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Preliminary Magnetization Pattern Study on Magnetic Gear

Mohd Firdaus Mohd Ab Halim[1,2], Erwan Sulaiman[1], R. N. F. K. R. Othman[3]
[1]Research Centre for Applied Electromagnetics, Faculty of Electrical and Electronic Engineering, Institute of Integrated Engineering,UniversitiTun Hussein Onn Malaysia Malaysia,erwan@uthm.edu.my
[2]FakultiTeknologiKejuruteraanElektrik&Elektronik, UniversitiTeknikal Malaysia, Malaysia. mohd.firdaus@utem.edu.my
[3] Centre for Robotics & Industrial Automation,FakultiKejuruteraanElektrik, UniversitiTeknikal Malaysia, Malaysia.norfirdaus@utem.edu.my

ABSTRACT

In this paper, radial anisotropic, circumferential anisotropic, parallel circular direction (PCD) and parallel radial direction (PRD) magnetization pattern are introduced and explained. Then, these magnetization pattern are simulated using JMAG Designer 16.0 on the coaxial magnetic gear with 2.33 gear ratio. Torque and efficiency are calculated and compared. The result shows that the radial anisotropic produce the highest torque and register the best efficiency versus the latter.With this study, it is hope that the designer can have second option to choose other type of magnetization without sacrificing the performance. The option may become in handy when the RAP becomes more expensive or difficult to procure.

Key words: Magnetic gear; machine design; torque; efficiency; finite element, electromagnetics.

1.INTRODUCTION

Magnetic gear (MG) has been researched for nearly 30 years and there are still plenty room to improve. It has the potential to compete with the mechanical gear due to its features, such as no contact between input and output, doesn’t require lubrication, low noise, low vibration and compact magnetic traction system [1]–[5].Despite of having better features, mechanical gears’ research optimization is not slowing either[6], [7]. Many recent publications adopt the concept of flux modulation technique [8]–[10] introduced in early 2000s to further improve the structure and design [11], [12]. This flux modulation MG is named coaxial magnetic gear (CMG). It was demonstrated to produce the most efficient magnetic gear and high torque density. Figure 1 shows the structure of CMG[13]. The inner permanent magnet is surface mounted at the inner yoke which act as inner pole pair, while the outer PM is surface mounted at the outer yoke act as outer pole pair. The pole piece is place in the middle of the air gap, and it is made of ferromagnetic material. It uses radial flux pattern at inner and outer PM which either pointing inward or outward respectively, shown in Figure 2. When the inner pole pair rotates, the magnetic field density change at the air gap. The change in the air gap depends on the rotational speed of the inner PM. However, due to existence of the pole piece, harmonic is generated with different frequency. The relation between the magnetic field density frequency and the harmonic frequency is expressed as

$$\omega = \frac{p_i}{p_i+n_s}\omega_r \qquad (1)$$

where ω is the harmonic frequency, p_i is the inner pole pair, n_s is the number of pole piece and ω_r is the rotational speed of the inner pole pair. Therefore, in order for the outer pole pair to rotate in the same speed as the harmonic frequency, the pole pair number has to be set as

$$p_o = p_i + n_s \qquad (2)$$

where p_o is the outer pole pair. Hence the gear ratio can be calculated as

$$G_r = \frac{p_o}{p_i} \qquad (3)$$

where Gr is the gear ratio which can be used to convert torque of CMG from the inner rotor to outer rotor.

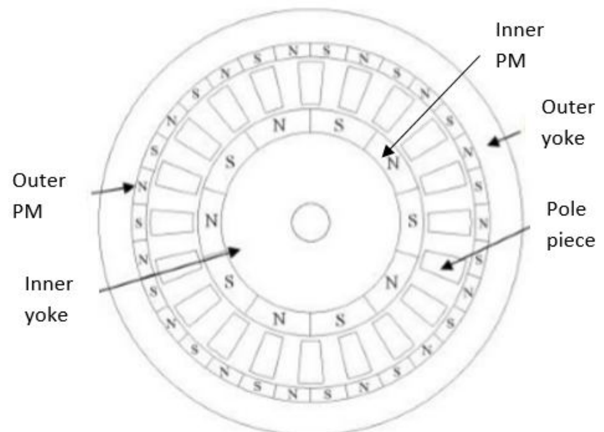


Figure 1: CMG structure

This structure uses radial flux pattern at inner and outer PM which either pointing inward or outward respectively, shown in Figure 2. There are attempts by researchers to use Halbach array but there are still numbers of flux direction that can be explored and analyse[14]–[17]. Many optimization and customization can be adapt from other electrical machine which includes rotor structure, stator structure and etcetera [18].

In this paper, radial anisotropic, circumferential anisotropic, parallel circular direction (PCD)and parallel radial direction (PRD)magnetization pattern are introduced and explained. Then, these magnetization pattern are simulated using JMAG Designer 16.0 on the coaxial magnetic gear with 2.33 gear ratio. Torque and efficiency are calculated and compared. The result shows that the radial anisotropic produce the highest torque and register the best efficiency versus the latter.

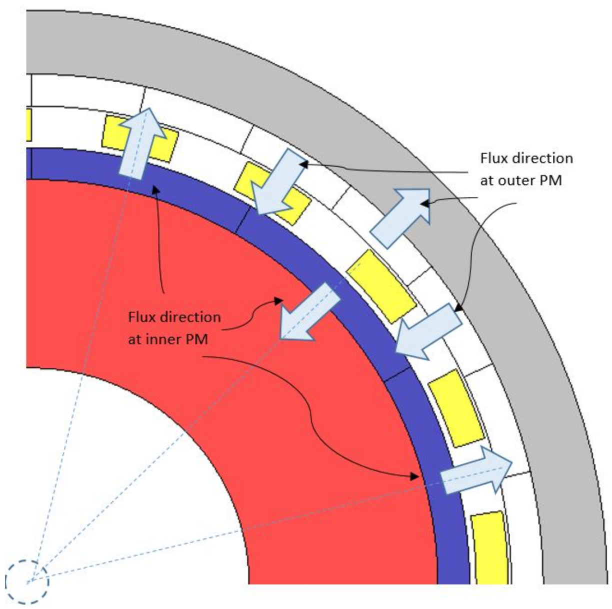


Figure 2: Radial flux direction at inner and outer PM

2. MAGNETIZATION PATTERN SETUP

2.1Radial Anisotropic Pattern (RAP)

All four pattern available in JMAG Designer [19]. Figure 3 shows the radial anisotropic magnetization pattern. This magnetization pattern sets the magnetizing vectors radially assuming circles or cylinders in the entire material. In CMG structure, the direction of the pattern is pointing to the centre point of the machine. Figure 4 shows the direction on a pair of magnet in CMG.

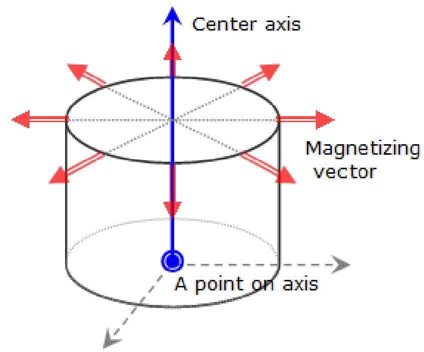


Figure 3: Radial anisotropic

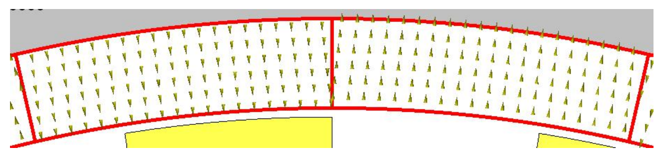


Figure 4: Radial anisotropic direction in CMG

2.2 Circumferential Anisotropic Pattern (CAP)

Figure 5 shows the circumferential anisotropic magnetization pattern. The magnetization pattern sets the magnetizing vectors in circumferential direction assuming circles or cylinders in the entire material. In CMG structure, the direction of the pattern is pointing towards the neighbouring magnet in clockwise or anti-clockwise direction. Figure 6 shows the direction on a pair of magnet in CMG.

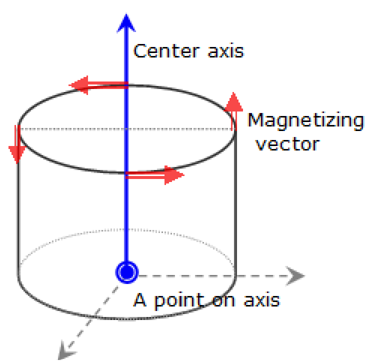


Figure 5: Circumferential anisotropic

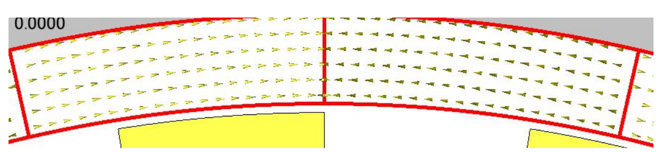


Figure 6: Circumferential anisotropic in CMG

2.3 Parallel Pattern Circular Direction (PCD)

Figure 7 shows the parallel pattern circular direction. This magnetization pattern is where the pole having parallel magnetizing vector repeats reversing itself in the circumferential direction. In CMG structure, the direction of all the pattern is parallel starting flux line. Figure 8 shows the direction on pair magnet in CMG.

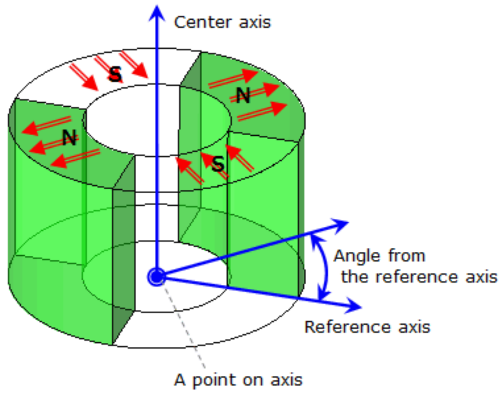


Figure 7: Parallel circular direction

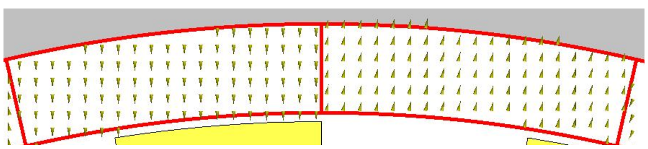


Figure 8: Parallel circular direction in CMG

2.4 Parallel Pattern Radial Direction (PRD)

Figure 9 shows the parallel pattern radial direction. This magnetization pattern is where the pole having the magnetizing vector in the radial direction repeats reversing itself in the circular direction. In CMG structure, the direction of all the pattern is parallel to the opposite flux line. Figure 9 shows the direction on pair magnet in CMG.

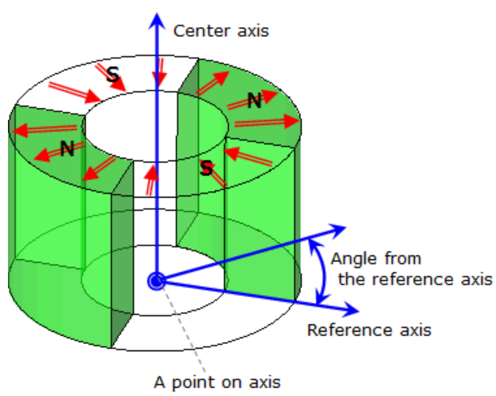


Figure 9: Parallel radial direction

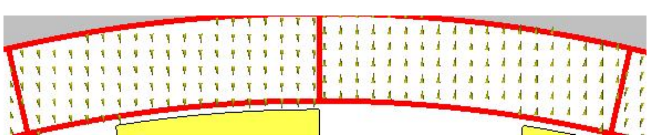


Figure 10: Parallel circular direction in CMG

3. SIMULATION CONFIGURATION

In this paper, 2D finite element software JMAG 16 is used. The structure of CMG is shown in Figure 11. It consists of 6 inner pole pair, 20 pole piece and 28 outer pole pair. Table 1 shows the dimension of CMG. The total PM volume is 0.000135m^3.or mass 1.0207kg

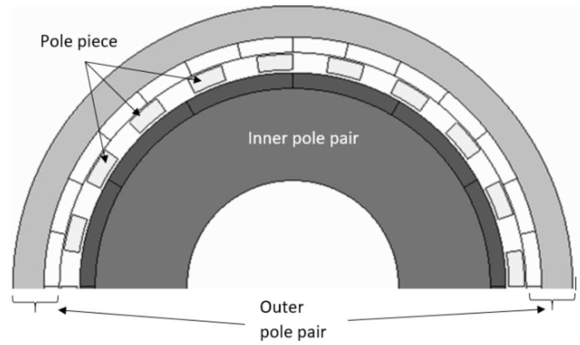


Figure 11: CMG structure drawn in simulation

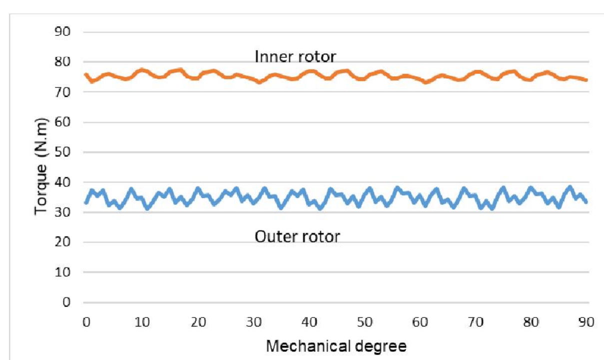
Table 1: Dimension of CMG in finite element.

Parts	**Model A**
Gear ratio	10/3
MG radius	90
Inner pole pair radius	68.5mm
Shaft	34mm
Axial length	30mm
Inner magnet arc	30^o
Pole piece arc	9^o
Outer magnet arc	12.857^o
Inner magnet width	5mm
Outer magnet width	5mm
Inner air gap width	1mm
Outer air gap width	0.5mm

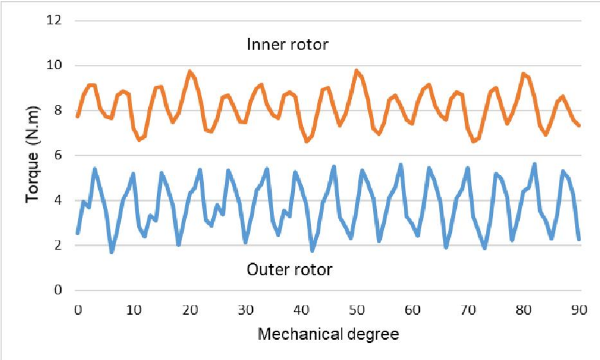
The CMG is torque multiplier type. Hence, the inner pole pair is connected to the prime mover while the outer pole pair is the output. The speed for input is set for 2100 rpm while outer rotor should rotate 900 rpm based on 2.33 gear ratio. Transient analysis is performed for 4 types of magnetization pattern separately.

4. RESULT

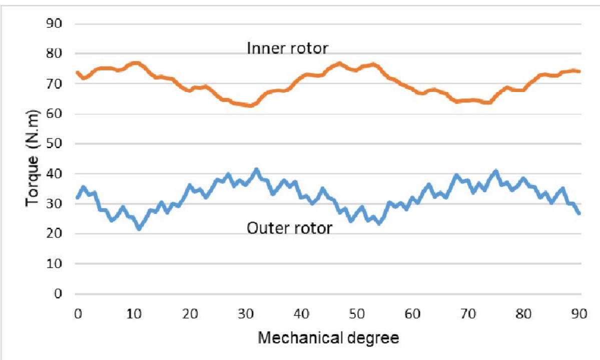
The torque waveform with four magnetization pattern are shown in Figure 12 (a)-(d)



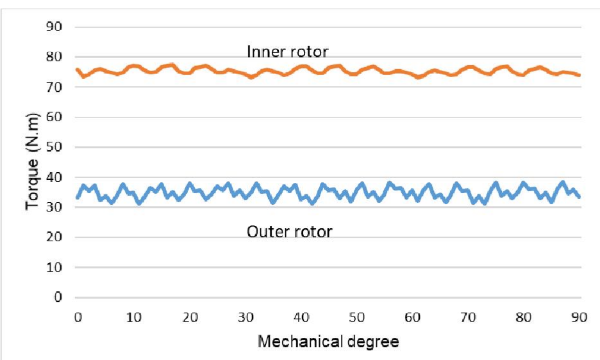
(a) Torque waveform in RAP



(b) Torque waveform in CAP



(c) Torque waveform in PCD



(d) Torque waveform in PRD

Figure 12: Torque waveform using different magnetization pattern.

From these graph, it is clear that magnetization pattern either RAP or PRD yield better result compares to the CAP or PCD. The low torque is due to the difficult to align between inner pole magnet and outer pole magnet. However, in radial direction, the alignment can be accomplished easily from inner pole to outer pole.Torque ripple can be calculated as

$$T_r = \frac{\tau_{max} - \tau_{min}}{\tau_{avg}} \quad (4)$$

where τ_{max} and τ_{min} is the maximum and minimum value of the torque, and τ_{avg} is the average torque.
Gear efficiency can be calculated as

$$E_{ff} = \frac{\tau_i \omega_i}{\tau_o \omega_o} \quad (5)$$

where τ_i and τ_o is the inner rotor torque and outer rotor torque, $\omega_i$and $\omega_o$is the inner rotor speed and outer rotor speed. Table 2 summarize the result of these study. The torque ripple in CAP and PRD are very high. This magnitude of torque ripple may result in rotor to stall and unusable. The efficiency calculated in all the magnetization pattern are almost the same, around 92.6%.

Table 2: Summary of magnetization pattern study

Pattern	RAP	CAP	PRD	PCD
Average inner torque	34.863	3.770	32.471	34.862
Average outer torque	75.303	8.144	70.243	75.301
Torque ripple (inner)	0.218	1.041	0.613	0.218
Torque ripple (outer)	0.057	0.384	0.205	0.057
Efficiency	0.926	0.926	0.927	0.926

3. CONCLUSION

In this paper, four magnetization pattern, RAP, CAP, PRD and PCD were applied on magnetic gear of 2.33 gear ratio. The performance of the magnetization in terms of torque, efficiency and torque ripple were simulated using 2D finite element in transient mode. The result showed that radial pattern which the direction of the flux towards the origin or outwards yield very good result compares to the circular pattern which the direction of the flux line is circling the magnet ring clockwise or anti-clockwise. The lower performance was due to the miss-alignment between inner and outer pole pair when this type of direction is used. Coaxial magnetic gear usually uses RAP then PRD. With this discovery, designer have another option to choose PRD without sacrificing the performance. The option may become in handy when the RAP becomes more expensive or difficult to procure.

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