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Article

Comparative Study of Two Cogging Torque Reduction Methods Used in Magnetic Gears

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Abstract

With the aim of studying the magnetic effect of cogging torque regarding the performance of magnetic gears (MGs), two approaches have been built and arranged in two parts. Firstly, a slicing approach is used and applied to the all parts (magnets, modulators, and back irons) of the MG to minimize the cogging torque (no load torque or static torque) generated in permanent magnet (PM) machines. Secondly, a slitting approach is used and applied only to the modulators of the MG. The two approaches have been analyzed using finite element method and the results achieved the desired goal in mitigating the cogging torque. By the slicing technique, the cogging torque cancellation was around 97 % on the inner rotor while was around 42 % on the outer rotor. Furthermore, by using the slitting method, the inner cogging torque is decreased to around 81 %. However, the useful torque is increased by the first method and slightly decreased by the second method.

Keywords: Radial flux density; Cogging torque; Torque ripple; Magnetic field.

1. Introduction

Comparing with mechanical gears systems, magnetic gears (MG) have the best opportunity to chosen owing to its numerous advantages including low cost, simple structure, contactless, long life, less maintenance, etc. However, the main disadvantage that these gears suffer from cogging torque which is undesired phenomenon, mainly at low speeds. This cogging torque producing fluctuations and vibration in torque and speed during operation. This torque produced from the rotor magnets and the stator teeth combination, where the rotor tends to "lock". Generally, the cogging torque is a result of slot-pole combination that occurs at any permanent magnet machine.

Different methods for cogging torque cancelation or minimizing can be found in the literatures. In [1] a circumferential magnet angle method in an axial flux PM machines is suggested with the cost of output power reduction. While in [2], skewing and arc shaping modifications are proposed on the axial flux magnets with negative effect on the (r.m.s) voltage. In [3], the machine parameters have been optimized to suppress the magnetic saturation and cogging torque in interior PM motors used in hybrid electric vehicles. In [4], a new method of magnet shifting with introducing the repeating unit concept to effectively mitigate the cogging torque in inset PM synchronous motor has been introduced. Flux bridges with short magnets is proposed by [5] to suppress the cogging torque for flux switching permanent magnet machine (FSPM). A consequent-pole by staggering the rotor is proposed by [6], this mechanism minimizes the harmonics of even order in the back electromagnetic force (e.m.f) and the torque ripple. In brushed DC motor, [7] the vibration is reduced by applied a Zigzag skewing technique to the rotor's PMs. In [8], four models are proposed using dual notched design for the PM and the stator core to suppress the torque ripple but a reduction in the useful torque is noticed. [9] proposed a flux barrier in the rotor core, and V-shaped PM in IPM synchronous motor (IPMSM) for the purpose of torque ripple mitigation. [10] developed a new algorithm named Advanced Inverse Cosine

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Function to alleviate the cogging torque of the IPMSM. In [11], stator segmentation and notches have been employed in PM brushless DC machines to cancel the no load torque.

The key challenge of all up mentioned research is to increase the efficiency of PM machines by maximizing output torque-to-cogging torque ratio. On another words, maximizing the torque ripple reduction with minimum suppression in the useful output torque. In this study, a comparison between two methods of cogging torque reduction methods of radial flux magnetic gears (MGs) have been carried out. The main structure and design of the selected MG is proposed and analysed in [12]. Moreover, the most effective methods, based on the MG performance have been taken. The first method named slicing technique is introduced in [13] and the second method, named the slitting technique, is illustrated in [14]. The magnetic modelling and analyzing have been carried out using Two-dimensional Finite Element (2D-FEA) software. “Simcenter”, namely, "MagNet" software package is used. This software is specified for electrical machines analysis. The element (mesh) size has been set manually for the re-mesh region and automatically for other machine parts. In this work, the optimization process has been done by using the sensitivity analysis, which offer accurate results with the cost of long consuming time. The structure of this paper is as follows: section 2 clarifies the two models, section 3 discusses the analysis of the magnetic flux density, section 4 compares the electromagnetic magnetic torques, and section 5 draws the conclusions.

2. Models Description

The selected MG is presented in Figure 1 with the tabulated parameters summarized in Table 1.

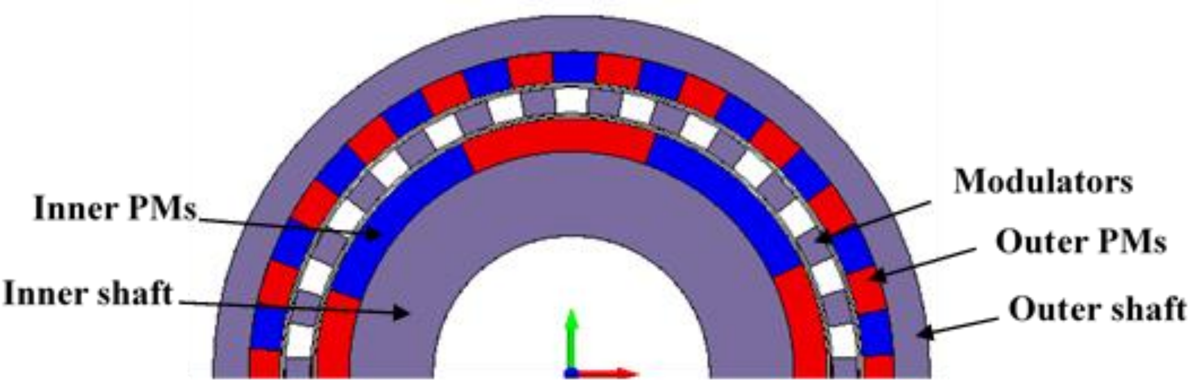


Figure 1. Selected MG.

Table 1. MG parameters [15].

Description	Value
High velocity rotor magnets	**4**
Low velocity rotor magnets	**22**
Number of modulators	**26**
Air gap width	**1 mm**
Axial length	**50 mm**
flux density permeance	**1.26 T**

The two methods for cogging torque reduction are illustrated below.

2.1 Slicing Technique

To solve the disadvantages of the skew approach, the rotors and modulators are sliced along the axial length l_{ax}. This mechanism of segmentation not only cancels the cogging torque but also improves the useful torque. Figure 2 illustrates a two slices rotor [16].

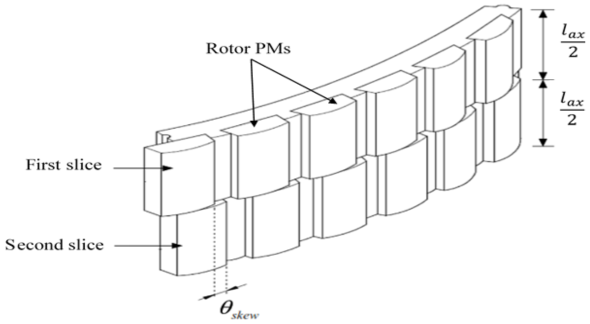


Figure 2. Rotor slicing approach.

The main concept of this method is by slicing both rotors of the MG with number of slices equal to (n). Then, each slice is shifted angularly with position angle equal to (2π/n). This method gives a good performance for accuracy purposes in speed and position. The authors in [13] analyzed nine models of sliced MGs with different (n), and after applying sensitivity analysis, the optimal model is recognized. The final model is composed of ten slices as shown in Figure 3.

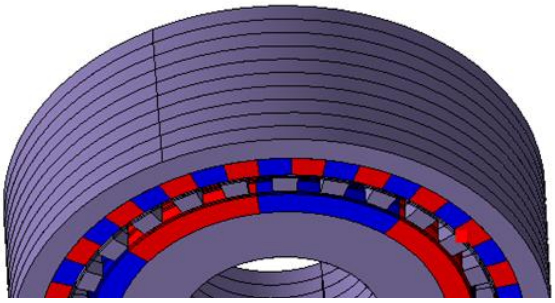


Figure 3. Ten slices model.

2.2 Slitting Technique

The basis for constructing this approach depends on separating or dividing each slot of the modulator by making radial slits through them. As described in [14], The crucial element is choosing the slits number, slits angle, and slits width relative to the median axis that bisects the modulator. The authors in [14] analyzed four models with different slitting pattern; single slit and twin slits. Based on the magnetic analysis, a twin slits of (0.1 mm) width are applied for each single modulator piece and considered as the final model design as shown in Figure 4.

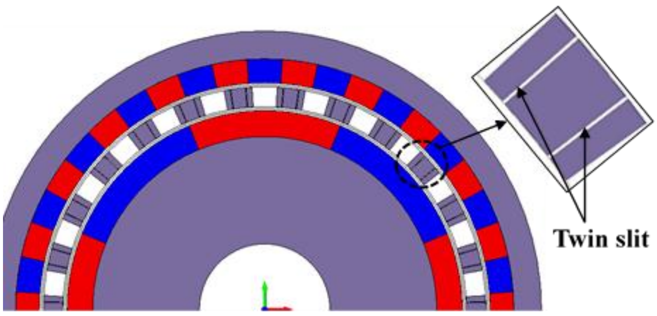


Figure 4. Twin slit model.

3. Magnetic field analysis

In this section, Magnetic flux density distribution map and radial flux density waveforms of the MG have been analyzed as shown in Figure 5 and 6.

As shown by Figure 5 that the second method "Slitting Technique" is better than the first method "Slicing Technique" from the magnetic saturation point of view. However, both methods kept the material saturation level within the acceptable value. In addition, the tangential magnetic flux density is slightly more in the First method compared with the other. This is because that the slits increase the reluctance along the tangential flux path. While, the radial magnetic flux density is almost the same for both methods.

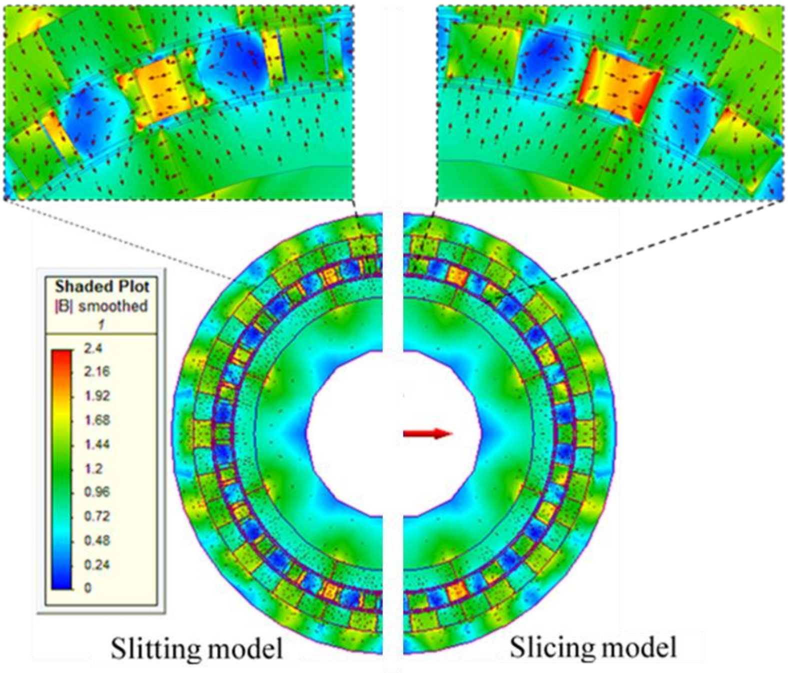


Figure 5. Flux density distribution map.

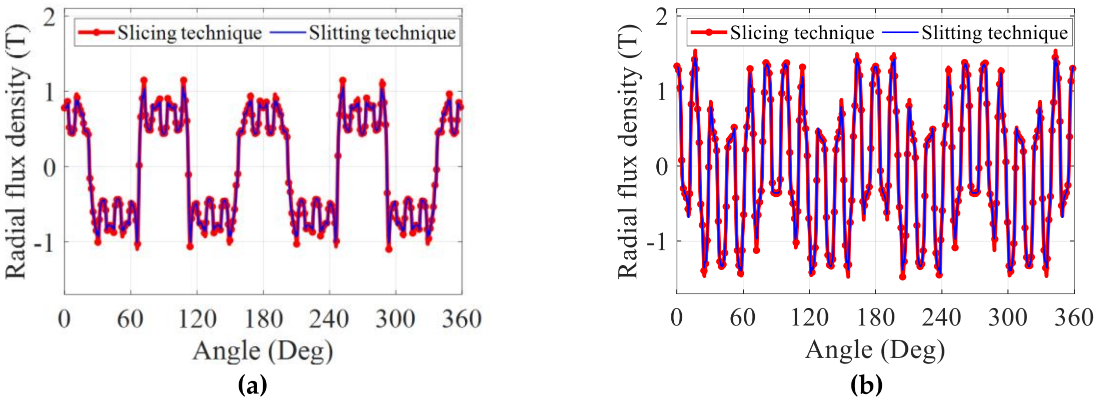


Figure 6. Radial flux density of the MG: (a) Inner air gap; (b) outer air gap.

4. Electromagnetic Torques

As displayed in Figure 7, the three proposed models (slicing, slitting, and original) are compared. It is clear that the cogging torque by the slicing approach is highly eliminated on both rotors even if the outer rotor is ripple free. In contrast to the slitting approach, the cogging torque is only reduced on the inner rotor.

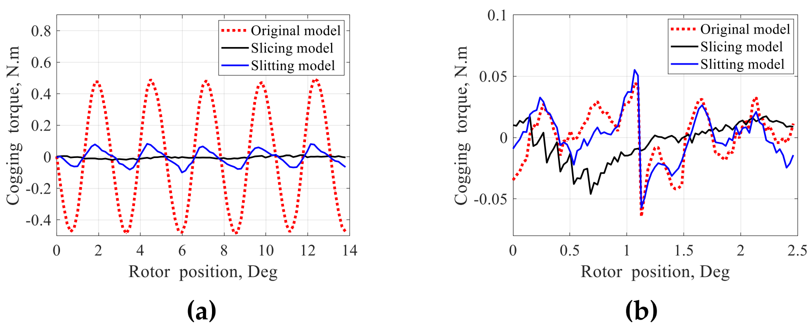
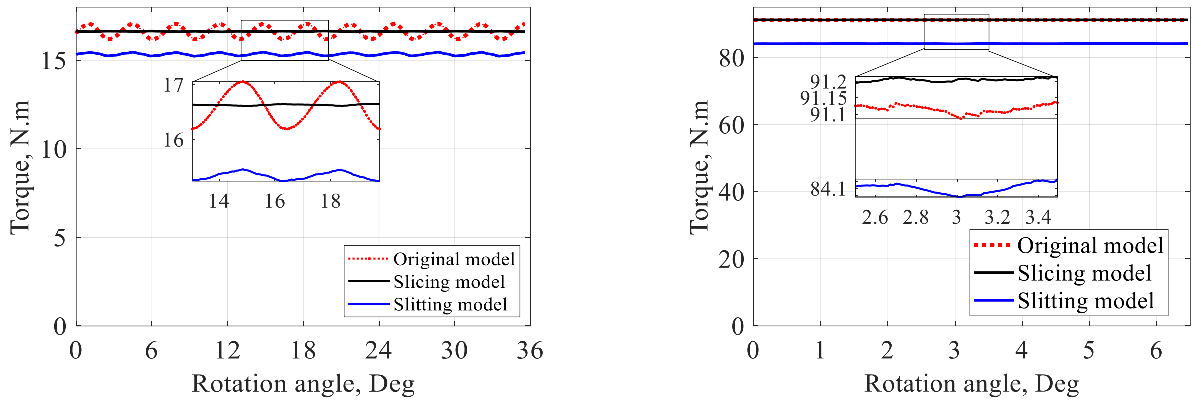


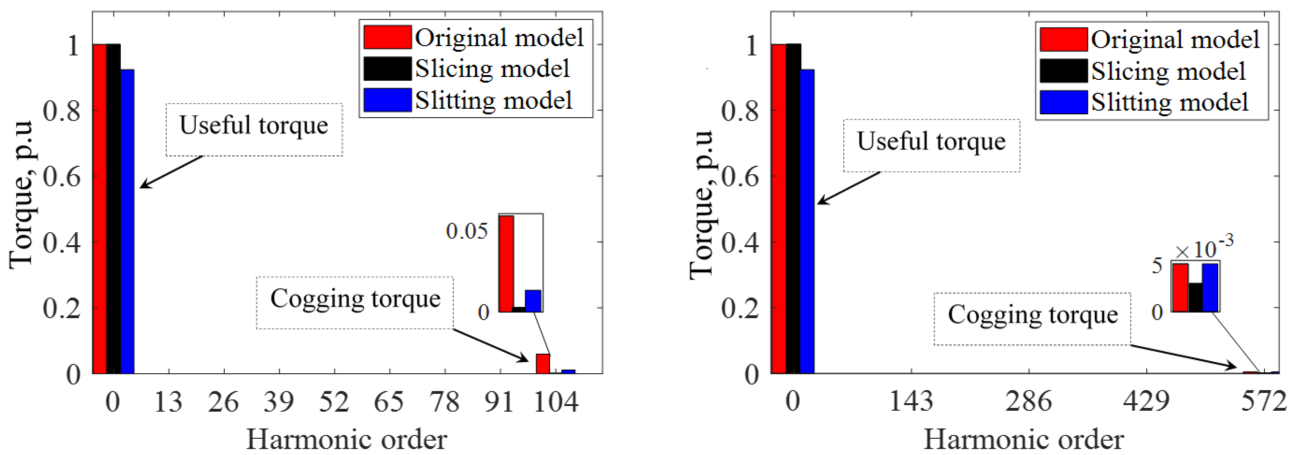
Figure 7. Cogging torque of the MG: (a) Inner rotor cogging torque; (b) Outer rotor cogging torque.

According to Figure 8, the load torques are compared. The most effective approach maintaining the average value of the useful torque within a specified limit is the slicing technique which slightly increases the useful torque. But the useful torque is decreased below the original value by using the slitting approach. To be clearer, FFT spectra is analyzed and displayed on Figure 9. Also, the results are summarized in Table 2. Finally, the torque to cogging torque ratio for the slicing technique shows (684) on the inner rotor while (1450) for the outer rotor. Furthermore, the ratio was (86) on the inner rotor and (751) on the outer rotor for the slitting technique which means that the slicing technique is more effective than the slitting technique. However, both methods are seemed to be effective in minimizing the cogging torque.



(a) **(b)**

Figure 8. Torque analysis of the three models: (a) Inner rotor useful torque; (b) Outer rotor useful torque.



(a) **(b)**

Figure 9. FFT spectra of the torques of the three models: (a) FFT spectra of the inner rotor; (b) FFT spectra of the outer rotor.

Table 2. Results summary.

Description	Original approach	Slitting approach	change (%)	Slicing approach	change (%)
Inner rotor useful torque, N·m	**16.62**	**15.344**	**-7.68**	**16.63**	**0.05**
Outer rotor useful torque, N·m	**91.11**	**84.122**	**-7.67**	**91.2**	**0.1**
Inner rotor cogging torque, N·m	**0.986**	**0.1785**	**81.9**	**0.0243**	**97.53**
Outer rotor cogging torque, N·m	**0.109**	**0.112**	**-2.75**	**0.0629**	**42.3**

5. Conclusions

This paper compared two methods of cogging torque minimization of MGs. As shown in the results, the slicing technique seems to be the most effective method in reducing the cogging torque and improving the useful torque. The complexity of this method is the assembly of the slices to create the full stacked model. The slitting technique seems to be acceptable method for reducing the cogging torque with a slight reduction in the useful torque. Because of the outer rotor considered as cogging free, the objective of using the slitting technique is to reduce the inner rotor cogging torque which is seem to be large. The advantage of slitting technique over the slicing technique is that the modification is applied to the modulator only (steel iron segments) without any modification on the PMs, so this method needs less machining process than the slicing technique.

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