ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 27(1), 51-55 (2022) https://doi.org/10.4283/JMAG.2022.27.1.051

Torque Ripple according to The Number of Permanent Magnet Poles of Magnetic Gear

Eui-Jong Park[1] and Yong-Jae Kim[2]*

[1]*Faculty of Smart Vehicle System Engineering, Chosun University, Gwangju, Korea*
[2]*Department of Electrical Engineering Chosun University Gwangju, Korea*

(Received 14 February 2022, Received in final form 18 March 2022, Accepted 21 March 2022)

The power transmission of magnetic gears, based upon the at-tractive force of magnets, does not involve direct contact between the power transmission shafts. Thus, vibration or noise, due to friction, can be reduced. However, magnets and iron cores, which are the main components of magnetic gears, generate cogging torque. This increases torque ripples that are the cause of the noise and vibration of permanent-magnet (PM) machines. In this study, a torque ripple reduction method, using the combination of number of poles and number of pole pieces was proposed. This method uses the structural characteristics of magnetic gears only. This method was suggested instead of the existing torque ripple reduction methods for PM machines to reduce the torque ripples of magnetic gears. Furthermore, the correlation between the numbers of poles, pole pieces, and torque ripples was analyzed. From this analysis, a design guideline that minimizes torque ripples in the initial design of magnetic gears was proposed.

Keywords : number of pole piece, number of pole, magnetic gear, torque ripple reduction, gear ratio, LCM, GCD

1. Introduction

Magnetic gears are power transmission devices that use the attractive force of magnets. They have no direct contact between shafts that transmit power since they are operated using the attractive force of magnets. This characteristic of magnetic gears can reduce the friction loss caused by mechanical contact and enable magnetic gears to exhibit lower vibration and noise thus requiring less maintenance than mechanical gears [1, 2]. Since the first magnetic gears were pro-posed, studies have been conducted on a structure similar to conventional mechanical gears, but there were problems of low torque transmission efficiency and torque density [3]. The coaxial magnetic gear, first proposed by Atallah et al., in the early 2000s, significantly improved the shortcomings of conventional magnetic gears and laid the foundation for recent active research activities on magnetic gears [4].

The coaxial magnetic gear consists of three parts: an inner rotor and an outer rotor composed of magnets and cores, and pole pieces made of iron cores. Among them, the pole pieces, made of iron cores, are key structures that enable the magnetic gear to exhibit its gear ratio. Additionally, they alter the flow of the magnetic flux. The pole pieces also facilitate the flow of the magnetic flux of permanent magnets to improve torque density. The space for installing the pole pieces in the coaxial magnetic gear is between the two rotors, and the pole pieces are placed in a circumferential direction at regular intervals. This structural characteristic of the pole pieces causes a magnetoresistance imbalance in the gap, because the pole pieces exhibit the shape in which the air and the iron core are placed alternately from the perspective of the magnets. As the magnetoresistance imbalance in the gap is magnetically unstable, the force is generated to allow the rotors to have magnetically stable positions. This force is ostensibly the attractive force between the magnets and iron cores, and it is called cogging torque in electrodynamics. As the cogging torque in a motor acts as a result of torque ripples and causes problems such as noise, reduced efficiency, and shortened life, it is one of the factors that needs to be reduced first when designing electric devices [5]. Previous studies on PM motors have proposed chamfering, bifurcating, slot skew, and permanent magnet skew as methods for reducing torque ripples [6-8].

*Corresponding author: Tel: +82-62-230-7034
Fax: +82-62-230-7034, e-mail: kimyj21@chosun.ac.kr

This study proposes a method that reduces torque ripples, using the characteristics of magnetic gears, as a differentiated method from the existing torque ripple reduction methods of PM motors. First, torque ripples were shown for models with various pole number combinations. These combinations use characteristics in which the gear ratio is determined by the number of poles and number of pole pieces. A structural de-sign guideline was then prepared to minimize torque ripples by analyzing the influence of the number of poles of magnetic gears on torque ripple.

To analyze the torque ripples of magnetic gears, accurate knowledge on the magnetic field distribution of the gap is re-quired. In this regard, an analytical model for the electromagnetic calculation of magnetic gears was presented in [9]. In this study, the torque characteristics of each model were analyzed using finite element analysis based on two-dimensional (2D) numerical analysis.

2. Combinations of Poles and Pole Pieces

Figure 1 shows the typical shape of the coaxial magnetic gear. In this study, the inner rotor was selected as high-speed and input rotor, and the outer rotor as low-speed and output rotor. The gear ratio is shown in (1). In this model, as the inner rotor has four poles and the outer rotor has 40 poles, the gear ratio was 10:1. The number of pole pieces was 22, calculated using (2). The size of the pole piece and the size of the empty space between the pole pieces are equal as determined by (2). Therefore, the total area of the pole pieces is always the same regardless of the number of pole pieces. The permanent magnets of each rotor were different in split numbers but are able to maintain the same area. Based on these characteristics, the magnet use amount and the pole piece area were selected as constraints in this study. The gear ratios of the basic model magnetic gear, according to the number of poles and the number of pole pieces, are listed in Table 1. The torque characteristics of each model analyzed are shown in Table 2 and Fig. 2. The analysis results show that the torque ripples at integer gear ratios were very high while those at fractional gear ratios were low when the number of poles of the inner rotor was four. Based on these results, it can be assumed that torque ripples of magnetic gears are lower at fractional gear ratios than at integer gear ratios. Therefore, additional models to support this assumption are analyzed in the next section.

Table 1. Gear Ratio according to The Numbers of Poles and Pole Pieces.

Inner poles	Outer poles	Number of Pole piece	Gear ratio
4	40	22	10.0
4	38	21	9.5
4	36	20	9.0
4	34	19	8.5
4	32	18	8.0
4	30	17	7.5
4	28	16	7.0
4	26	15	6.5
4	24	14	6.0
4	22	13	5.5
4	20	12	5.0
4	18	11	4.5
4	16	10	4.0
4	14	9	3.5
4	12	8	3.0
4	10	7	2.5
4	8	6	2.0
4	6	5	1.5

$$G_r = \frac{P_2}{P_1} = \frac{\omega_1}{\omega_2} \quad (1)$$

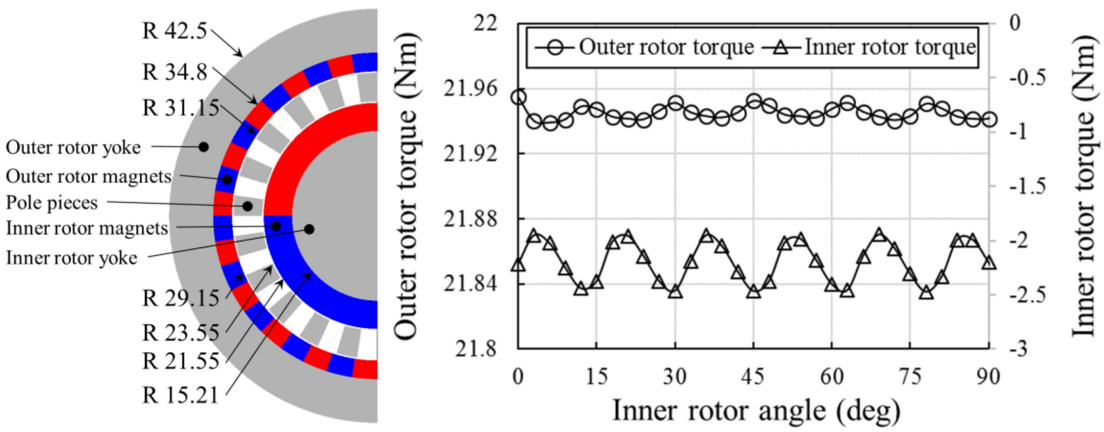

Fig. 1. (Color online) Magnetic gear basic model.

Table 2. Torque Characteristics according to The Gear Ratios.

Gear ratio	Inner torque	Outer Torque	Inner ripple	Outer ripple
10.0	2.2	21.9	24.5 %	0.1 %
9.5	2.4	22.2	3.0 %	0.1 %
9.0	2.5	22.4	101.9 %	2.4 %
8.5	2.7	22.6	4.3 %	0.1 %
8.0	2.9	22.8	25.8 %	0.2 %
7.5	3.1	22.9	4.4 %	0.1 %
7.0	3.4	23.0	106.6 %	5.1 %
6.5	3.6	23.0	4.4 %	0.1 %
6.0	3.8	22.9	28.9 %	0.5 %
5.5	4.2	22.7	5.3 %	0.2 %
5.0	4.7	22.3	111.2 %	12.9 %
4.5	4.9	21.8	6.1 %	0.3 %
4.0	5.4	21.1	33.3 %	2.5 %
3.5	5.9	20.1	6.8 %	0.8 %
3.0	6.7	18.1	139.0 %	45.1 %
2.5	7.0	16.7	8.6 %	2.8 %
2.0	7.4	14.1	52.4 %	25.2 %
1.5	8.1	10.3	12.5 %	15.1 %

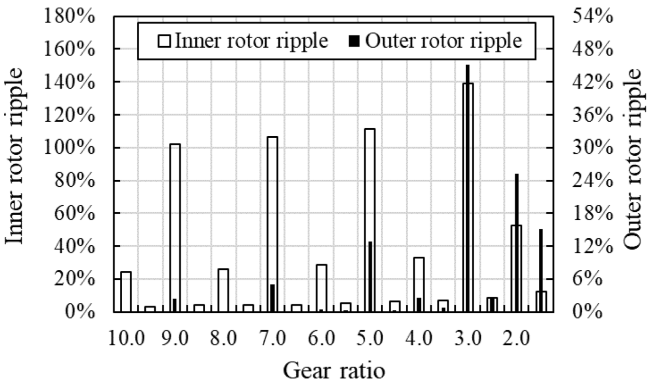

Fig. 2 Torque characteristics of models with four inner poles according to the gear ratios.

$$N_s = \frac{P_1 + P_2}{2} \quad (2)$$

where G_r is gear ratio, P_1 is number of inner rotor poles, P_2 is number of outer rotor poles, ω_1 is revolution speed of inner rotor, ω_2 is revolution speed of outer rotor, N_s is number of pole piece

3. Numbers of Poles and Pole Pieces for Minimizing Torque Ripples

3.1. Inner rotor model with 6, 8, 10, and 12 poles

First, models with six poles in the inner rotor were analyzed. For the models with six inner poles, integer gear ratios are available when the number of poles in the outer rotor is a multiple of six: e.g. 12, 18, 24, 30, and 36. Fig. 3 shows the torque characteristics of these models according to the gear ratios. The six-pole models also show higher torque ripples at integer gear ratios as in the four-pole models.

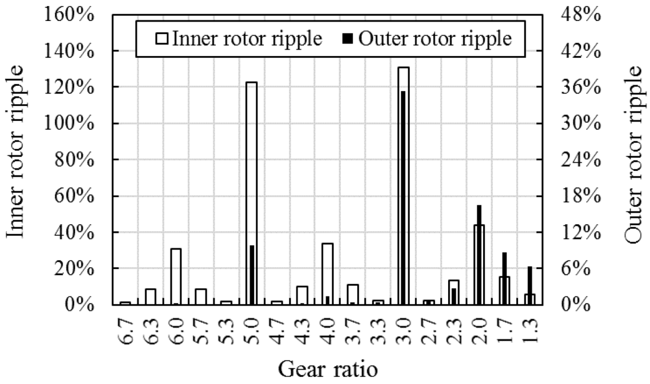

Fig. 3. Torque characteristics of models with six inner poles according to the gear ratios.

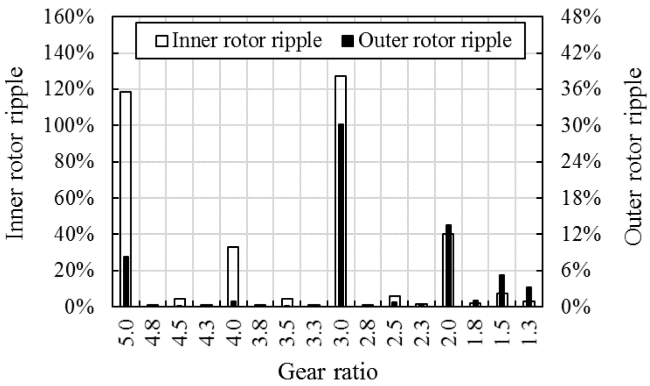

Fig. 4. Torque characteristics of models with eight inner poles according to the gear ratios.

In addition, the torque characteristics of models with 8, 10, and 12 poles in the inner rotor were analyzed as shown in Figs. 4-6. As a result, higher ripples occurred at

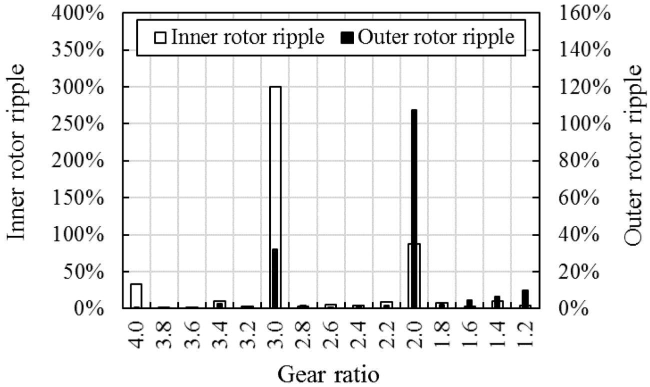

Fig. 5. Torque characteristics of models with ten inner poles according to the gear ratios.

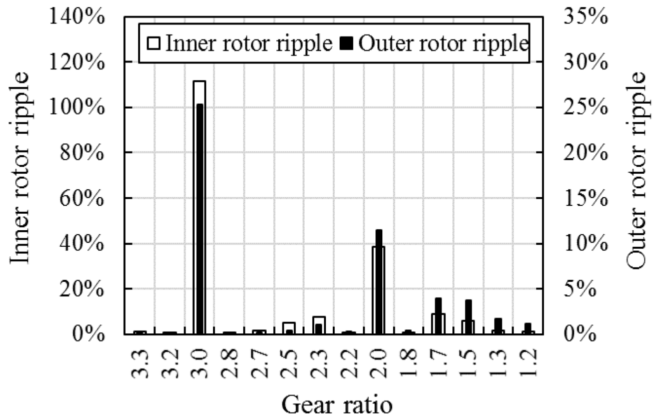

Fig. 6. Torque characteristics of models with twelve inner poles according to the gear ratios.

integer gear ratios as in the previous models. Some models exhibited very high torque ripples, which is analyzed in detail in the next section.

3.2. LCM and GCD analysis

Although the above results show that integer gear ratios exhibited higher ripples, Figs. 3-6 show that the gear ratio models: 5:1 and 3:1 with six poles, 5:1 and 3:1 with eight poles, 3:1 and 2:1 with 10 poles, and 3:1 and 2:1 with 12 poles exhibited much higher torque ripples that other integer gear ratio models. The common characteristics of these models are found in the least common multiple (LCM) and the greatest common divisor (GCD) between the number of poles and the number of pole pieces. Fig. 7 and Fig. 8 show inner and outer ripple according to LCM of inner poles and pole pieces; outer poles and pole pieces. First, among the models with six poles in the inner rotor, the model with the lowest LCM between the number of inner poles and the number of pole pieces is the model with a 3:1 gear ratio (LCM: 12, Ripple: 130 %). In this model, the GCD between the number of inner

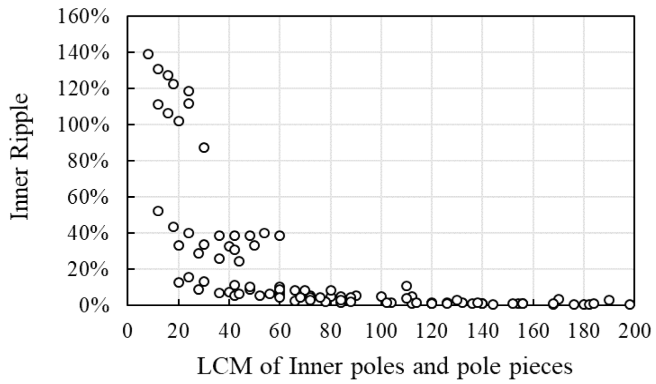

Fig. 7. Inner ripple according to LCM of inner poles and pole pieces.

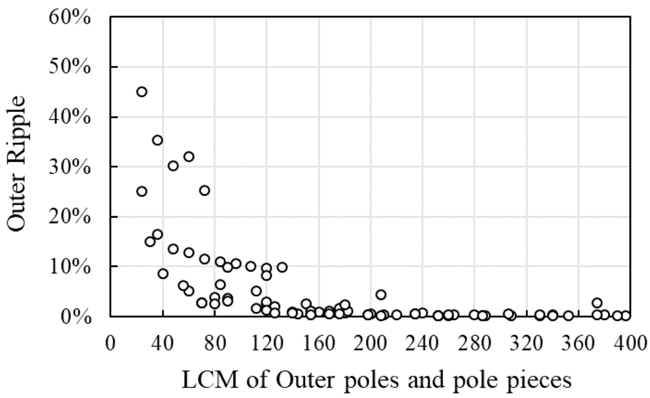

Fig. 8. Outer ripple according to LCM of outer poles and pole pieces.

poles and the number of pole pieces was the highest compared to other six-pole models (GCD: 6). As a result, the inner and outer ripples were 130 % and 35 %, respectively, which were higher than other models. The 5:1 model ranked second in terms of the LCM and GCD and showed the second highest ripple values as well (LCM: 18, GCD: 6, Ripple: 123 %).

Among the eight-pole models, the 3:1 model also exhibited the lowest LCM and highest GCD (LCM: 16, GCD: 8). Its inner and outer ripples were the highest at 127 % and 30 %, respectively, followed by the 5:1 model

Table 3. Torque Ripples of 14-20 Poles according to The LCM and GCD.

Inner poles(in)		20	20	18	18
Outer poles(out)		40	38	40	36
Pole pieces(pp)		30	29	29	27
LCM	in-pp	60	580	522	54
	out-pp	120	1102	1160	108
GCD	in-pp	10	1	1	9
	out-pp	10	1	1	9
Gear Ratio		2 : 1	1.9 : 1	2.22 : 1	2 : 1
Inner ripple		38.79 %	0.32 %	0.37 %	40.17 %
Outer ripple		9.64 %	0.14 %	0.13 %	10.09 %

Inner poles(in)		16	16	14	14
Outer poles(out)		38	32	40	28
Pole pieces(pp)		27	24	27	21
LCM	in-pp	432	48	378	42
	out-pp	1026	96	1080	84
GCD	in-pp	1	8	1	7
	out-pp	1	8	1	7
Gear Ratio		2.375 : 1	2 : 1	2.857 : 1	2 : 1
Inner ripple		0.33 %	38.53 %	0.37 %	38.35 %
Outer ripple		0.12 %	10.58 %	0.12 %	11.03 %

(LCM: 24, GCD: 8, Ripple: 119 %). Among the ten-pole models, the 3:1 models showed the lowest LCM and the highest GCD (LCM: 20, GCD: 10, Ripple: 300 %). Among the 12-pole models, the 3:1 model was followed by the 2:1 model (LCM: 24, GCD: 12, Ripple: 112 %).

From the above results, it was confirmed that not only the integer gear ratio but also the LCM and GCD between the number of poles and the number of pole pieces affect torque ripples. The reverse interpretation of this analysis may indicate that the model with the highest LCM and the lowest GCD is advantageous for ripple reduction.

In addition, for the models with 14, 16, 18, and 20 poles, the gear ratio model of 2:1 and the adjacent model with the highest LCM and the lowest GCD were compared as shown in Table 3. The results also show that the LCM and GCD affect the size of ripples.

4. Conclusion

This study proposed a torque ripple reduction method by combining the number of poles and the number of pole pieces, characteristics of magnetic gears only, to reduce the torque ripples of magnetic gears. As a result, fractional gear ratios exhibited the lowest torque ripples. For models with high ripples, additional analysis was conducted, and it was further confirmed that the LCM and the GCD between the number of poles and number of pole pieces directly affect ripples. The analysis of other arbitrarily extracted models show the same results as the results noted above thus ensuring the reliability of this analysis.

Therefore, based on the above results, it is proposed that integer gear ratios be avoided as much as possible. Fractional gear ratios should be selected in order to minimize ripples when magnetic gears are designed. If integer gear ratios must be used, it is advised to use the combination with the highest LCM between the number of poles and number of pole pieces as well as the GCD of one must be selected to obtain the lowest ripples.

Depending on the field of the application, the ripple reduction method applied to PM motors must be applied under conditions in which the number of poles and number of pole pieces are limited. That said, in most magnetic gear design situations with other conditions, the results of this study will be utilized.

Acknowledgments

"This study was supported by the Korea Electric Power Corporation. (Grant number: R19XO01-34)".

We would like to thank Editage (www.editage.co.kr) for English language editing.

References

[1] K. Atallah, S. D. Calverley, and D. Howe, Proc. Inst. Elect. Eng.-Electr. Power Appl. **151**, 2 (2004).
[2] P. O. Rasmussen, T. O. Andersen, F. T. Jorgensen, and O. Nielsen, IEEE Trans. Ind. Appl. **41**, 3 (2005).
[3] E. Gouda, S. Mezani, L. Baghli, and A. Rezzoug, IEEE Trans. Magn. **47**, 2 (2011).
[4] K. Atallah and D. Howe, IEEE Trans. Magn. **37**, 4 (2001).
[5] M. Aydin, Z. Q. Zhu, T. A. Lipo, and D. Howe, IEEE Trans. Magn. **43**, 9 (2007).
[6] Z. Q. Zhu and D. Howe, IEEE Trans. Energy Convers. **15**, 4 (2000).
[7] X. Jiang, J. Xing, Y. Li, and Y. Lu, IEEE Trans. Magn. **45**, 10 (2009).
[8] W. Fei and P. C. K. Luk, IEEE Trans. Ind. Appl. **46**, 4 (2009).
[9] N. Chen, S. L. Ho, and W. N. Fu, IEEE Trans. Magn. **46**, 6 (2010).