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Research paper

Comparison of Loss Characteristics of Coaxial Magnetic Gear According to Three Types

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Abstract

Background/Objectives: Recently, there has been a problem of instability in rare earth prices worldwide. Due to these problems, various structures are being studied to minimize the use of permanent magnets.
Methods/Statistical analysis: In this paper, we analyze the loss characteristics of three different types of coaxial magnetic gear (CMG)s using two - dimensional finite element analysis.
Findings: This paper, 3 types of CMGs have been analyzed by using the 2-D FEA. The shapes used for the analysis are three types: Surface mounted coaxial magnetic gear (SMCMG), Consequent pole coaxial magnetic gear (CPCMG) and Reluctance coaxial magnetic gear (RCMG).The three types of gear ratios are all seven. For CPCMG and RCMG, the maximum torque is reduced as compared to SMCMG as the permanent magnet usage decreases. However, in case of loss, CPCMG is advantageous for PMloss and RCMG is for coreloss. The efficiency of SMCMG is advantageous, although the three types do not have much difference.
Improvements/Applications: Through the two - dimensional finite element analysis, the results of analysis of the losses occurring in three types of magnetic gears were obtained.

Keywords: *coaxial magnetic gear, consequent pole magnetic gear, reluctance magnetic gear, two-dimensional finite element analysis, core loss, PM loss.*

1. Introduction

A gear is a mechanical device consisting of teeth as shown in Figure 1 [1]. Gears have the principle that the teeth on the primary side and the secondary side transmit rotation or power through physical contact. Currently, gears are used in many industrial sites, such as high-speed or low-speed rotating machinery, generators, automotive systems, conveyor systems, and other mechanical devices [2]. However, since mechanical gears are driven by physical contact, they have many disadvantages such as noise, vibration and dust due to mechanical friction [3].Also, gears are mainly made of metal materials, which can cause gears wear or system breakage due to extreme conditions, system overload and backlash. To overcome these shortcomings, mechanical gears always require maintenance work that requires lubricant. Recently, magnetic gears that transmitting power by using the magnetic field of PMs have been studied as alternatives to mechanical gears [4].The magnetic gear uses the inner and outer permanent magnets instead of the toothed wheels to transmit power. The permanent magnets mainly use neodymium (NdFeB) or samarium cobalt (SmCo) [5].Magnetic gears have no physical contact, so they are free of noise, vibration, dust and maintenance [6].In addition, when the system is overloaded, the magnetic gear has the advantage that the gear is not worn through the slip or the system is not damaged. However, recently, the price of rare earths has become unstable due to China's rare earth export sanctions, and it has a problem of fluctuation of rare earths price worldwide. Due to these problems, various structures are being studied to minimize the use of permanent magnets.
In this paper, we compare the characteristics of high speed magnetic gear according to three shapes of SMCMG, CPCMG and RCMG by using 2-D FEA method. The rotational speed, gear ratio and design specifications of the magnetic gear according to the shape were performed under the same conditions.

2. Coaxial Magnetic Gear

The CMG is structured as shown in Figure 2. PMs are attached to the outer and inner core. And is driven in a noncontact manner by having a air-gap between the inner and out rotor. The CMG has a similar structure to the permanent magnet coupling. However, the fixed core is located between the inner and outer PM.

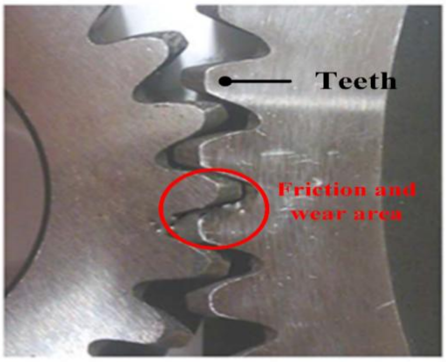

Figure 1: Structure of mechanical gear

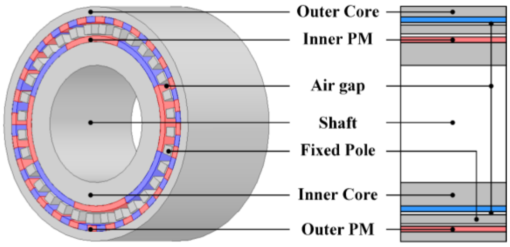

Figure 2: Structure of coaxial magnetic gear

Gear ratio of the magnetic gear can be calculated using Equation (1).G_r is the gear ratio, and $P_{in}$and $P_{out}$are the pole pairs of the inner and out PM.

$$G_r = \frac{P_{out}}{P_{in}} \tag{1}$$

The role of the fixed poles` is to modulate the magnetic field generated by the inner and out PMs. Therefore, the outer rotor rotates in the opposite direction of the inner rotor. The number of fixed poles used in the magnetic gear can be calculated by Equation (2).

$$F_p = P_{in} + P_{out} \tag{2}$$

The rotational speed of the out rotor according to the gear ratio of the magnetic gear can be calculated using Equation (3).

$$\omega_{out} = -\frac{\omega_{in}}{G_r} \tag{3}$$

The inner and outer rotation speeds are expressed as ω_{in} and ω_{out}.The negative sign means that the outer rotates in the opposite direction of the inner.
This paper, the design specifications of the reference model designed to compare the characteristic according to the shape are shown in Table 1.

Table 1: Design specifications of reference model

Parameter	Value	Unit
Out diameter of Out rotor	120	mm
Inner diameter of Out rotor	110	mm
Out diameter of Fixed pole	102	mm
Inner diameter of Fixed pole	92	mm
Out diameter of Inner rotor	84	mm
Inner diameter of Inner rotor	60	mm
Stack	70	mm
Inner / Outer PM Thickness	3	mm
Inner / Outer Air gap	1	mm

Table 2: Gear ratio according to the shape of the magnetic gear

Parameter	Shape		
	SMCMG	CPCMG	RCMG
Inner Permanent magnet pole numbers	8	4	2
Outer Permanent magnet pole numbers	56	28	14
Fixed pole numbers	32	32	16
Gear ratio	7		

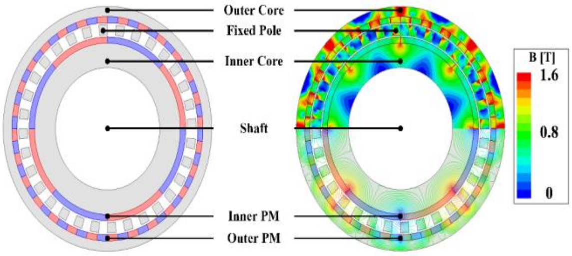

Figure 3: Structure and flux density and flux line of surface mounted coaxial magnetic gear

2.1. Characteristic Analysis of Magnetic Gears According to Three Types

Equations (1), (2), and (3) can be used to calculate the gear ratio of the magnetic gear and number of fixed poles. As shown in Table 2, it shows the results of calculation using the formula. The shape and the number of poles of the permanent magnet used are different. But all three types have the same gear ratio. The torque THD and ripple characteristics in the analysis of magnetic gear can be calculated using Equations (4) and (5).

$$T_{THD} = \left(\frac{\sqrt{T_2^2 + T_3^2 + \cdots + T_n^2}}{T_1} \right) \times 100 \tag{4}$$

$$T_r = \frac{T_{max} - T_{min}}{T_{avg}} \times 100 \tag{5}$$

2.2. Surface Mounted Coaxial Magnetic Gear

Shown in Figure 3 is the structure, flux density and lines of the SMCMG analyzed in this paper. First, the pull-out torque characteristics of SMCMG were analyzed. Then transient analysis of SMCMG was performed using pull-out torque. The analysis results are shown in Figure 4.As a result of SMCMG characteristics analysis, the PM loss is the largest as the permanent magnet is used the most among the three types.

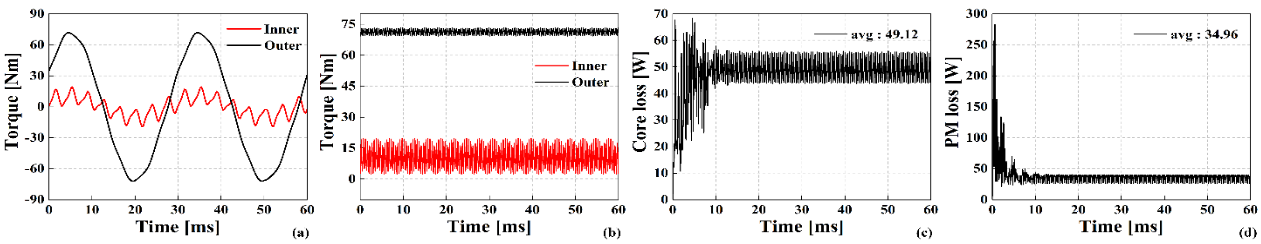

Figure 4: Analysis results of SMCMG characteristics: (a) Pull-out torque, (b) Transient torque (c) Core loss (d) PM loss

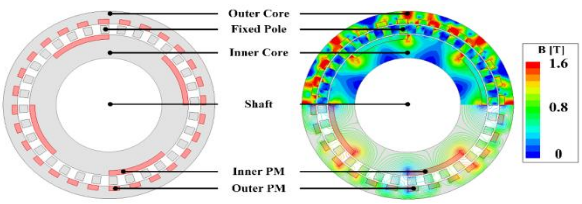

Figure 5: Structure and flux density and flux line of consequent pole coaxial magnetic gear

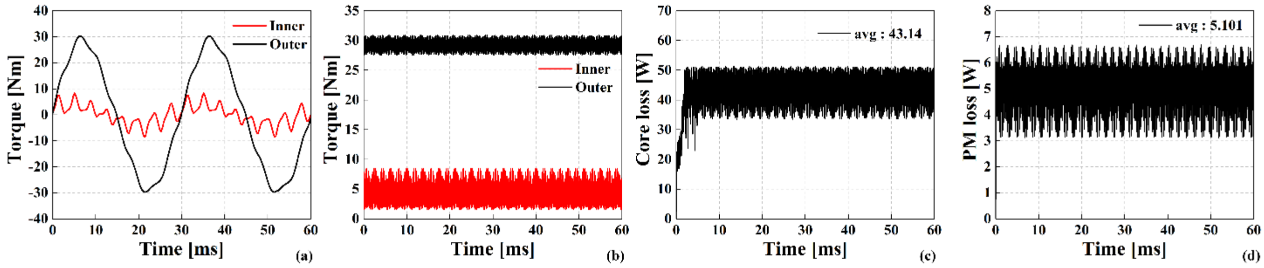

Figure 6: Analysis results of CPCMG characteristics: (a) Pull-out torque, (b) Transient torque (c) Core loss (d) PM loss

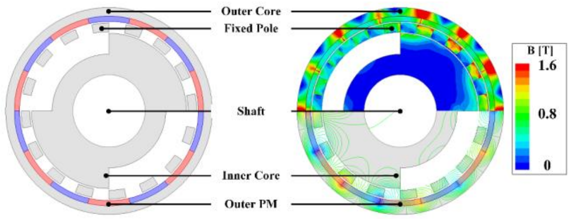

Figure 7: Structure and flux density and flux line of reluctance coaxial magnetic gear

2.3. Consequent Pole Coaxial Magnetic Gear

Figure 5 is shown the structure, flux density and lines of the CPCMG.CPCMG has a structure similar to that of SMCMG, but uses permanent magnet only N pole [7]. Figure 6 shows the analysis results of CPCMG. In the case of CPCMG, the maximum torque during pull-out and transient analysis decreased by half as the permanent magnet usage decreased. The PM loss also decreased.

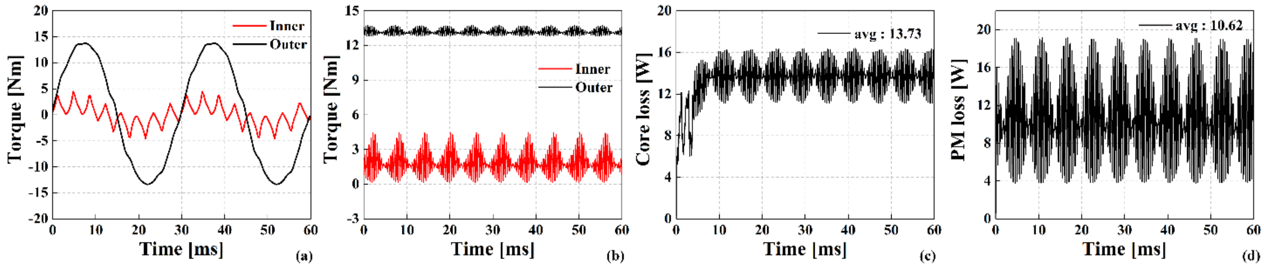

Figure 8: Analysis results of RCMG characteristics: (a) Pull-out torque, (b) Transient torque (c) Core loss (d) PM loss

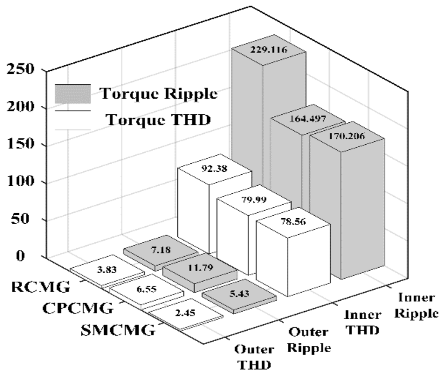

Figure 9: Three types of torque THD and torque ripple characteristics

2.4. Reluctance Coaxial Magnetic Gear

Unlike SMCMG and CPCMG, the RCMG has a structure in which the permanent magnet is used only on the outer side and the inner side is not used. The RCMG has the principle that the reluctance torque is generated by the salient pole structure of the rotor.The structure, flux density and flux lines of RCMG are shown in Figure 7. As shown in Figure 8, it is the analysis results of RCMG. The analysis results show that RCMG has more ripples in characteristics than the other two types.

2.5. Torque THD and Torque Ripple Characteristics

As shown in Figure 9, it is a graph showing torque THD and torque ripple characteristics according to the three types using the analysis results and Equations (4) and (5).The characteristics analysis shows that SMCMG has the lowest THD characteristics. CPCMG showed no significant difference from SMCMG. In the case of RCMG, Inner Ripple appeared to be larger than SMCMG and CPCMG.

3. Results and Discussion

Through the analysis of the characteristics of three types of CMGs, the loss values of each gear were derived. In case of SMCMG, PM loss was the most caused by using magnet more. The RCMG has the least permanent magnet usage among the three types of gears. Therefore, we obtained the analysis result that core loss and PM loss are the least. The efficiency of the three types of gears is 96.4% for SMCMG, 95.8% for CPCMG, and 96.7% for RCMG.

4. Conclusion

In this paper, we compare the loss characteristics of three types of CMGs using 2-D FEA. In the case of CPCMG and RCMG, the permanent magnet usage is reduced but the maximum pull-out torque is reduced due to the decrease of the PM. However, CPCMG and RCMG showed better results than SMCMG in loss characteristics. Also, in terms of efficiency, the three types do not show a large difference, but the results of the order of RCMG> SMCMG> CPCMG were obtained. Therefore, it is considered that SMCMG is advantageous to use maximum torque but RCMG is more advantageous in terms of efficiency and loss.

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