IUST Iran University of Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Research Paper

An Axial Magnetic Gear With Improved Torque Density and Reduced Cogging Torque

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Abstract: A new axial magnetic gear (AMG) with enhanced torque density and reduced cogging torque is proposed in this paper. In the new structure, the direction and width of permanent magnets in high-speed rotor are changed and permanent magnets are removed from the modulator while the low-speed rotor remains unchanged. The torque density of the proposed magnetic gear is enhanced by using an appropriate direction and pole pitch for permanent magnets of high-speed rotor. The proposed AMG is compared with recent structures in the literature with the highest torque density. Three-dimensional (3D) finite element analyses are employed to obtain the cogging torque and torque density. The results of the analysis indicate that not only torque density increases but also cogging torque decreases dramatically.

Keywords: Coaxial Magnetic Gear, Axial Magnetic Gear, Cogging Torque, 3D Finite Element Method.

1 Introduction

MAGNETIC gears (MGs) compared to usual mechanical gears, have many excellences, including reduced maintenance, ameliorated reliability, intrinsic overload protection, space separation between input and output shafts, low vibration, no need for lubrication, and low losses [1, 2]. Based on the magnetic flux orientation, MGs can be categorized into these two main groups: axial magnetic gears (AMGs), coaxial magnetic gears (CMGs), as shown in Fig. 1. Compared to CMGs, axial magnetic gears have unique features such as simple mechanical structure, complete separation of input and output axes, ability to design with a large number of poles, adjustability, and uniformity of air-gaps [3].

Selection of the most suitable topology for a particular application is one of the most important steps in integrated systems. CMGs have been mostly used, traditionally. However, it seems that CMGs are no more the most appropriate selection for some particular applications. AMGs can be a better alternative if the axial length is limited or if the machine should be designed with a large number of poles. Furthermore, the separation between input and output axes is an important demand in industries such as chemical, pharmaceutical, food, and aerospace, and this is only possible with AMGs.

Despite the many and sometimes unique features of AMGs, axial magnetic gears have been less studied, compared to CMGs. Therefore, it is obvious that the process of designing and improving this type of magnetic gears is still developing. Furthermore, MGs have so far been more optimized towards a higher torque density, while a lack of attention to cogging torque will lead to mechanical unreliability, high noise, and high-performance vibration.

Mezani *et al.* [1] have proposed an axial magnetic gear with high performance for completely separated systems. Permanent magnets (PMs) made of NdFeB were fixed on back iron of low and high-speed rotors and the modulator does not have PMs. The proposed AMG provided a torque density of 70 kN/m^3. In [2], a new design of AMG with ferrite PMs has been proposed in which back irons were removed and AMG torque density reached 47 kN/m³. Another MG design towards a higher torque density has been suggested in [3]. The proposed structure was a combination of AMG and transverse flux modulated magnetic gear (TFMMG). The modulator has L shape. The torque density of 3 kN/m³ and 74 kN/m³ can be obtained by this

Iranian Journal of Electrical and Electronic Engineering, 2021.
Paper first received 28 November 2020, revised 29 January 2021, and accepted 14 February 2021.
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https://doi.org/10.22068/IJEEE.17.4.2043

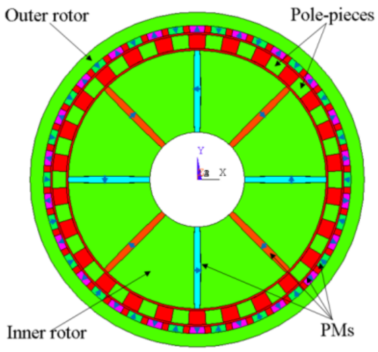
configuration using ferrite and NdFeB magnets, respectively. Proposed AMG in [4] included a high-speed rotor, a low-speed rotor, and two non-moving rings. The torque density of 77 kN/m³ could be obtained. Authors in [5] have also presented an MG that is a combination of AMG and TFMMG. The proposed MG is similar to that of [3] unlike the modulator of [5] has T shape. The torque density of the AMG reached to 261 kN/m³. In [6], an MG has been introduced in which the PMs were used in the modulator of AMG. The torque density of the base AMG was 150.7 kN/m³ by using rare earth PMs. In 2018, superconducting bulk magnets (SBMs) have been used instead of permanent magnets in AMG [7]. The effect of SBM on torque density was investigated and it was compared with conventional AMG equipped with a permanent magnet. It was shown that higher torque density can be achieved with SBM. However, the manufacturing cost is significantly increased. In [8], a new axial flux magnetically geared permanent magnet machine for power split application in hybrid electric vehicles has been proposed. The influences of the machine parameters such as inner and outer radius on the output torque as well as the machine performance are investigated. However, cogging torque was not considered and other parameters were kept constant. Authors in [9] suggested an axial flux focusing magnetically geared generator for low-speed applications. A flux focusing high-speed rotor is common between stator and MG. The main focus of the paper is to evaluate the structural aspects of the machine and does not study the torque density and cogging torque. In [10], another flux focusing axial flux magnetic gear for an ocean generator application has been introduced. In order to maximize torque density, a sweep analysis has been utilized. The main drawback of the proposed structure is the complexity of its structure. In 2020, an AMG with rectangle magnets was suggested [11]. Special topology of AMG drastically reduced torque density, but it had advantages such as easy construction, inexpensive, and simple structure.

Recently, various studies were conducted on cogging torque reduction techniques in magnetic gears [12-16]. Reference [12] described the harmonic ranges of the cogging torque of a CMG. In [13], the influence of the pole numbers on the cogging torques of a CMG has been described. Also, it has been shown that how continuous and discrete skewing could suppress torque harmonics effectively. A novel CMG design has been introduced in [14] in which, unlike the conventional CMGs, the modulator was out part of the magnetic gear and the low-speed rotor was located between the modulator and high-speed rotor. In this new design, the cogging torque was significantly reduced. For the first time, new definitions of cogging torque in [15] for magnetic gears and electrical machines equipped with magnetic gear were proposed. In this reference, the synchronous and the true cogging torques were introduced. If MG worked without load, the cogging torque would be defined as synchronous cogging torque and if MG worked on load, the cogging torque would be defined as true cogging torque. An improved quasi 3D analytical method has been used to investigate the consequences of skewing of PMs and pole-pieces made of ferromagnetic on the cogging torque (as a temporary state of AMG) by appropriate step changes as a parametric analysis [16].

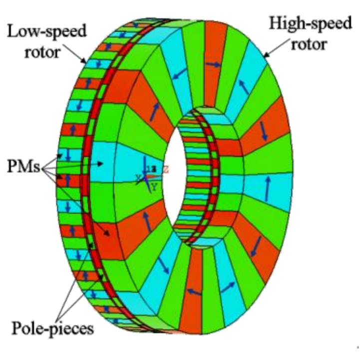
In this paper, an improved AMG is presented. To the best of the authors' knowledge, in the literature, this topology has not been mentioned. Not only it has lower cogging torque but also it has higher torque density compared with the base AMG of [6]. Description of improved AMG configuration will be shown in the following and proposed topology is analyzed by 3D finite element method. The performance of the improved AMG is quantitatively compared with those of its base AMG.

2 Proposed Configuration

The configuration of the proposed AMG is shown in Fig. 2. As illustrated, the brown color indicates those PMs that have been magnetized in a negative peripheral direction, the blue color indicates those PMs that have been magnetized in a positive peripheral direction and the purple color indicates those PMs that have been magnetized in a negative axial direction. Also, the green and the red colors in Fig. 2 represent the iron and air



(a)



(b)

Fig. 1 Two main magnetic gears: a) coaxial magnetic gears and b) axial magnetic gears.

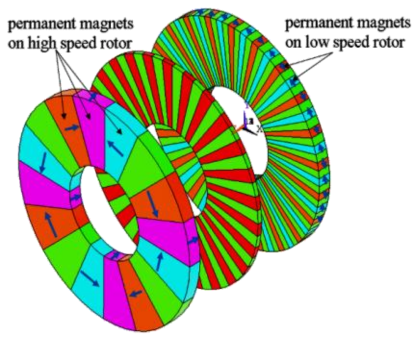


Fig. 2 Structure of the proposed AMG.

parts, respectively.

The low-speed rotor and length of air-gaps in the proposed AMG and base AMG are exactly the same. Magnetic characteristics of PMs used are kept constant to have a fair comparison. The modulators are dimensionally the same. Unlike base AMG, PMs are removed from the modulator in the proposed AMG and consequently fewer magnets have been used. Furthermore, similar to [6] and unlike [5], in improved AMG, the total area of the high-speed rotor is divided into sixteen equal segments. As it is clear from Fig. 2, the first three segments are respectively magnetized in the positive circumferential, the negative axial, the negative circumferential, while the fourth sector is made of iron and so on.

3 Working Principal

In the considered AMG, the low-speed and high-speed rotors have respectively p_l and p_h pole-pairs. The modulator has n_p pole pieces. The magnetic fields created by low and high-speed rotors are modulated after passing through the modulator. If the magnetic field created by low-speed has p_l pole-pairs, it will be converted to p_h pole-pairs after passing through the modulator and if the magnetic field created by high-speed has p_h pole-pairs, it will be converted to p_l pole-pairs after passing through the modulator. For modulating the magnetic fields generated by low and high-speed rotors, the following situation is necessary [17]:

$$n_p = p_l + p_h \tag{1}$$

In steady-state, the following relationships can be established between the angular velocity of low-speed rotor ω_l, the angular velocity of high-speed rotor ω_l, and the angular velocity of the modulator ω_m.

$$\omega_l = \frac{p_h}{p_h - n_p} \times \omega_h + \frac{n_p}{n_p - p_h} \times \omega_m \tag{2}$$

$$p_l w_l = -p_h w_h + p_m w_m \tag{3}$$

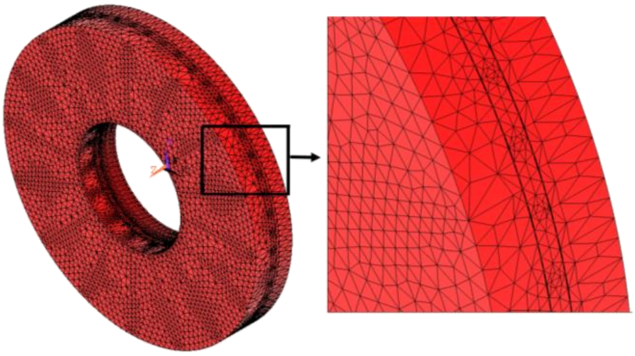


Fig. 3 3D FE model of the proposed AMG.

Assuming zero losses, the following relationships can be established between the torque applied to the low-speed rotor T_l, the torque applied to the high-speed rotor T_h, and the torque applied to the modulator T_m.

$$T_l w_l + T_h w_h + T_m w_m = 0 \tag{4}$$

$$T_l + T_h + T_m = 0 \tag{5}$$

Usually, two components of the three components rotate and the third component remains stationary. In the base AMG, the modulator is stationary $\omega_m = 0$, while both of the low and high-speed rotors rotate. Therefore, the gear ratio is defined as:

$$G_r = \frac{p_h - n_p}{p_h} = \frac{T_l}{T_h} = \frac{w_h}{w_l} \tag{6}$$

4 Performance Analysis and Comparsion Results

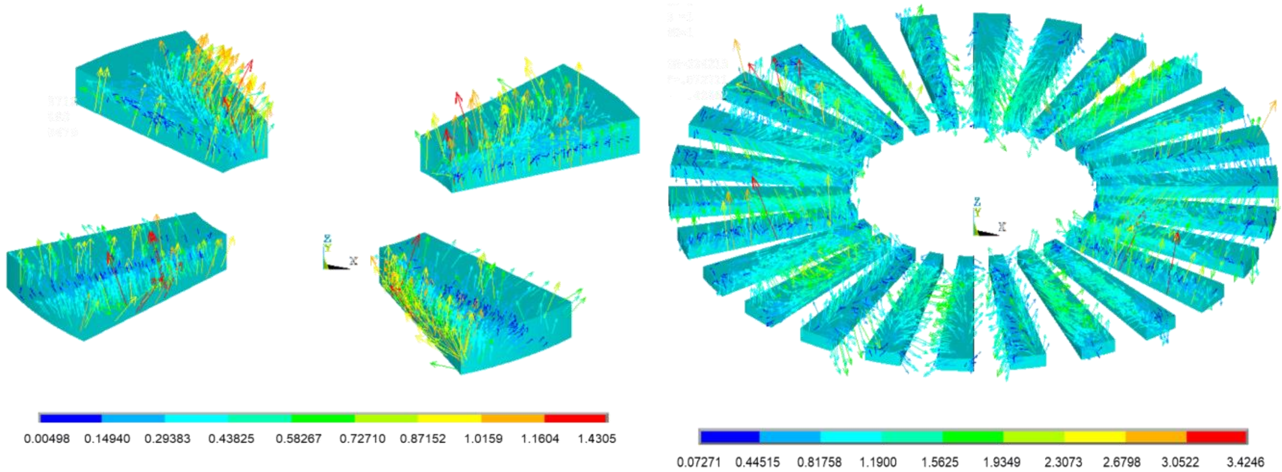
In order to appraise the performance characteristics of the proposed AMG and to have a fair comparison, 3D finite element analyses are performed. 3D FEA makes it possible to take the intrinsic 3D structure of AMG and thereby the actual 3D behavior of the flux into account. The used FEA software is ANSYS and the execution time required for analysis of once is about 1200 s with Intel Core i7, 2.20 GHz/8.00 GB system requirements.

Fig. 3 shows the FE model of the proposed AMG. It must be noted that to have an accurate enough result a denser mesh pattern should be used in the air-gap region especially for cogging torque calculation. The basic geometric parameters of the proposed AMG are arranged in Table 1. The remanence flux density of the PM materials is 0.9 T. Fig. 4 indicates the distribution of magnetic flux density in various parts of the proposed AMG.

It is obvious to appraise the transmission performance of AMGs, the curves of torque-angle are very significant. Whilst the low-speed rotor is kept in a fixed situation, twirling of the high-speed rotor step by step,

Table 1 Geometric parameters of the base and improved AMGs.

Nominal power	1.1 kW
Total axial length	42.6 mm
Axial length of high-speed rotor	18 mm
Axial length of low-speed rotor	18 mm
Axial length of iron segments (modulator)	6 mm
Outside radius of PMs of high-speed rotor	148 mm
Inside radius of PMs of high-speed rotor	60 mm
Outside radius of segments of stator (modulator)	148 mm
Inside radius of segments of stator (modulator)	60 mm
Outside radius of PMs of low-speed rotor	148 mm
Inside radius of PMs of low-speed rotor	60 mm
Number of pole pairs of high-speed rotor	4
Number of pole pairs of low-speed rotor	22
Number of stator segments	26
Gear ratio	5.5



(a) (b)

Fig. 4 The distribution of magnetic flux density; a) irons parts of high-speed rotor and b) irons parts of the modulator.

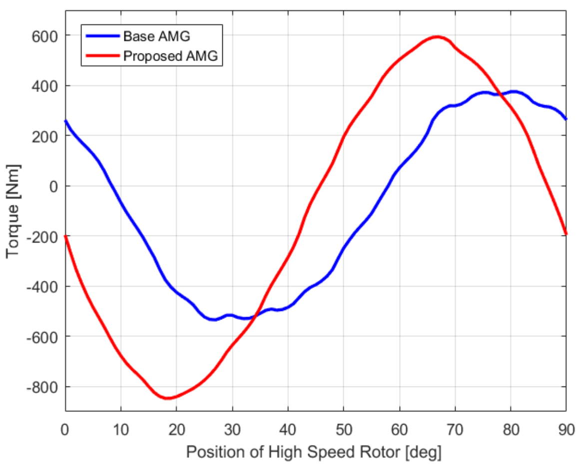


Fig. 5 Low-speed torque-angle curves of the base AMG and proposed AMG.

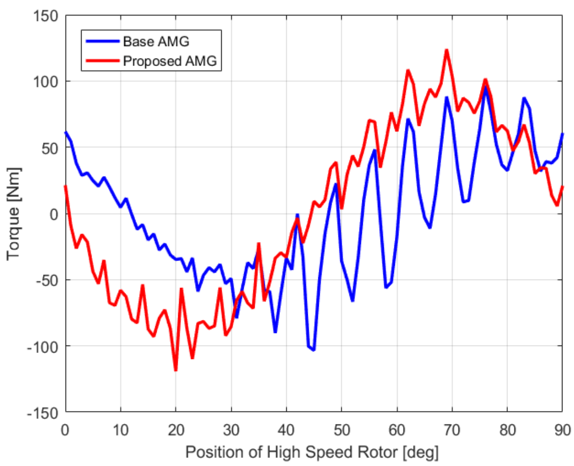


Fig. 6 High-speed torque-angle curves of the base AMG and proposed AMG.

the curves of torque-angle can be obtained. The maximum value of the curve of low-speed rotor torque-angle indicates the capacity of pull-out torque. One way to evaluate the transmission stability of a magnetic gear is to assess the high-speed rotor torque-angle curve [14]. The closer the curve of high-speed rotor torque-angle is to the sine, the more stable it is. The low-speed rotor torque-angle curves for the base AMG and proposed AMG are shown in Fig. 5. Similarly, the high-speed rotor torque-angle curves are shown in Fig. 6. The blue-colored curves are related to the base AMG while the red-colored curves belong to the proposed AMG.

As it is clear from the figures, the torque-angle curve of the proposed AMG is closer to a sinusoidal curve. So, the improved AMG is expected to have more transmission stability compared to the base AMG. In addition to torque-angle curves, the transmitted torque curves are important. Fig. 7 indicates the changes of the transmission torque with respect to the rotor position for 5.5:1 ratio AMGs. The blue-colored curves are related to the low-speed rotors while the red-colored curves belong to the high-speed rotor.

The selected base AMG presented in [6] has the second rank with the highest torque density among other structures reported in the literature. Furthermore, the structure of [6] is the most similar structure to the structure presented in this article. Therefore, this structure is selected as the base structure and the proposed AMG in this paper is compared with [6]. It must be noted that, although the torque density of the structure proposed in [5] is slightly higher than the structure presented in this paper, the permanent magnet used in [5] has a higher remanent flux density compared to other structure and with the same permanent magnets the structure presented in this paper performs better.

The curves of connected transmitted torque are compared and arranged in Tables 2 and 3 for low-speed and high-speed rotors, respectively. In tables T_{max}, T_{min}, T_{avg} denote the maximum, minimum, average values of transmitted torque, respectively. K_{ripple} is the transmitted torque ripple which is defined as

$$K_{ripple} = \frac{T_{\max} - T_{\min}}{T_{ave}} \times 100 \quad (7)$$

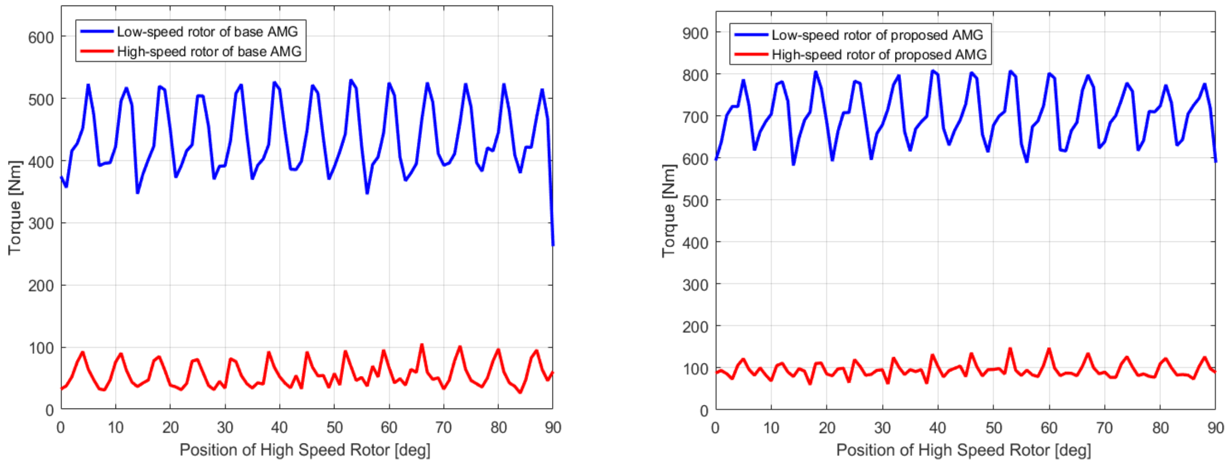


Fig. 7 Changes of transmission torque with rotor position for 5.5:1 ratio AMGs. a) Base AMG and b) improved AMG.

Table 2 Curves comparison of transmission torque at low-speed rotor in 5.5:1 ratio AMGs.

	Low-speed rotor	
Items	Base AMG	Improved AMG
T_{max} [N.m]	530.6	808.3
T_{min} [N.m]	262.3	581.9
T_{avg} [N.m]	436.3	702.4
K_{ripple} [%]	61.5	32.2
Torque/Volume [kNm/m^3]	150.7	237.5
PM Volume [10^{-3} m^3]	1.24	1.29
Torque/PM Volume [kNm/m^3]	323.0	544.5

Table 3 Curves comparison of transmission torque at the high-speed rotor in 5.5:1 ratio AMGs.

	High-speed rotor	
Items	Base AMG	Improved AMG
T_{max} [N.m]	105.5	148.4
T_{min} [N.m]	26.0	60.0
T_{avg} [N.m]	56.4	95.1
K_{ripple} [%]	141.0	92.9

As it can be seen from Table 2, low-speed torque ripple in base AMG and improved AMG are 61.5% and 32.2%, respectively and as it is obvious from Table 3, high-speed torque ripple in base AMG and improved AMG are 141.0% and 92.9%, respectively. Comparing the torque-angle curves of Figs. 5 and 6 and the torque ripple of Tables 2 and 3, it can be concluded that the lower the torque ripple, the closer the torque-angle curve is to the full sinusoidal curve.

The lower high-speed torque ripple in the proposed AMG will lead to mechanical reliability, low noise, and low vibration in performance. It is noteworthy that the torque density of the base AMG and the improved AMG are 150.7, 237.5 [kNm/m^3], respectively.

As it can be seen from Table 2, the volume of permanent magnets used in the base AMG and improved AMG are 1.24 and 1.29 [10^{-3} m^3], respectively. In other words, the volume of permanent magnets used in the improved AMG is 4% more than the base AMG. If the amount of torque density per constant volume of permanent magnets is also extracted from Table 2 and compared, it can be seen that torque density per constant volume of permanent magnets in the improved AMG is 69% more than the base AMG. Therefore, it can be concluded that the effect of the appropriate arrangement of permanent magnets added between the main poles is greater than the volume of permanent magnets used in the performance of the flux-axis magnetic gear.

5 Theoretical Analysis

To have an ideal magnetic gear, the air-gap magnetic flux density generated only by each rotor must be sinusoidal. This can be realized by using an appropriate arrangement of the magnets and their direction. Not only cogging torque reduces with a sinusoidal flux density in the air-gap but also output torque increases [18]. In [19], the effect of permanent magnet arrangement on the performance of a coaxial magnetic gear has been investigated. Accordingly, the average magnetic torque of AMG developed on the low-speed rotor can be obtained by calculating the Maxwell stress in the low-speed air-gap. If the relations are rewritten for the axial-flux structure, the produced torque will be a function of the product of the axial and tangential components of the flux density in the air-gap. Therefore, for non-sinusoidal magnetization, the air-gap flux density contains harmonic components and the torque ripple caused by these harmonic contents lead to an increase in cogging torque and a decrease in the produced average torque. Actually, in the proposed structure, the direction and width of permanent magnets in high-speed rotor are changed and permanent magnets are removed from the modulator while the low-speed rotor remains unchanged. This causes the magnetic field produced by the high-speed rotor to be closer to sinusoidal in air-gap, thus eliminating a number of harmonics. The deleted harmonics can be divided into two categories: the first group rotates in the same direction as the main harmony, so by removing the first group of harmonics, the torque ripple decreases. The second group moves opposite to the main harmony. By removing the second group, the output torque increases.

6 Conclusion

According to the principle of field-modulation, an improved AMG is proposed in this paper. The ameliorated mechanical reliability can be prepared. In improved AMG, the cogging torque is effectively lessened. The improved AMG and the base AMG have been compared quantitatively and this comparison has emphasized that the improved AMG can attain more resistant transmission with lessened cogging torque. In addition to the above benefits, torque density also increases.

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