Design Optimization and Comparison of High Torque-Density Magnetic Gears

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High torque-density magnetic gear (MG) is a new type of magnetic device that has great potential in many industrial applications. Because of the limited supply and high fluctuating costs of permanent magnet (PM) materials, the optimized utilization of PMs in MGs is vital and necessary. This paper presents several topologies of MGs and their structures optimized and their maximum torque densities are being scrutinized and compared. An optimal design method based on genetic algorithm (GA) and finite element method (FEM) is proposed for the comparison of MGs.

***Index Terms*— Finite element method, high torque-density, magnetic gear, optimization, permanent magnet**

I. Introduction

MAGNETIC GEARS (MGs) are magnetic devices that can transmit torque and speed by virtue of their interactive magnetic fields [1,2]. MG has many merits over their mechanical counterparts, including contactless operation, noise reduction, less usage of lubrication, less maintenance requirements, and overload protection [3]. Due to the poor performance of the ferrite permanent magnet (PM) materials because of their low efficiency and low torque density, MGs was not an attractive option for researchers when it was initially invented in 1913 [4]. Thanks to the advent of neodymium magnets (NdFeB), the development of MGs based on NdFeB have been re-visited. MGs fabricated using NdFeB is very compact because this new PM material has an adhesive force that is about 8 to 10 times higher than that of a comparable ferrite magnet. However the supply of NdFeB material is limited and their price is fluctuating. In order to minimize the usage of NdFeB and hence reduce the cost of MG, various topologies of MGs are proposed. Nevertheless, most papers are only focused on initial design and some of them are only illustrated qualitatively.

This paper gives a comprehensive study of diverse topologies of MGs. Optimization and quantitative comparisons among different designs of MGs are presented. Furthermore, taking the maximum torque of each type of MGs as an objective function, the diameters of inner rotor, outer rotor, and modulating rings of the MGs, are optimized.

II. General Configuration of MGs

In general, the main components of MG include the inner rotor, outer rotor and stationary modulator. In order to achieve a high torque density performance, the inner rotor uses PM as the excitation source. Taking consideration of distribution of PMs in the rotors, there are two possible inner-rotor PM arrangements, which are, namely, the NS type surface mounted PMs and consequent-pole PMs. For each kind of PM arrangements of the inner rotor, the middle layer of MGs can be designed with only ferrite modulation poles or consequent PM arrangements, whereas the outer layer can be designed with only ferrite modulation poles, consequent PM poles and NS type surface mounted PMs.

Based on the combination of PMs and ferrite modulation poles in three layers of MGs, twelve possible topologies of MGs are obtained. Depending on the PM arrangements in the inner rotor, two different topologies of MGs are shown in Fig. 1 and Fig. 2. Table I illustrates the overall combinations of PMs and ferrite modultaion poles in MGs. The first column of Table I lists all possilbe topologies of MGs. The three layers of MGs with all possible components are then shown in the second to seventh columns of the table. The intersection of each row and column is marked with either 0 or 1, where 1 signifies that there exist such a component in that topology, whereas 0 means there is no such component.

TABLE I

Combination of PMs and Ferrite Modulation Poles in MGs

	Inner layer		Middle layer		Outer layer	
	PMs	Ferrite segments	PMs	Ferrite segments	PMs	Ferrite segments
MG1	1	0	1	1	1	0
MG2	1	0	1	1	1	1
MG3	1	0	1	1	0	1
MG4	1	0	0	1	1	0
MG5	1	0	0	1	1	1
MG6	1	0	0	1	0	1
MG7	1	1	1	1	1	0
MG8	1	1	1	1	1	1
MG9	1	1	1	1	0	1
MG10	1	1	0	1	1	0
MG11	1	1	0	1	1	1
MG12	1	1	0	1	0	1

III. Optimized Design of MGs

After obtaining the initial topology in Section II, an optimal design method based on GA and FEM is proposed to further improve the torque performance of the proposed MGs. During the optimization, the outer diameter and the shaft diameter of MGs are fixed and the PM area is kept constant. In other words, the volume and cost of the MGs are constrained. For each GA element, the objective function is the output torque which is computed using FEM. Hence the optimized torque performance is obtained. Depending on the configuration of MGs under study, it is observed that there are four parameters, including the height of inner rotor's PM layer (h_1), the height of stator's segments (h_2), the height of outer rotor's PM layer (h_3), the distance between the shaft and inner rotor (r), that govern directly the distribution of PMs and also the torque density of the MGs. In this study, the air gap lengths (a) are set as 1 mm. The radius of the shafts (r_i) are set as 20 mm. The outside radius of the gears (r_o) are set as 120 mm. In order to compare the torque density of each type of MGs with equal cost, the total volume of PMs being used in each MG is fixed. Apparently, any parameter can be expressed as a function of the other three parameters for simplifying the optimization process. The detailed explanations are described below.

For the inner layer, the total cross-sectional area, except the inner ferrite circle, is

$$S_{inner} = \pi(r_i + r + h_1)^2 - \pi(r_i + r)^2 \tag{1}$$

The total cross-sectional area of the middle layer is

$$S_{middle} = \pi(r_i + r + h_1 + a + h_2)^2 - \pi(r_i + r + h_1 + a)^2 \tag{2}$$

Also, the total cross-sectional area of the outer layer is

$$S_{outer} = \pi\left(r_i + r + h_1 + a + h_2 + a + h_3\right)^2 - \pi\left(r_i + r + h_1 + a + h_2 + a\right)^2 \tag{3}$$

For each MGs listed in Table I, the consumption of PMs in each layer can be calculated by a linear combination of (1), (2), and (3) with suitable coefficients. For instance, when the layer made up of PMs completely, the coefficient is determined as 1. When the layer made up of consequent-pole pairs, the coefficient is determined as 1/2. When the layer made up of only ferrite segments, the coefficient is determined as 0. Thus the sum of (1), (2), and (3) with appropriate coefficients should be equal to the total area of the PMs, S_{PM}.

In this paper, S_{PM} is set as 14947.70 mm^2 which is one-third of the area of the entire materials. The lengths of the MGs are set as 100 mm. When considering the constraints on the actual technological design of the MGs, the height of each layer should be no less than 4 mm. The final results of maximum torque density of each MGs are listed in Table II.

TABLE II
OPTIMIZED DESIGNS OF MGS

	h1(mm)	h2(mm)	h3(mm)	r(mm)	Maximal Torque(Nm)
MG1	15	6	6	65.56	105.31
MG2	16	9	9	60.50	137.83
MG3	20	12	8	57.58	68.49
MG4	20	10	6	55.73	118.76
MG5	18	8	16	54.19	94.19
MG6	26	4	5	58.50	11.05
MG7	26	8	8	53.20	94.48
MG8	25	14	14	42.48	107.42
MG9	28	28	4	36.46	35.30
MG10	26	8	12	48.24	98.22
MG11	38	6	18	34.39	75.50
MG12	60	4	4	29.30	17.83

IV. REFERENCES

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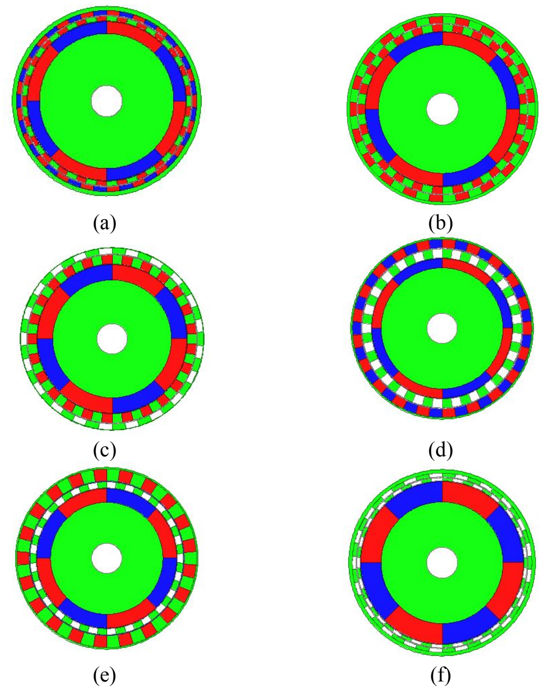

Fig. 1. Inner rotor with NS type surface mounted PM design. (a) MG1. (b) MG2. (c) MG3. (d) MG4. (e) MG5. (f) MG6.

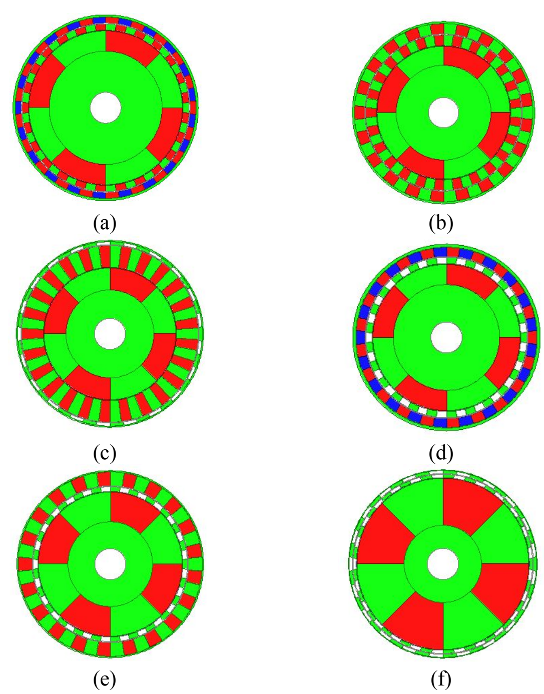

Fig. 2. Inner rotor with consequent pole PM design. (a) MG7. (b) MG8. (c) MG9. (d) MG10. (e) MG11. (f) MG12.