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TORQUE RIPPLE MINIMIZATION OF ROTATING POLE PIECE CONCENTRIC MAGNETIC GEAR USING ROTOR SKEWING AND POLE PIECE MODIFICATION

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Abstract

Rotating pole piece magnetic gear (RPMG) produces higher average torque than the conventional concentric magnetic gear (CMG). However, it also exhibits a higher torque ripple at the outer rotor as a result of switching of the rotating component from the outer pole pair (OPP) to the ferromagnetic pole piece (FMP). This paper explores a torque ripple suppression strategy through rotor skewing applied to the inner pole pair (IPP), outer pole pair (OPP), and ferromagnetic pole piece (FMP). Additionally, this study evaluates the impact of four distinct FMP shapes on the RPMG torque profile. Two gear ratio structures were tested at 4.33 and 5.66 ratio using 2D JMAG Designer finite element software. When skewing was performed on the IPP, it is observed that the inner torque ripple was reduced in both gear ratios when compared to the original structure with a slight drop in average torque for both rotors and gear ratios. Similarly, when smooth shape FMP was used in RPMG, it produced nearly the same average torque and slightly minimized the torque ripple in both gear ratios versus the original structure. The inner torque ripple was reduced to 2.9% at a 4.33 gear ratio and 4.1% at a 5.66 gear ratio, compared to the original structure. This improvement resulted in a slight average torque decrease of 1-2.5% across both rotors and gear ratios. Theoretically, simulation results have shown that rotor skewing, and FMP shape modification could minimize the torque ripple in RPMG especially at the inner rotor with moderately declined average torque for EV application where minimizing torque ripple is essential for smoother driving experience and reducing mechanical stress on components.

Keywords: Flux modulation, Magnetic gear, Rotor skewing, Torque density, Torque ripple.

1. Introduction

Concentric magnetic gear (CMG) is known to be more effective to utilize the energy of the permanent magnet (PM) when compared to the planetary, worm, spur and harmonic typed magnetic gear [1-4] CMG consist of three main components; namely inner pole pair (IPP), outer pole pair (OPP) and ferromagnetic pole piece (FMP) [5]. In CMG, IPP and OPP are usually selected as the rotors, while FMP is let to be stationary. However, when the stationary component is either from OPP or IPP, the CMG would produce different torque behaviour and gear ratios. In our past studies, the OPP was let stationary, while the FMP act as the outer rotor [6- 8] The term used to describe machine with this arrangement is "rotating pole piece magnetic gear" (RPMG).

The study showed that in this condition, the average torque served by FMP increase by 18 % versus the original CMG condition with considerably high torque ripple. Seemingly, any approach of producing a lower torque ripple would result in a reduced average torque and on the other hand, any approach intended to produce a larger average torque would yield a higher torque ripple [9].

Torque ripple contributes to an undesirable vibration and acoustic noise. The torque generated in the original CMG is due to the interaction between the air gap flux harmonic and the fundamental flux of the IPP or OPP. In RPMG, by switching the rotating component from the IPP to the FMP, the torque is produced by the interaction between the magnetic material and the flux harmonic of the IPP or OPP.

Meanwhile, the air gap between the FMP and the stator magnetic varies according to the rotor position. This situation leads to an abrupt change in torque when the FMP leaves its aligned position. This problem is similar to the one that occurs to switched reluctance machine (SRM), only in SRM, torque fluctuation can be minimized by controlling the amount of flux during the operation through power electronics. Since RPMG is an unconventional type of CMG operation, there is limited research done to investigate and minimize the torque ripple in RPMG.

Hence, in this paper, several optimization methods applied in CMG are reviewed to identify its influence on RPMGs. Two structures with 4.33 and 5.66 gear ratio were selected in this study. These ratios and its combination has been identified to produce high average torque and low torque ripple in our previous pole pair combination study [7]. Rotor skewing and FMP shape modification are evaluated in 2D finite element method. The rotor skewing was implemented on IPP, OPP and FMP individually according to the predetermined angle.

Four shapes namely trapezoid, half chamfer, smooth and bridge were modified as the FMP piece. Finally, the torque ripple and average torque are compared and discussed in both strategies. The manuscript presents an analysis of CMG optimization, starting with an overview of existing approaches. The structure and evaluation methods are then detailed, followed by a comparison of simulation results for rotor skewing and FMP shapes. The paper concludes with key findings based on the analysis.

2. Current State of Concentric Magnetic Gear Optimization

In this section several CMG optimization strategies proposed in the previous literature were discussed. These methods might not directly minimize the torque ripple in RPMG. However, through the improvement of the torque output or torque density, it could increase the torque magnitude and directly increase the numerator of the torque ripple equation. This section also reviews several shapes applied on FMP by other researchers.

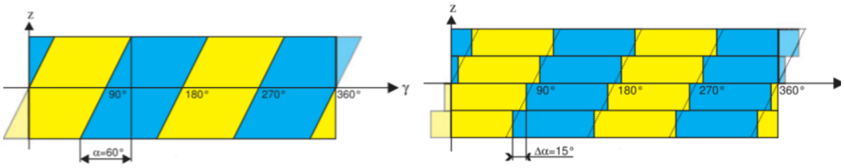
2.1. Design optimization in concentric magnetic gear

Parametric optimization has been proposed widely to improve the performance of CMG. In [10], the influence of design parameters on the torque capability of the CMG was analysed, achieving a torque ripple of 1.2% through the application of the least common multiple (LCM) method and testing three different permanent magnet (PM) radial thicknesses at both the inner and outer rotors. A general guideline that assists machine designers in filtering high-cogging-torque pole pair combinations is to use the least common multiple (LCM) method LCM. Since the harmonic appears more when integer pole number is used, hence the sum of the harmonic will be greater. A higher value of the LCM translates to a higher fundamental order of the cogging torque waveform, and lower ripple [10]. Nevertheless, LCM values for ratio which equals to integer number is low. Thus, this method is suitable only for non-integer's gear ratio.

A magnetically geared machine was assessed in [11] using a prescribed optimum ratios between thickness in the PM and the pole piece and the pitch angle between the two. The result demonstrated that the optimum ratio between the PMs and the pole pitch is 1, similar to the ratio between the FMP and its pole pitch. Higher flux density was obtained when PMs radial thickness is larger than the FMP radial thickness. Nonetheless, this can be explained by the increase in the PM's mass which directly increase the flux in the air gap [11].

Similarly, parametric optimization was performed by analysing the air slot opening to pole pitch ratio, magnet-arc to PM pole pitch ratio and PM thickness [12]. The paper showed that the highest torque occurred when the air slot width equals to the FMP segment. This paper also evaluated three FMP designs; namely radial slots, parallel teeth, and parallel slots. The result verified that the parallel slots design produced the lowest torque capability when compared to the radial slots and the parallel teeth [12].

On the other hand, continuous skewing and discrete skewing were applied in CMG to minimize the cogging torque in [13]. Figure 1 shows the arrangement of the skewing. This study managed to show that in general, the skewed rotor can minimize up to 80 % of the cogging torque, at 3.6 % torque ripple by suppressing torque harmonic of several orders. The author also suggest that skewing is suitable for low torque application [13].



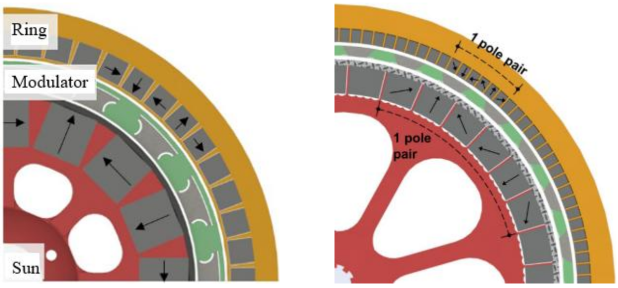
(a) Continuous skewing. **(b) Discrete skewing.**

Fig. 1. Skewing arrangement.

2.2. Ferromagnetic pole piece shape

A fast analytical model of iron losses in the ferromagnetic parts of the magnetic gear was proposed in [14]. In this paper, the iron losses in pole pieces were found to be higher than losses occurred in either of the external or internal yoke. This result comes from the fact that ferromagnetic pole piece (FMP) is subjected to a rotating magnetic field, imposed by permanent magnets as opposed to the yoke regions. Hence, focusing on optimizing FMP geometry to minimize the torque ripple would be beneficial as it could also improve the efficiency of the machine [14].

In 2018, two magnetic gear prototypes with Halbach array PM was built by NASA research team to investigate its torque density [15]. Figure 2(a) illustrates the design of the first and the second prototype. The first prototype uses square shape FPM with a half-circle chamfer on each side, with off the shelve rectangular PM. The torque density in the first prototype was 20 Nm/kg. Meanwhile, the second prototype changes the FMP to a symmetrical trapezoidal shape and arc shape PM. These two changes were made to reduce the gap between the PMs and between the FMPs. Figure 2(b) displays the structure of the machine. The torque density in the first prototype was 44.7 Nm/kg [15].



(a) half-circle chamfer shape. (b) trapezoidal shape.

Fig. 2. FPM shapes design for the prototype [14, 16].

The NASA research team published an optimize version of the first prototype to improve the torque density and efficiency of the magnetic gear [16]. The FMP geometry shown in Fig. 3 was found to scale well with the changes in the higher-level variables and it gives close to the same torque density result to that of the original FMP shape. Yet, the geometry used in this study is not recommended for actual magnetic gear design because it could weaken the support posts in the modulator structure [16].

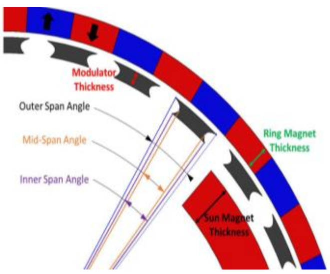


Fig. 3. FPM with a half-circle chamber (improved design).

Similar FMP shape was enhanced based on a Box-Behnken design to reduce the torque ripple in magnetically geared machine [17]. Response surface analysis and the initial model characteristics were compared to validate the performance of the improved model. According to the author, the model was able to reduce the torque ripple down to 9 % from 72 % of the initial model. Figure 4 demonstrates the graph of the outer rotor torque from the initial and the optimized model [17].

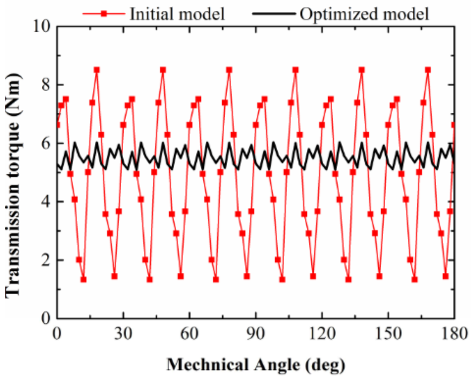


Fig. 4. Outer rotor torque profile in the initial model and optimized model-based on Box-Behken design.

To be more cost effective, the FMP segment connected with bridge was proposed in a magnetic gear [18]. It can be seen that it uses non-round yoke surface and leaving gap between the PM. Unfortunately the authors did not make any comparison with other structure either in terms of torque density or cost [18]. Figure 5 shows the FMP shape incorporated with the bridge.

Next, FMP segment with fillet was proposed to reduce torque ripple in [19]. Figure 6 illustrates four fillet locations evaluated in this paper. The radius of A and B were grouped together as one parameter and was reduced gradually down to half of the length. Similar steps were applied in C and B fillet. The acquired results revealed that C and D group could reduce the torque ripple up to 89 % [19].

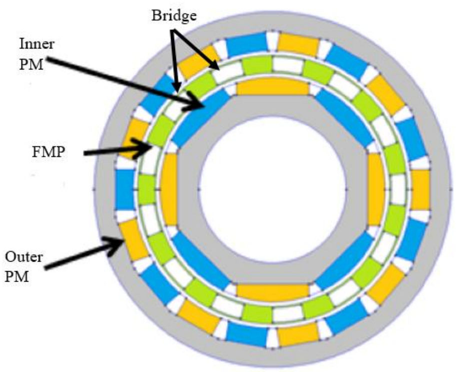


Fig. 5. FMP shape connecting each other with bridge.

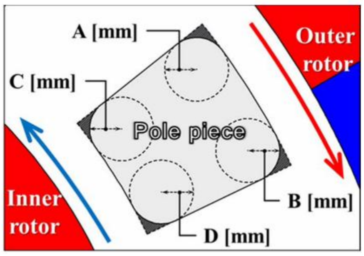


Fig. 6. FMP shape with 4 locations of fillet to be removed.

2.3. Design consideration

Based on the aforementioned reviews; to minimize the torque ripple in magnetic gear, LCM is calculated at the initial design stage by selecting appropriate pole pair number to increase the fundamental harmonic. Besides that, the best design structure always maintains two ratios of parameters. The first ratio is the PMs angle and the pole pitch angle that must be equals to 1 [20]. This ratio means that no gap should exist between the PMs. The second ratio is the FMPs angle and its gap angle to the next FMP must also be equal to 1. This ratio means that the circumference length of the FMP segment is equal to the gap separated between the FMPs.

However, the ratio of radial thickness between the FMP and PMs did not provide enough evidence to show that maintaining the PM's thickness and the air gap could influence the torque characteristic of the CMG. As PM size increases, the magnetic field density also will increase, which directly impacts the total toque. On the other hand, the FMP acts as an alternating pole. If the size or surface is not enough, the magnetic field will leak. Among the FMP designs, parallel slots were verified to produce a slightly lesser torque than its counterparts, which are radial slots and parallel teeth. Meanwhile, rotor skewing is capable to minimize the torque ripple in CMG especially in low radial force application [13]. Continuous skewing reduces cogging torque in concentric magnetic gears by averaging the magnetic pole interactions, resulting in smoother torque, less noise, and better efficiency, but it is complex and costly to manufacture.

Discrete skewing offers a simpler, more flexible approach by segmenting magnets or teeth into steps, making it easier to produce, though it may not reduce cogging torque as effectively. While continuous skewing offers better performance, discrete skewing is more practical and cost-effective, depending on design needs. The unconventional shapes are motivated by different objectives such as improving torque density, efficiency, cost, or torque ripple. To identify which shapes that yield the best result in terms of minimizing torque ripple, these shapes will undergo an evaluation with the same machine dimension and condition.

3. Methods

3.1. RPMGs structure as the reference model

In this study, integer gear ratios are avoided. Instead, RPMG gear ratios of 26/6 and 34/6 are selected. Previous research [6, 7] indicates that the torque ripple in these configurations' ranges between 5% and 9%. The dimension and specification are shown in Table 1. Table 2 shows the material used for this simulation.

Table 1. Dimension and specification of the RPMG structure.

Gear ratio	26/6 = 4.33	34/6 = 5.66
OPP	20	28
FMP	26	34
IPP	6	6
MG radius (mm)	90	95
IPP radius (mm)	68.5	68.5
Shaft radius (mm)	34	34
Axial length (mm)	30	30
Width of magnet piece (mm) in OPP and IPP	5	5
Inner air gap width (mm)	1	1
Outer air gap width (mm)	0.5	0.5
Skew angle (radian)	Θ_1 and Θ_2	Θ_3 and Θ_4

Table 2. Materials used in simulation.

Component	Material	Remarks
Inner yoke	NSSMC 35H210	Saturation point: 1.8*T*
Outer yoke		
Pole piece		
Magnet	Hitachi NEOMAX 35AH	1.2 *T* residual

3.2. Torque characteristic evaluation in RPMG when rotor skewing is applied at the inner rotor.

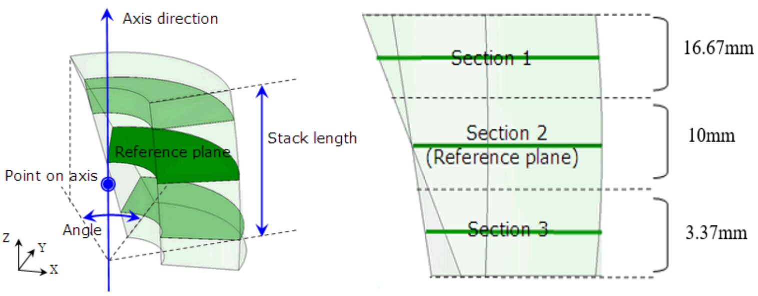
To determine the harmonic order, flux density air gap was measured in three scenarios, which are when either one of the OPP, IPP or FMP is removed.

The angle of the skew is expressed as

$$\Theta = 360/k \tag{1}$$

where k is the harmonic order.

There are many harmonics appears for every pole pair combination, but only three harmonics are utilized for torque transfer that correspond to each of the rotor pole. Therefore, by applying skew to the harmonic that is not responsible for the torque transfer, we can eliminate this unwanted harmonic. The angle calculated from (1) is used as the skewing angle. The dimensions are kept the same. Multi-slice condition is applied on FMP, IPP and OPP to mimic the skew in z-direction illustrated in Figs. 7(a) and (b). The number of slices is set to 3.



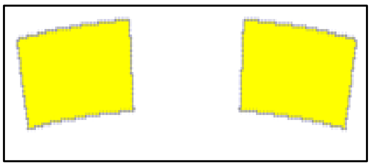
a) 3D view **b) Side view**

Fig. 7. Illustration of multi-slice condition perform on the rotor.

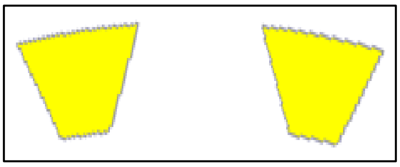
The section lengths are set equal to 10 mm each. Clockwise (cw) and anticlockwise (acw) skew direction are assessed. Transient analysis was also performed in both structures. The rotational speed for 4.33 gear ratio is 3250 rpm and 750 rpm at the inner and outer rotor, respectively. While the rotational speed for 5.66 gear ratio is 4250 rpm and 750 rpm at the inner and outer rotor, respectively.

3.3. Evaluation of torque characteristics in RPMG with different FMP shapes.

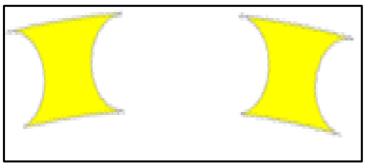
The shapes reviewed earlier are applied individually to the structure on the original model. The dimension of the shapes is bound to the initial FMP shape. Figure 8 displays the shapes to be evaluated at this stage. The simulation conditions are set similar to stage 1. The FMP was designed within 1 mm2 of the conventional FMP area.



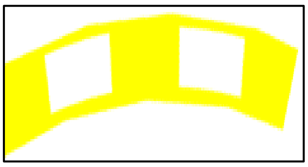
(a) Original.



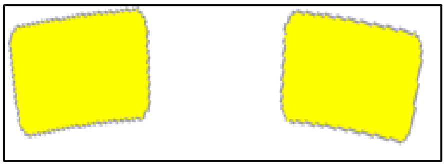
(b) Trapezoidal.



(c) Half chamfer both sides.



(d) Bridge between.



(e) Smooth edge.

Fig. 8. FMP shape used for RPMG evaluation.

4. Results and Discussion

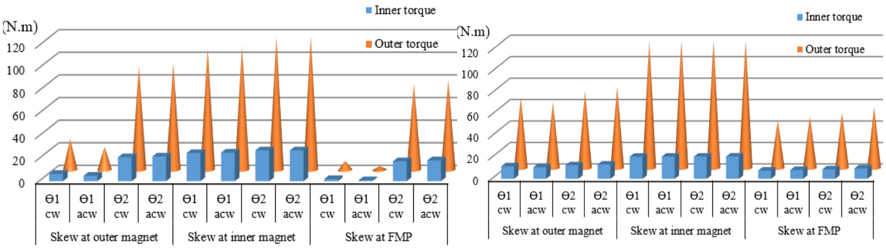
4.1. Rotor skewing

Harmonic orders which registered high harmonic amplitude in radial and tangential direction when one of the components; OPP, IPP or FMP is removed are listed in Table 3. This test was performed in static condition. In 4.33 ratio structure, 6th and 20th order are the fundamental harmonics. Meanwhile, in 5.66 ratio structure, the fundamental harmonics are of the 6th and 28th order. Based on the results shown in this table, the two highest harmonic orders were identified to be suppressed in each structure.

Table 3. Harmonic order in 4.33 and 5.66 gear ratio in radial and tangential direction.

		Field direction		
Gear ratio	**Harmonic order**	**Radial**	**Tangen**	**Skew angle (ϴ)**
4.33	8	✓	✓	ϴ1 = 45º
	18	✓	✓	ϴ2 = 20º
	20	✓	✓	
	6	✓	✓	
	19		✓	
5.66	16	✓	✓	ϴ3 = 22.5º
	18	✓	✓	ϴ4 = 20º
	6	✓	✓	
	28	✓	✓	
	30		✓	

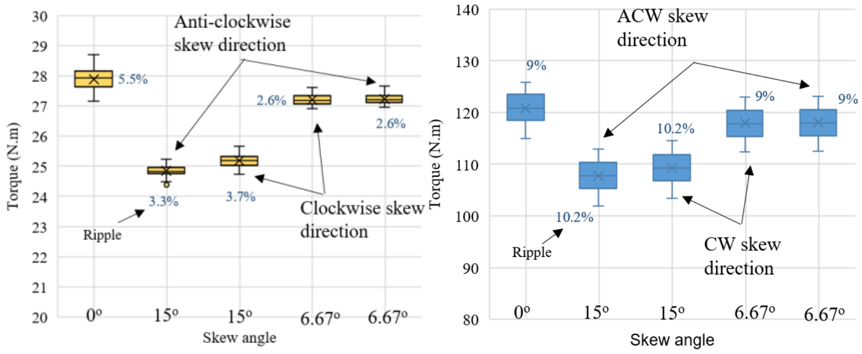
Figures 9(a) and (b) indicate that the average torque is arranged based on the skewing angle and its direction. The highest average torque was observed when the IPP magnet was skewed, and the lowest average torque was observed when the FMP was skewed. No definite correlation can be seen when either cw or acw direction was applied with respect to torque characteristic. The best part to perform skewing is on the IPP magnet yield the least torque reduction of between 1-2.5 % when compared to the original structure.



(a) Ratio 4.33. **(b) Ratio 5.66.**

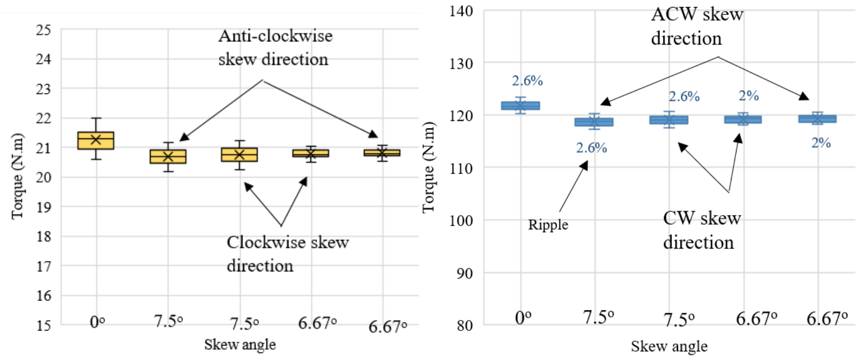
Fig. 9. Average torque comparison for different gear ratio.

In the meantime, Figs. 10 to 15 illustrate the inner and outer rotor torque candle stick plot for 4.33 and 5.66 gear ratio, respectively. Five candlesticks were drawn which represent the RPMG without any skew and two angles at clockwise and anticlockwise direction. The ripple percentage in each case was labelled near the candlestick. RPMG without any skew serves as the reference structure with the best predetermined parameters defined earlier in Table 1. The average torque in both rotors shows a reduction when skewing is applied on any rotor. Skewing the FMP component should be handled carefully as it may lead to a very high torque ripple at the inner rotor as shown in Figs. 14(a) and 15(a). Skewing at IPP magnet resulted in the reduction of inner torque ripple of 2.9% in 4.33 gear ratio and 4.1% in 5.66 gear ratio.



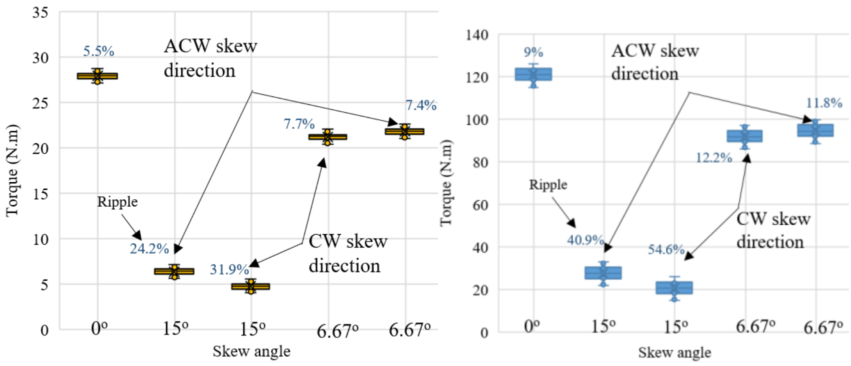
(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 10. Candle stick plot at (Inner pole magnet skew) at 4.33 ratio.



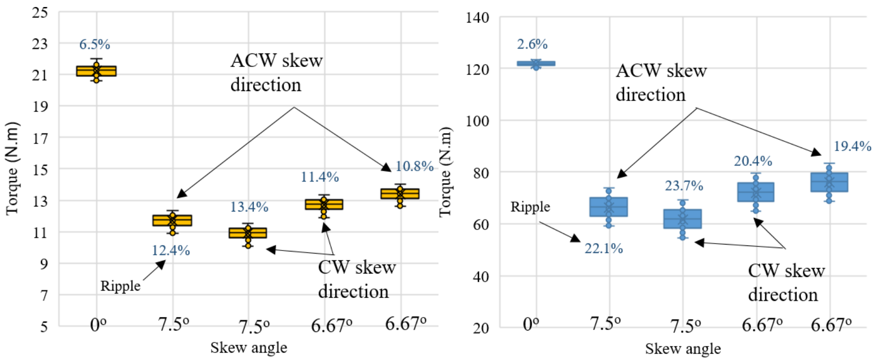
(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 11. Candle stick plot at (Inner pole magnet skew) at 5.66 ratio.



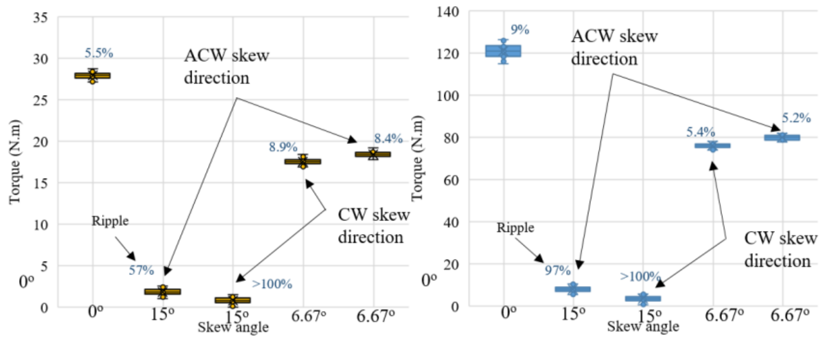
(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 12. Candle stick plot at (Outer pole magnet skew) at 4.33 ratio.



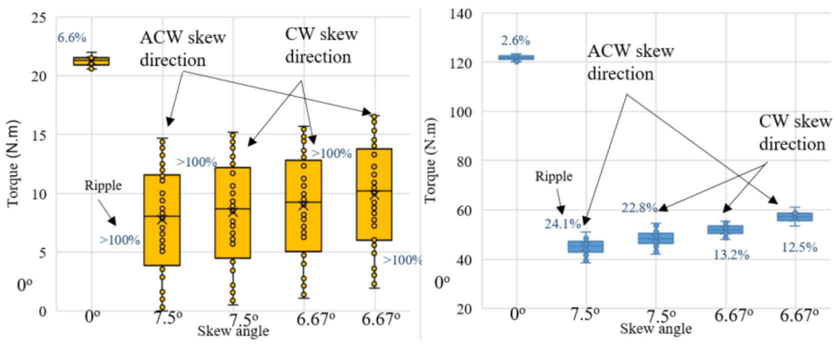
(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 13. Candle stick plot at (Outer pole magnet skew) at 5.66 ratio.



(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 14. Candle stick plot at (FMP skew) at 4.33 ratio.



(a) Inner rotor torque. (b) Outer rotor torque.

Fig. 15. Candle stick plot at (FMP skew) at 5.66 ratio.

4.2. Influence of FMP shape in torque profile

Figures 16 and 17 show the torque in transient mode at the inner and outer rotor gear ratio of 4.33 and 5.66 structures. In both structures, the smooth shape FMP which possesses a very similar shape to the original shape, exhibits nearly the same torque behaviour as the original shape. The bridge shape FMP torque magnitude is the lowest among other shapes even if it carries the most volume. This is due to the effect bridge connection applied.

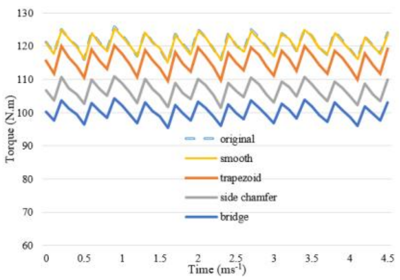
Figure 18 on the other hand shows the torque ripple percentage at outer and inner rotor at different FMP shape. The lowest torque ripple at the inner rotor for 4.33 gear ratio was from the trapezoid shape, whereas for 5.66 gear ratio was from bridge shape. The lowest torque ripple at the outer rotor for gear ratio 4.33 and 5.66 was from smooth shape. The torque ripple percentage in 4.33 gear ratio is smaller compared to 5.66 gear ratio at the inner rotor. Yet, at the outer rotor, 5.66 gear ratio shows much smaller torque ripple than in 4.33 gear ratio structure.

The analysis of different Flux Modulation Pole (FMP) shapes reveals significant effects on torque ripple in both the inner and outer rotors for gear ratios of 4.33 and 5.66. Figures 16 and 17 show the torque in transient mode, with the smooth shape FMP (closely resembling the original design) producing nearly identical torque behaviour to the original. However, the bridge-shaped FMP, despite its larger volume, generates the lowest torque magnitude due to the damping effect of the bridge connection.

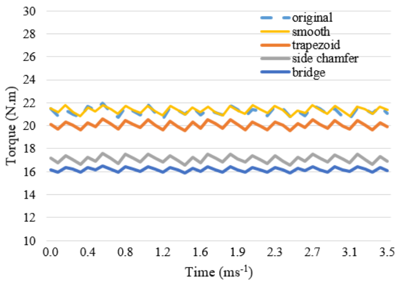
For torque ripple percentages (Fig. 18), the trapezoid-shaped FMP shows the lowest torque ripple at the inner rotor for a gear ratio of 4.33, while the bridge-shaped FMP performs best at the 5.66 gear ratio. At the outer rotor, the smooth FMP minimizes torque ripple for both gear ratios. Notably, the 4.33 gear ratio structure exhibits a smaller torque ripple at the inner rotor compared to the 5.66 gear ratio, but the trend reverses at the outer rotor, where the 5.66 gear ratio structure demonstrates a much smaller torque ripple than the 4.33 structure.

These effects can be quantified and compared by calculating the torque ripple percentage for each shape at both rotors and gear ratios, enabling a clearer understanding of the relationship between FMP shape, torque performance, and ripple reduction.

The torque ripple percentage varies between the 4.33 and 5.66 gear ratios, with the 4.33 ratio showing lower ripple at the inner rotor (best minimized by the trapezoid FMP) and the 5.66 ratio showing lower ripple at the outer rotor (with the smooth FMP performing best). Analytical methods like transient Finite Element Analysis (FEA), harmonic analysis, and optimization algorithms can be used to evaluate and compare different FMP shapes, helping to determine the most effective design for minimizing torque ripple in each case.

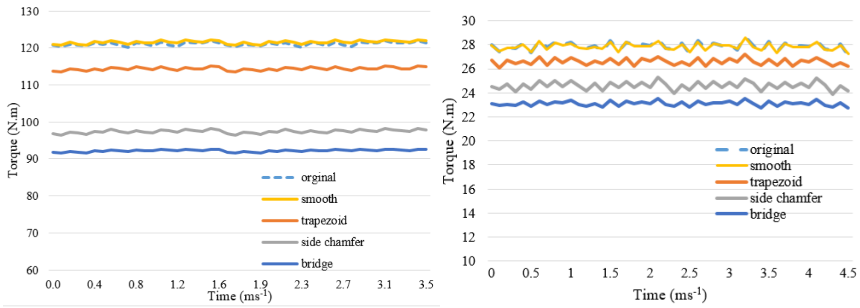


(a) Inner rotor torque.



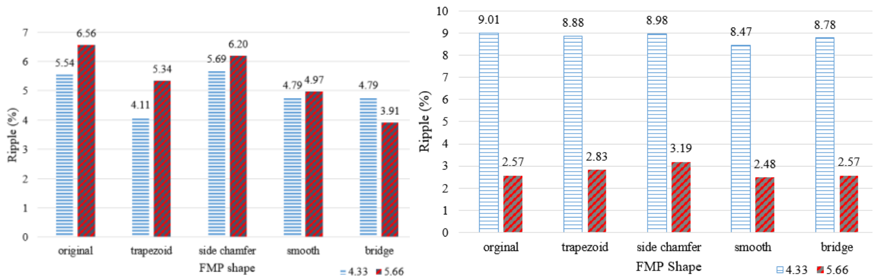
(b) Outer rotor torque.

Fig. 16. Torque profile in transient mode for different FMP shape at 4.33 ratio.



(a) inner rotor torque. **(b) outer rotor torque.**

Fig. 17. Torque profile in transient mode for different FMP shape at 5.66 ratio.



(a) Inner rotor torque. **(b) Outer rotor torque.**

Fig. 18. Torque ripple percentage at outer and inner rotor at different FMP shape for ratio 4.33 and 5.66.

4.3. Practical application of the research

The practical applications of this research are primarily in fields where precise torque control and smooth power transmission are critical, such as electric vehicles (EVs), hybrid electric vehicles (HEVs), renewable energy systems (wind turbines), and industrial robotics. The focus on reducing torque ripple while maintaining acceptable torque output makes the findings particularly valuable in systems that rely on high-performance, efficient, and reliable rotary motion. The performance of RPMG designs could be significantly improved by selecting materials with higher magnetic permeability, better saturation limits, and superior thermal properties.

Exploring materials like amorphous metals, nanocrystalline alloys, and advanced silicon steels could yield better overall performance, particularly in torque ripple suppression, while maintaining or even improving torque output. However, cost and manufacturing complexity remain critical factors when selecting these materials for practical applications.

5. Conclusion

This paper investigates the impact of rotor skewing and FMP shape on torque behaviour in RPMG, revealing that applying skewing to either rotor reduces average torque. The best place to employ the skew technique was at the IPP magnet. The inner torque ripple was reduced down to 2.9% at 4.33 gear ratio and 4.1% at

5.66 gear ratio. This is when compared to the original structure with a slight drop of between 1-2.5% in average torque in both the rotors and gear ratios.

This paper also evaluates the torque performance of RPMG with four distinct FMP shapes. Among the FMP shapes evaluated, the smooth FMP shape yielded the highest average torque, closely resembling the performance of the original design. The torque ripple in all shapes at the inner rotor in both gear ratios exhibit a decline against the original shape. However, the ripple reduction did not reflect at the outer rotor torque.

Hypothetically, the 2D finite element method analysis done has shown that rotor skewing and FMP shape modification are applicable to minimize the torque ripple in RPMG especially at the inner rotor albeit with a moderate decline of the average torque. Future work could focus on optimizing rotor skewing and FMP shape modifications to further minimize torque ripple while mitigating the reduction in average torque. Additionally, investigating alternative design strategies or materials that can enhance torque performance without compromising torque ripple at the outer rotor would be beneficial. The proposed methods offer a balance between simplicity, cost, and efficiency. While there is a modest reduction in average torque, these techniques provide a practical and less expensive approach to torque ripple suppression, especially for systems where maintaining low complexity and cost is critical.

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Nomenclatures

k	Harmonic order

Greek Symbols

θ	Skew angle in degree.

Abbreviations

2D	2 Dimension
acw	anticlockwise
CMG	Concentric Magnetic Gear
cw	counterclockwise
EV	Electric Vehicle
FEA	Finite Element Analysis
FMP	Ferromagnetic Pole Piece
FRGS	Fundamental Research Grant Scheme
HEV	Hybrid Electric Vehicle
IPP	Inner Pole Pair
LCM	Least Common Multiple
NASA	National Aeronautics and Space Administration

OPP	Outer Pole Pair
PM	Permanent Magnet
RPMG	Rotating Pole Piece Magnetic Gear
SRM	Switched Reluctance Machine
UTeM	Universiti Teknikal Malaysia Melaka
UTHM	Universiti Tun Hussein Onn Malaysia

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