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ANALYSIS OF WOUND STATOR MAGNETIC GEAR USING THREE SEGMENT HALBACH ARRAY

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Abstract

The present study discusses a new structure of single layer magnetic gear (SL-MG) with Halbach array in external rotor, which is named single layer magnetic gear with Halbach array (HSL-MG). The key point in this design is using three segment Halbach array instead of the conventional permanent magnets in magnetic pole pairs of external rotor in single layer magnetic gear, and this leads to increasing the magnetic couple between wound stator and permanent magnets of external rotor. Electromagnetic function and FEM two dimensional analysis are done on both magnetic gears and these two magnetic gears of wound stator are compared with each other. The results show that the magnetic gear under study has a higher torque density than its conventional version; therefore, this kind of magnetic gear is more suitable for low-speed engines and high torque direct drive applications.

Keywords: Magnetic gear, Halbach Array, Direct Drive Applications, Wound stator

1. INTRODUCTION

Today, low-speed and high-torque engines in Direct Drive Applications have attracted so much attentions. Among them, permanent magnet engines are more famous because of their high torque density and high efficiency [1]-[3]. However, traditional direct drive applications still suffer from problems like large size and low torque density. Usually, Mechanical gearboxes are used beside permanent magnetic engines, so that the size of machines be smaller and output torque be increased, which in return decreases factor of safety and overall efficiency of system. Direct drive applications with high torque density are considered for solving these problems and must be developed.

Axial magnetic gears have been suggested for 20 years [4]-[5]. These magnetic gears use a modulation ring to increase pairing of magnetic fields induced from magnets in internal and external rotors. Using this idea, different kinds of magnetic gears have been made and investigated [6]-[10]. In the study [8], a new kind of magnetic gears was introduced which is shown in figure 1. This kind of magnetic gear was known as single layer magnetic gear, the permanent magnets of which were on the external rotor and wound stator was used instead of permanent magnet in external rotor. This single layer magnetic gear can provide high torque density, and in addition, it is suitable for direct drive applications with high torque and low speed. Halbach arrays have also attracted much attention in the field of electronic machines and they have significant advantages. It is well Known that Halbach PM arrays hold some attractive features, namely , near sinusoidal airgap flux density distribution, strong field intensity, and good self-shielding magnetization [11]-[14]. The present study discusses a new structure of single layer magnetic gear. In this structure, Halbach array is used in external rotor, instead of magnets of external rotor polar pairs. In this study, the researchers introduce the structure of this magnetic gear and its function. To analyze the single layer magnetic gear with Halbach array, the finite element method (FEM) was used and the electromagnetic function of both single layer gears were evaluated and compared quantitatively. Using two dimensional analysis of FEM, the radial flux density and harmonic spectrums in both single layer gears were analyzed. As these gears have high torque and low speed, they are used in a broad range in electronic engines like electric vehicles, generators and washing machines.

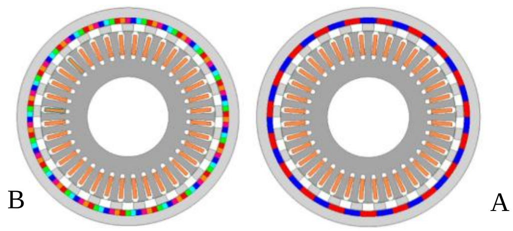


Fig. 1. SINGLE LAYER MAGNETIC GEAR, (A) CONVENSIONAL, (B) HALBACH

2. CONFIGURATION AND FUNCTION

2.1. Configuration of Wound Stator Magnetic gears Using Three Segment Halbach Array

The general structure of single layer magnetic gears with Halbach array is shown in Fig. 1.B. It consists of three basic parts, named internal stator, external rotor and modulation rings which are located between external rotor and stator. In this structure, three segments Halbach array is used in external rotor. Figure 2 shows the installation of permanent magnets with Halbach magnetic direction for a pole pair of single layer magnetic gear. Halbach arrangement of permanent magnets can be achieved through arrangement of discrete parts of permanent magnets. Arrangement of permanent magnets with Halbach direction leads to increase of magnetic field in one side and on the other side, fiend strength is eliminated. Also, using this array, distribution of magnetic field approximates sinusoidal. Figure 3 shows one part of single layer magnetic gear with Halbach array and magnetic direction in each part of permanent magnets is obtained by:

$$\vec{M} = M_x + jM_y = \cos\big((1+p)\theta\big) + jM\sin((1+p)\theta) \quad (1)$$

In which p equals number of magnetic polar pairs, θ is the angle between X axis and the imaginary line between each part of magnet. In equation (1), M equals:

$$M = \frac{B_r}{\mu_0} \quad (2)$$

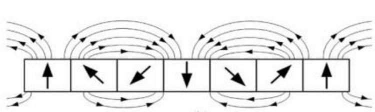


Fig. 2. HALBACH ARRAY

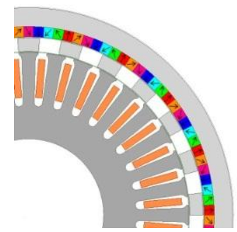


Fig. 3. A CLOSE-UP OF HALBACH ARRAY IN WOUND STATOR MAGNETIC GEARS

2.2. Functional principles of magnetic gears

To transfer torque between internal stator and external rotor, magnetic gears work based on modulation of flux density distributed in air gaps. This modulation is done by modulation rings in internal stator and external rotor. Choosing the suitable number of polar pairs in external rotor and adjustment of internal stator, a stronger magnetic couple can be made. To do so, the following equation can be used:

$$MR = P_{ro} + P_{ri} \quad (3)$$

Where P_{ro} is the number of polar pairs in external rotor, P_{ri} is the number of polar pairs in internal stator, and MR is the number of fixed rings. In internal stator, armature windings are arranged in 3 phase with 6 polar pairs and 36 gaps and the external stator has 19 polar pairs. So the number of modulation rings between internal stator and external rotor is 25. The gear ratio in wound stator magnetic gears is defined by:

$$NG = {}^{P_{ro}}/_{P_{ri}} \quad (4)$$

Where NG is the gear ratio and in the gear under discussion, this ratio is 3.17. The relation between mechanical rotation frequency of engine F and Electrical frequency f is as follows.

$$f = F.{}^{P_{ri}}/_{P_{ro}} \quad (5)$$

3. FUNCTION ANALYSIS AND COMPARISON

Table 1 shows all the information regarding simulation of two single layer wound stator magnetic gear. The function of these two gearboxes is analyzed and compared using FEM method. To fairly compare the conventional gear and the proposed gear, structural information in both gearboxes is considered identical.

TABLE. 1. STRUCTURAL INFORMATION OF THE MACHINE

Total diameter of machine	245
Axial length	120
Air gap length	0.7
Modulation ring thickness	8
External rotor thickness	11.5
External rotor permanent magnet thickness	5.93
Number of armature polar pairs	6
Number of external rotor permanent magnet polar pairs	19
Number of modulator segments	25
Number of stator grooves	36
Number of phases	3
Number of conductors	25
Magnetic flux density (NdFeB)	1.1 Tesla
Relative magnetic permeability	1.0446
Nucleus material	steel
Internal rotor rated speed	480

3.1. Magnetic Field Distribution and Harmonic Analysis

Figure 4 shows magnetic field distribution in both magnetic gears. It is evident that magnetic flux density in external yoke of the proposed magnetic gear rotor is less than magnetic flux density in external yoke of conventional magnetic gear rotor. So, using this method, external yoke length can be reduced, which in return can reduce the overall volume and weight of magnetic gear. It also reduces rotor inertia.

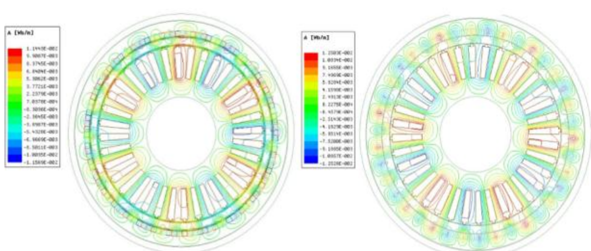
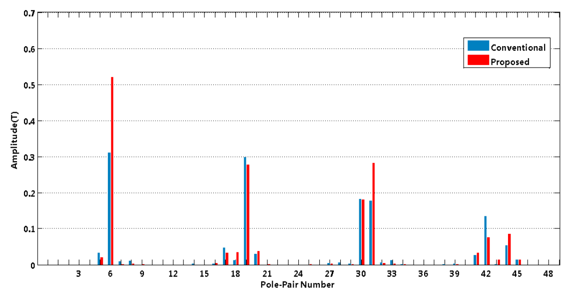


Fig. 4. MAGNETIC FIELD DISTRIBUTION, (A) CONVENTIONAL, (B) PROPOSED

B A

Figures 5, 6, 7, and 8 show harmonic spectrum of tangential and radial flux density in internal and external air gap. As for the effect of modulation rings, magnetic flux density in both air gaps consists of particular harmonics. Based on the analysis of [15], it can be found that a number of harmonics are synchronous harmonics and help sustainable torque transfer, therefore they can be called desirable harmonics. A number of harmonics are asynchronous harmonics which lead to torque ripple and they can be named undesirable harmonics. Synchronous harmonics in single layer wound stator gears are harmonics 6, 19, 31, and 44; and undesirable harmonics are 4, 7, 18, 30 and 42. Figure 5 shows the harmonic spectrum of tangential and radial flux density in internal air gap. In this figure, all desirable harmonics, except harmonic 19, have increased, which is due to Halbach array of external rotor magnets. The amplitude of harmonic 19 is decreased in internal air gap. Figure 6 shows the harmonic spectrum of tangential and radial flux density in external air gap. It is clear from the figures that the external air gap of synchronous harmonics has increased in single layer magnetic gear with Halbach array compared to single layer magnetic gear, and this is the main reason of decreasing ripple and increasing torque which is explained in part b. in detail.

A



B

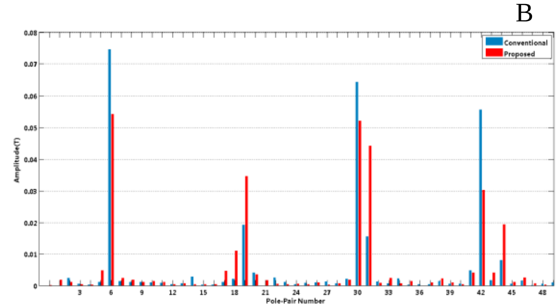


Fig. 5. HARMONIC SPECTRUM OF FLUX DENSITY IN INTERNAL AIR GAP, (A) RADIAL, (B) TANGENTIAL

3.2. Torque Analysis

Figure 7 .A. shows torque vs. rotor angle curve for the conventional and proposed single layer magnetic gears. Stator windings are fueled with sinusoidal balanced current and current density of 8 A/mm^2. Figure 7. B. shows torque vs. time curve for the single layer magnetic gears. As a whole, figure 7 shows that single layer magnetic gear with Halbach array can produce a torque of 220 Newton per meter, which has 20% increase compared to the conventional single layer magnetic gear. When the modulation rings between wound stator and external rotor are omitted, the output torque is reduced to a great extent. It's evident from figure 7 that although modulation rings are deleted from single layer magnetic gears with Halbach array, the gear still works, but the output torque reduces from 220 to 136

Newton per meter, which shows that modulation rings produce 38% of the whole output torque.

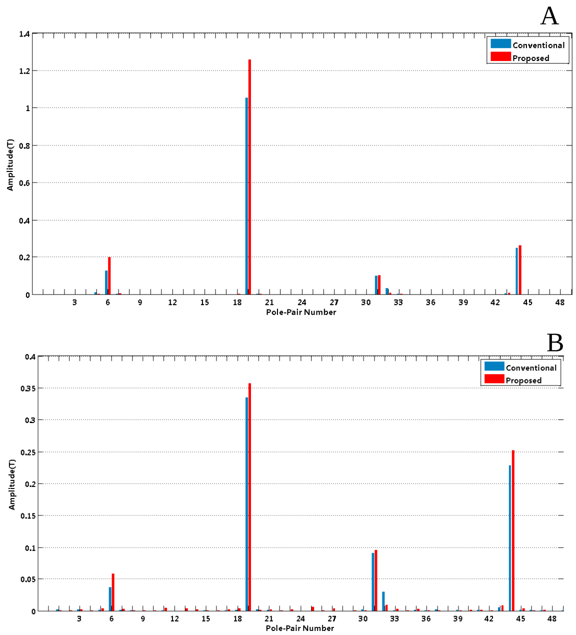


Fig. 6. HARMONIC SPECTRUM OF FLUX DENSITY IN EXTERNAL AIR GAP, (A) RADIAL, (B) TANGENTIAL

3.3. Torque ripple analysis

Figure 10 shows the torque ripple of external rotor in both conventional and proposed magnetic gears. It can be seen in figure 10 that the torque ripple of external rotor in magnetic gear with Halbach array is much less than the torque ripple of external rotor in the conventional magnetic gear. Torque ripple of magnetic gear with Halbach array is 3 N/m, which is 40% less than the torque ripple in conventional magnetic gears. Torque ripple of the conventional magnetic gear is 5 N/m.

3.4. Analysis with different currents

Figure 11 shows the curve of torque vs. current density in magnetic gears. As you can see in the figure, the torque of magnetic gear increases as the current density increases. When the current density of 20 milliampere enters the stator windings, the torque output of wound stator magnetic gear reaches 340 and 360 N/m. After that, as the current increases, the curve approaches a linear mode, since a high current density leads to magnetic saturation, which prevents torque increase. In the present study, a current of 8 A/mm2 is chosen for the research, because in this current, the curve is on its knee point. Magnetic gears in higher currents may get involved in magnetic saturation and windings may burn as well.

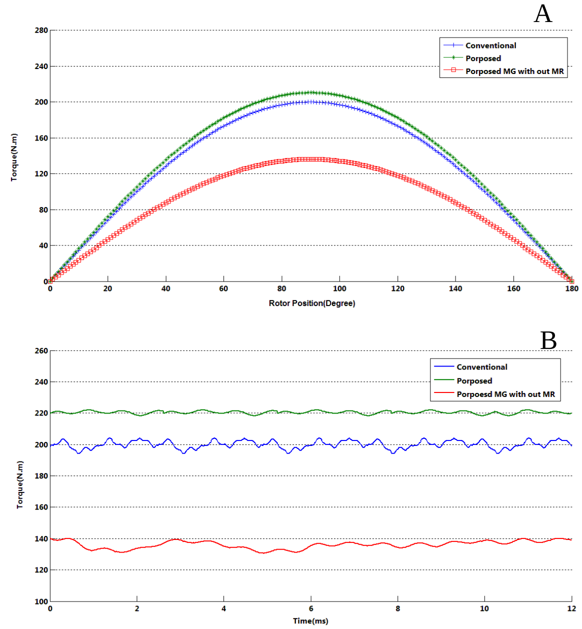


Fig. 7. (A) TORQUE-ANGLE CURVE IN SINGLE LAYER WOUND STATOR MAGNETIC GEAR, (B) TORQUE-TIME CURVE IN SINGLE LAYER WOUND STATOR MAGNETIC GEAR

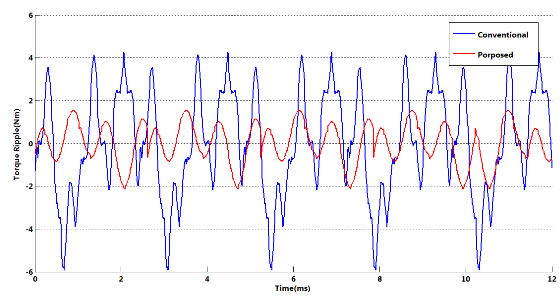


Fig. 10. TORQUE RIPPLE IN EXTERNAL ROTOR

4. CONCLUSION

The present study aimed to design and analyze a new form of single layer magnetic gear with Halbach array. This magnetic gear is suitable for low-speed engines and high torque direct drive applications. The important point in this magnetic gear is the reasonable integration of fields produced by stator and rotor magnets. Torque output in this magnetic gear increased 10 percent compared to the conventional form. Also torque ripple decreased for 40% compared to the conventional gear. In this study, harmonic analysis of magnetic fields in air gaps of these tow gears was done. It was found that synchronous harmonics increased and asynchronous harmonics decreased to a great extent.

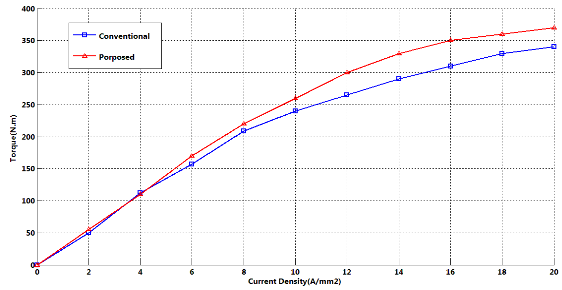


Fig. 11. TORQUE VS. CURRENT DENSITY CURVE

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