DISCUSSION

The torque waveform shown in Figure 3 is measured for 0.06 seconds which is equivalent to the ¼ of a full rotation of the inner rotor. The magnetic flux density contour plot is shown in Figure 4. The iron loss at the magnetic materials, eddy current loss at PM and distribution of all the losses in percentage were illustrated in Figures 5, 6 and 7 respectively.

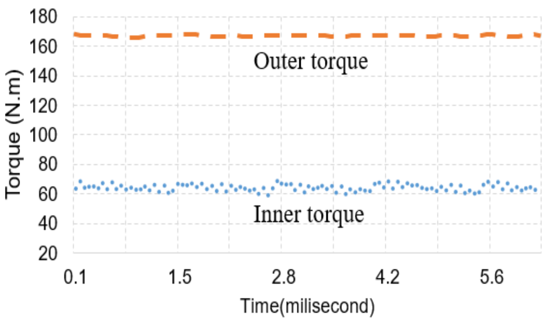

Figure 3. Torque versus simulation time

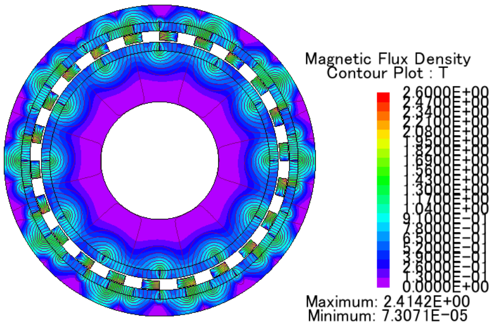

Figure 4. Magnetic flux density contour plot

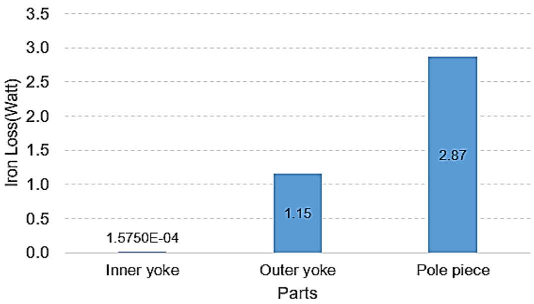

Figure 5. Iron loss at the magnetic materials

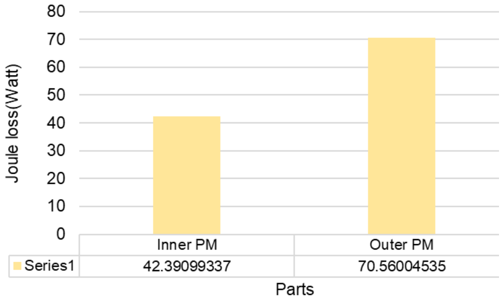

Figure 6. Eddy current loss at inner and outer PM

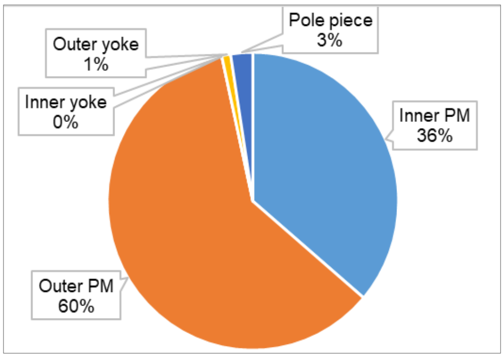

Figure 7. Loss distribution in MG by parts

The average value at inner and outer torque were 64.19 N.m and 167.08 N.m respectively. From these values, gear efficiency yield 0.97 or 97%. Torque ripple at the inner rotor is slightly higher, 18% compares to the outer rotor, 0.15%. The bar graph in Figure 5 shows that the ferromagnetic pole piece produced the highest iron loss of 2.87 Watt. Pole piece experienced highest flux density, which came from both inner PM and outer PM. In contrast, inner yoke and outer yoke experienced the flux density at each locality and small fraction of the PM across the large air gap. The bar graph in Figure 6 shows that the outer PM loss is greater than the inner PM. The larger volume of the outer PM contributed to this difference. The distribution of all the loss revealed that eddy current loss contributes much higher loss to the CMG in comparison to the iron loss. Only 4% of the loss came from magnetic material. The iron loss (1) presented in the introduction also revealed that magnetic field frequency does not have an exponent number unlike the eddy current loss in (2). This finding agrees with many previous studies [17]–[20]. Unlike electrical motor that has an armature coil which contributes to copper loss, the loss in CMG is lower in magnitude [21], [22].

It is also well known that the eddy current loss will increase exponentially as the rotor speed increase. Therefore, at higher rotational speed, the iron loss may be worthwhile to be examined and preferably excluded. The usual practices to reduce eddy current are by dividing each magnet piece into smaller segment or to introducing lamination to increase insulation on the magnet surface [23], [24]. The eddy current can also be calculated as (8) [10], [25],

$$P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt \quad (8)$$

where Pc is the eddy current loss at the PM, V is the magnet piece volume, ρ is he magnet resistivity, w is the magnet width, l is the stack length, T is the magnetic field period in one cycle and B is the magnetic field density. Table 3 summarized the results obtained from the simulation.

Table 3. Summary of the simulation result

	Parts	Values
Average torque (N.m)	Inner rotor	68.19
	Outer rotor	167.08
Eddy current loss (Watt)	Inner PM	42.39
	Outer PM	70.56
	Inner yoke	1.5750E-04
Iron loss (Watt)	Outer yoke	1.15
	Pole piece	2.87
Efficiency (%)	CMG	97.6

4. CONCLUSION

In this paper, the efficiency of the CMG is determined through torque waveform obtained from the simulation. Besides that, CMG loss from iron loss and eddy current loss has been presented as well using finite element software. The highest iron loss came from the ferromagnetic pole piece. This is because it received two sources of flux density changes, inner PM and outer PM in relation to the location of the part. Eddy current loss at outer PM registered higher value versus the inner rotor because the size of the PM at outer rotor is larger than the inner rotor. The result showed that the eddy current loss contributes to 96% of the total loss. Usually, in an electrical machine, eddy current loss is neglected from the loss calculation because the copper loss overwhelmed the overall loss. However, this result showed that CMG loss mostly came from eddy current at inner and outer PM. The eddy current loss may increase exponentially as the rotor speed increase. Efficiency might deteriorate further and may overshadow the performance of the CMG. There are many techniques to reduce the eddy current loss, such as magnet segmentation and increase insulation. These reduction methods will be discussed further in the future research.

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