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Design and Analysis of Magnetic-Geared Permanent Magnet Motor considering Magnetic and Mechanical Structure

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Abstract

Background/Objectives: There is an increased interest in high-torque, low-speed machines for applications such as home appliances, and traction systems. The magnetic-geared permanent magnet (MGPM) machine is optimized for high-torque, low-speed applications.

Methods/Statistical analysis: An electromagnetic characteristics analysis is performed using the finite element method to design a structure that satisfies the optimum electromagnetic performance, while considering the manufacturing structure of the magnetic flux modulation pole.

Findings: The MGPM machine overcomes the disadvantages of maintenance and axial length through the use of mechanical gears and high-speed machines, and is an effective alternative to the mitigate the problem of low operating ranges of multi-pole PM machines. This is because the iron pole is used inside the MGPM machine, to modulate the magnetic flux to determine the gear ratio. However, as the structure of the modulation pole is complex, it is supported by using a molding or a bobbin, which causes mechanical and manufacturing problems. Therefore, in this paper, we propose a modulation pole structure that considers the magnetic circuit analysis and manufacture prototype. The electromagnetic performances of the designed model are analyzed by finite element analysis.

Improvements/Applications: From this study, it is possible to derive a design method that improves the fabrication and electromagnetic characteristics of MGPM machines.

***Key Words*:** Magnetic-geared permanent magnet machine, non-contact magnetic device, modulation effect, magnetic gear ratio, electromagnetic analysis.

1 Introduction

Recently, electric machinery for low-speed and high-torque applications have become necessary in renewable energy, electric vehicles, home appliances, etc. These electric machines primarily use an induction machine-reducer structure and multipolar permanent magnet machines.

However, due to the mechanical contact, the reducer inevitably generates noise and vibration, and the efficiency is low, which can reduce the life and reliability of the system. The mechanical reducer has a large installation space and lacks working clearance, which causes contact interference, or reduces the operating range of the machine operating portion, thereby increasing the weight of the machine1. In addition, a multi-pole permanent magnet machine has a simple structure, light weight, and high efficiency, as described in many papers, but it is has the disadvantages that it is weak in magnetic saturation, high temperature rise, and so on[2–4].

In order to solve these problems, research on magnetic gears has been actively conducted recently. These magnetic gears have no wear and no lubrication, as the input and output shafts are physically separated and have no mechanical contact. In addition, when the efficiency is higher than that of the mechanical gear and overload torque is applied, the overload protection function (torque fuse) is advantageous as the gear can be safely rejoined, and the influence of noise and vibration is small[5]. In order to overcome the limitations of magnetic gears, various papers on magnetic-geared machines integrated with magnetic gears and permanent magnet machines have been published since Atallah's paper[1].

These magnetic-geared permanent magnet (MGPM) machines are classified differently from conventional electric machines. They have a very high torque density because the machine and the gear are integrated, and the volume occupied in the axial direction can be remarkably reduced.

Unlike magnetic gears, an MGPM machine has a permanent magnet power shaft, which corresponds to the stator of a conventional permanent magnet synchronous motor, and the distribution of the magnetic field can be generated by using a three-phase rotating magnetic field. The operation principle of the MGPM machine has three power axes, and movement can be obtained by fixing two power axes.

In the stator of the magnetic field characteristic, the magnetic field generated by the winding is modulated by the iron pole located at the center, and the magnetic field of the rotor is synchronized to move with a constant gear ratio. Since the knowledge related to fabrication has not been obtained, the principle of operation and finite element analysis for such MGPM machines are mostly studied in the literature. Therefore, in this paper, design and characteristic analysis considering the manufacturability using finite element method are presented, and proposed models suitable for fabrication are presented, based on various analysis results.

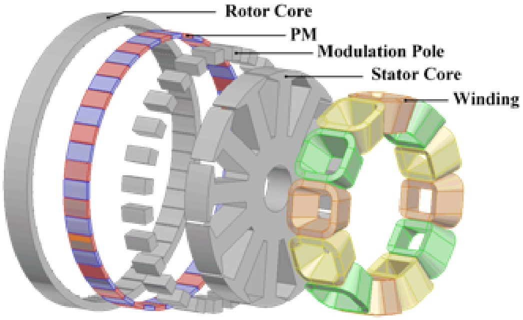

Fig. 1.Structure of MGPM machine

2 Electromagnetic analysis of MGPM machine

2.1 Analysis of MGPM machine

The structure of an MGPM machine is shown in Figure 1. The analysis model shown in this paper consists of a rotor with 46 poles and a stator with 8 poles, and consists of 27 flux cores between the stator and the rotor. The magnetic field generated by the permanent magnet of the rotor and the magnetic field generated by the coil of the stator are modulated by the magnetic flux modulation core, to operate with a gear ratio.

2.1.1 Structure of MGPM machine

The number of modulation poles in the MGPM machine is determined by the number of magnetic poles inside and outside, which is the same as the principle of magnetic gears[6−8].

$$N_m = p_s + p_r \tag{1}$$

whereps and p_r represent the number of magnetic poles of the stator and rotor, respectively.

If the mechanical rotation frequency of the rotor is f_r, the frequency induced in the armature can be expressed as (2).

$$f_s = \frac{p_r}{p} f_s \tag{2}$$

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2.1.2 Operating characteristic of MGPM machine

As a magnetic gear, the motion of the MGPM machine can be divided into a rotor, a stator, and a magnetic flux modulation pole, and the speed relational expression at this time can be expressed by the following equation (3)[9−10].

$$\omega_r = \frac{mp_s}{mp_s + kN_m} + \frac{KN_m}{mp_s + kN_m} \tag{3}$$

wherem = 1, 3, 5, $\cdots$, ∞ , k = 0, 1, 2,$\cdots$, $\pm\infty$,ω_s, ω_r, and ω_m represent the synchronous speed of the stator, the rotor speed, and the speed of the modulation pole, respectively.

When the magnetic flux modulating core is fixed, the gear ratio of the MGPM machine can be expressed by Equation (4).

$$G = \frac{mp_s}{mp_s + kN_m} \tag{4}$$

In order to transmit the torque at the outer and inner speed conditions, the number of poles of the rotor must be equal to the number of poles of the spatial harmonic(k≠0). Since the asynchronous spatial harmonics are largest for m=1and k=-1, the gear ratio can be expressed by Equation (5).

$$G = \frac{p_s - n_m}{p_s} \tag{5}$$

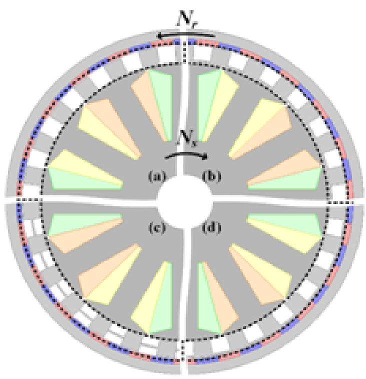

Fig. 2. 2D Structure of MGPM machine according to modulation pole structure

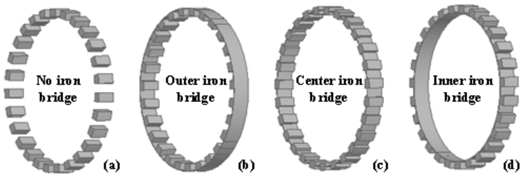

Fig. 3. Various flux modulating iron pole structures of the MGPM machine: (a) no bridge, (b) outer bridge, (c) center bridge, and (d) inner bridge

Table 1. Characteristic analysis of MGPM machine with different modulation structure

Parameters	Value	Unit
Inner radius of stator	17.5	mm
Outer radius of stator	27.8	mm
Inner radius of modulation pole	89.5	mm
Outer radius of modulation pole	99.5	mm
Inner radius of PM rotor	100.5	mm
Outer radius of PM rotor	110	mm
Effective stack length	21	mm
Height of PM	3	mm
Reference speed	130	mm
Rated current	25	A
Turn per coil	30	-
Number of stator slot	12	-

2.2 Electromagnetic analysis of MGPM machine according to rotor structure

Figures 2 and 3 show the shape of the MGPM machine's flux modulation core bridges. The flux modulation pole area consists of an iron core and an air gap, which has a complicated manufacturing process. Therefore, in this paper, a model with optimal characteristics is selectedas shown in Table 1, which simplifies the manufacturing process by using the same structure as the bridge in the interior permanent magnet synchronous machine, and analyzing it according to bridge position.

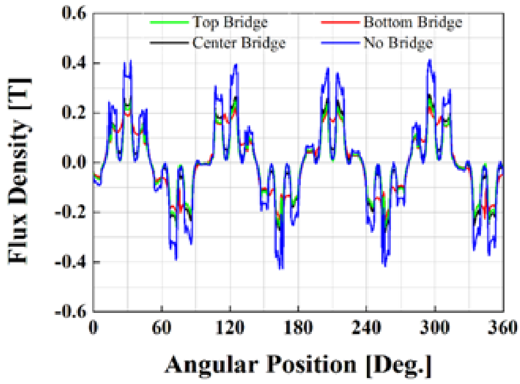

Fig. 4. Flux density at the inner air gap according to modulation pole structure

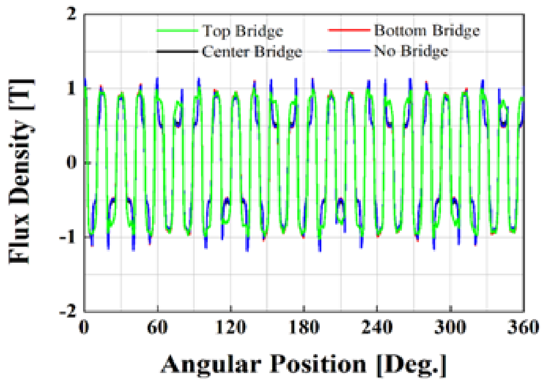

Fig. 5. Flux density at the outer air gap according to modulation pole structure

Figures 4 and 5 show the magnetic flux densities of the inner and outer air-gap regions, respectively. It can be seen that the largest space harmonic is successfully modulated by the modulation pole from 4 pole-pairs in the inner airgap to 23 pole-pairs in the outer airgap.

2.2.1 NO-load

Figures 6 and 7 show the analysis results of the cogging torque and counter-electromotive force analysis of the MGPM machine during a no-load condition, respectively. The largest cogging torque occurs when the bridge is located inside, but the leakage component is relatively small and the counter electromotive force is the largest.

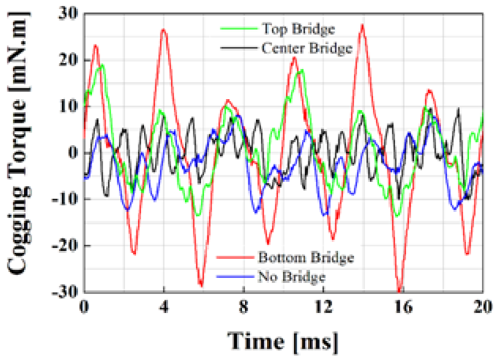

Fig. 6. Cogging torque analysis according to modulation pole structure

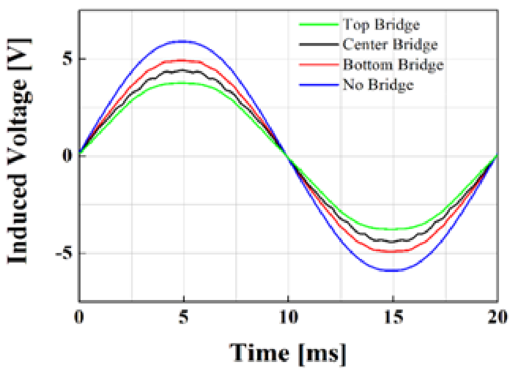

Fig. 7. Induced voltage analysis according to modulation pole structure

2.2.2 On-load

Figure 8 shows the results of the torque characteristics analysis under the rated load condition. In the presence of a bridge, the distortion component is relatively increased in the air gap magnetic field, so that a large torque ripple occurs, and the average torque is small due to the leakage component. Figure 9 shows the results of the analysis of the iron loss characteristics under the rated load, according to the bridge position. When the bridge exists, the magnetic flux saturates in the bridge, and the iron loss is larger than in the case where the bridge is absent. In addition, since the flux saturation increases when the bridge is located on the inner side, and it can be seen that the iron loss is largest when the bridge is located on the inner side.

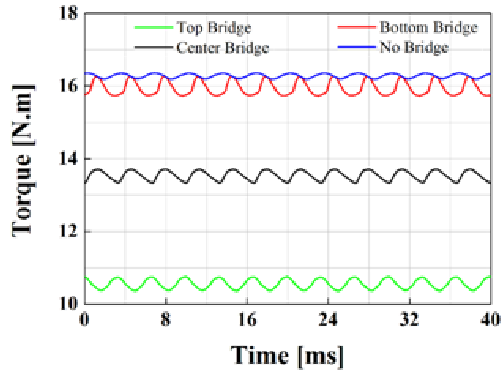

Fig. 8. Electromagnetic torque analysis according to modulation pole structure

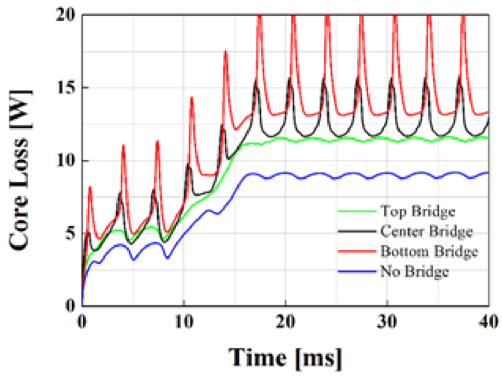

Fig. 9.Core loss analysis according to modulation pole structure

3 Results and Discussion

Table 2 shows the analysis results for each bridge position. Model 1 is the upper bridge, Model 2 is the middle bridge, Model 3 is the lower bridge, and Model 4 is the bridgeless model. It can be seen that the magnetic leakage component decreases when the bridge is located on the inner side, thereby improving the output characteristics. However, the cogging torque, torque ripple, and iron loss were found to be large compared with other models.

Table 2. Characteristic analysis of MGPM machine with different modulation structure

Parameters	No bridge	Outer bridge	Center bridge	Bottom bridge
EMF [V]	3.17	2.72	3.12	3.52
Cogging [mN·m]	21.213	34.061	20.429	58.373
Torque [N·m]	12.332	10.562	13.542	15.942
Core loss [W]	8.2303	11.462	12.68	14.664
Rotor loss [W]	0.322	0.303	0.513	0.586
Copper loss [W]	13.5	13.5	13.5	13.5

4 Conclusion

In this paper, based on the structure and operation principle of an MGPM machine, characteristic analysis is performed for each bridge position. Leakage magnetic flux is generated due to the bridge structure, which has the disadvantage of reducing the performance of the motor, but the bridge area is essential as it simplifies the complicated manufacturing processes. Therefore, the model with the best characteristics was selected by analyzing the characteristics of the flux modulation core according to the position of the bridge.

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