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Research Paper

Investigation of the Cogging Factor of CMG and RPMG for Several Pole Pair Combinations

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Abstract: The design of magnetic gear (MG) involves determining the gear ratio specific to its application. The gear ratio can be determined by the pole number of the inner rotor, outer rotor, and pole piece. This research investigates the cogging torque of several pole pair combinations in concentric magnetic gear (CMG) and rotating pole piece magnetic gear (RPMG). The gear ratio equations are initially derived for both the CMG and RPMG. Based on these equations, four sets of pole pair combinations are determined. The cogging factor is calculated in each combination. To determine the cogging factor significance towards the cogging torque, the magnetic gears are simulated in 2D finite element software. The result revealed that the lower pole pair combination generates 6 % to 9 % lower cogging torque than the higher pole pair combination. The simulation result also shows that the rate of increase in cogging factor did not correlate directly to the cogging torque in the simulation. It can be concluded that the cogging factor is not a suitable tool to assess the cogging torque level in CMG and RPMG.

Keywords: Machine design, Magnetic gear, Cogging torque, Finite element

1. Introduction

Gears and gearboxes are used regularly for torque transmission in many applications including electric vehicles (EVs). It is one of the main components of a driving system. The mechanical gear of a drive system has a high torque-over-volume ratio, but it suffers from inherent problems such as friction, noise and heat, vibration, and reliability. It requires contact to transmit torque and motion. Due to the engagement of the toothed wheel of the gears, regular maintenance is required to minimize the wear and tear of the tooth. To overcome the drawback arising from mechanical gears, magnetic gears (MG) and magnetically geared machines have been designed and evolved as realistic and practical alternatives to conventional mechanical gearboxes in recent times [1]. Magnetic gear (MG) is an attractive alternative to mechanical gear due to several features it possesses. For example, it has no mechanical fatigue, requires no lubrication, is contactless, has overload protection, and has minimal acoustic noise due to contact [2][3][4][5][6]. On the other hand, the determination of M, G design parameters starts with identifying the gear ratio for its application. The gear ratio of CMG depends on the ratio of the pole pairs between the inner rotor and outer rotor. Meanwhile, less number of pole pair translates into a simpler machine design and fabrication. However, this approach would result in higher torque ripple in some pole pair combinations [7]. Due to the reduction in the pole size, there is a physical constraint in developing a higher pole pair number. A general guideline that assists the machine designer to select the best pole pair combination is the application of the least common on multiple (LCM) methods. Based on the equation below, the higher the LCM, the lower the cogging factor, f_c is.

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$$f_c = \frac{2pn_s}{LCM(2p, n_s)} \quad (1)$$

where p is the pole pair number of either OPP or IPP. If the stationary part is changed from FMP to IPP or OPP, then the term n_s would be replaced with the new stationary part.

Figure 1 shows the f_c versus the gear ratio, G_r with a fixed number of inner pole pairs which equals 3 [8]. Several publications also reported a significant decrease in cogging torque when the f_c is considered during the initial design stage [7][9][10] [11].

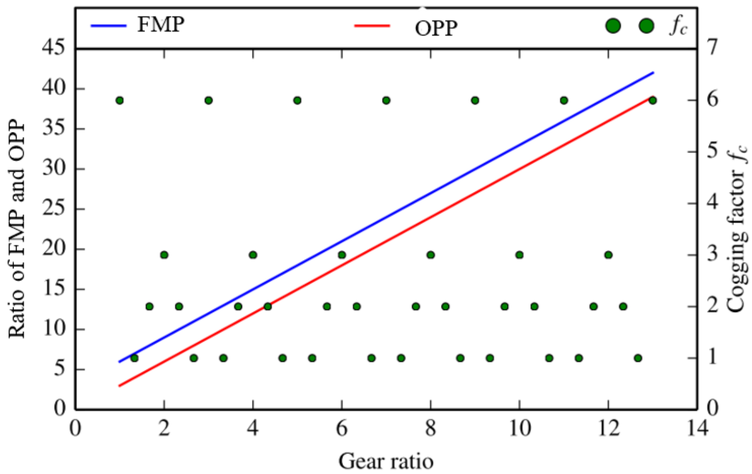


Figure 1. Classification of dc electrical machine f_c versus the G_r with a fed inner pole pairs pair

The objective of this study is hence to determine the best pole pair combination of CMG and RPMG based on the cogging factor and LCM method. The fundamental equation of determining the pole pair combination is first derived for CMG and RPMG. While a list of pole pair combinations is determined based on the derived equation. The cogging factor in each combination is calculated and compared with the LCM method. Finally, the best pole pair combinations that produce the highest torque at the lowest torque ripple are proposed in this research.

2. Formulation of gear ratio equation of RPMG from CMG fundamental equation

CMG uses the flux modulation principle to transfer torque and speed from the input rotor to the output rotor. Figure 2 illustrates the structure of CMG [12]. CMG consists of 2 rotors, an inner pole pair (IPP) and outer pole pair (OPP). The rotors are made of PM surfaced that are mounted on a ferromagnetic yoke. The number of the PM poles at the inner and outer rotor can be labeled as p_i and p_o. Ferromagnetic pole pieces (FMP) are inserted between the rotor.

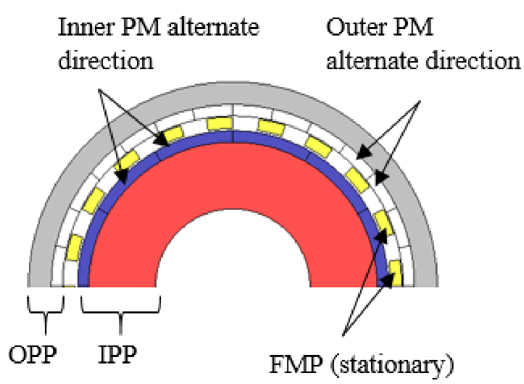


Figure 2. Structure of CMG [12]

The relationship between FMP pole pair, n_s, IPP, p_i, and OPP p_o, when the pole piece is left stationary, is

$$n_s = p_i + p_o \tag{2}$$

When each term in equation (1) is multiplied by its rotational speed, it can be expressed as

$$w_o p_o + w_i p_i = w_p n_p \tag{3}$$

where w_i is the inner rotor speed, who is the outer rotor speed and w_p is the FMP speed. Since the FMP is let stationary, the equation becomes

$$w_i p_i = -w_o p_o \tag{4}$$

Meanwhile, the gear ratio which is the ratio between the rotor speed and can be written as

$$G_r = \frac{w_i}{w_o} = -\frac{p_o}{p_i} \tag{5}$$

Several past studies have shown that CMG is capable to achieve a torque density of more than 100 kNm/m³. However, a more recent study showed that if the OPP is let stationary while the FMP rotates, the torque would increase slightly together with its gear ratio [CITE]. The gear ratio when the OPP is let stationary can be expressed as follows

$$G_r = \frac{w_i}{w_p} = \frac{n_p}{p_i}, \qquad w_l = 0 \tag{6}$$

The difference in gear ratio between these two conditions can be calculated as follows

$$\Delta G_r = \frac{n_p}{p_i} - \left|\frac{p_o}{p_i}\right| = \frac{n_p}{p_i} - \frac{n_{p-}\, p_i}{p_{hi}} = 1 \tag{7}$$

3. Identification of the Best Pole Pair Combination Through LCM Value

To demonstrate the cogging factor, f_c in equation (1), four sets of pole pair combinations are determined for CMG and RPMG using equations (5) and (6). In this study, the middle range of EVs final drive ratio is considered, which is between 4 to 8, whilst in pra previous study, only one combination was assessed for each gear ratio [13]. Table 1 to 4 show the pole pair combinations, set A, B, C, and D. The outer rotor pole number is denoted as either p_h or n_p which represent the CMG or RPMG topology.

Table 1. Pole pair combination for set A

	Gear ratio											
	4.33		5		5.66		6.33		7		7.66	
	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p
A1	13	3	15	3	17	3	19	3	21	3	23	3
A2	26	6	30	6	34	6	38	6	42	6	46	6
A3	52	12	60	12	68	12	76	12	84	12	92	12

Figure 3 displays four sets of f_c values versus the gear ratio in three CMG combinations. Figure 4 on the other hand shows four sets of f_c values versus the gear ratio in three RPMG combinations. Overall, the *FC* in the integer gear ratio across all the sets produced a higher value than the non-integer gear ratio. When only non-integer gear ratios are considered, lesser f_c is observed in the lower pole pair

Table 2. Pole pair combination for set B

	Gear ratio											
	4		4.66		5.33		6		6.66		7.3	
	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p
B1	12	3	14	3	16	3	18	3	20	3	22	3
B2	24	6	28	6	32	6	36	6	40	6	44	6
B3	48	12	56	12	64	12	72	12	80	12	88	12

Table 3. Pole pair combination for set C

	Gear ratio											
	4		4.5		5		5.5		6		6.5	
	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p
C1	16	4	18	4	20	4	22	4	24	4	26	4
C2	32	8	36	8	40	8	44	8	48	8	52	8
C3	64	16	72	16	80	16	88	16	96	16	104	16

Table 4. Pole pair combination for set D

	Gear ratio											
Set	4.25		4.75		5.25		5.75		6.25		6.75	
	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p	p_o	p_i or n_p
D1	17	4	19	4	21	4	23	4	25	4	27	4
D2	34	8	38	8	42	8	46	8	50	8	54	8
D3	68	16	76	16	84	16	92	16	100	16	108	16

combination, especially in D1. The rate of f_c increase is doubled from the 1st combination to the 2nd combination, and from the 2nd combination to the 3rd combination. The f_c in RPMG and CMG are the same when compared between the same set.

To validate the f_c significance in predicting the cogging torque, the cogging torque in several pole pair combinations is simulated. Since the f_c variation appears only when the pole pair combination is increased, it was decided to narrow down this study toward the highest gear ratio for each set. However, considering that the third combination has a very small pole piece and outer PM arc, the third combination is excluded from this study. Figure 5 demonstrates the OPP arch angle from all the combinations. Since the CMG is symmetrical, the arc angles at p_i, p_l, and n_p can be expressed as:

$$\theta_{arc} = \frac{180}{P} \tag{8}$$

where θ_{arc} is the arc angle and P is either p_i, p_o, or n_p. The higher the pole number, the smaller the arc of the PM poles.

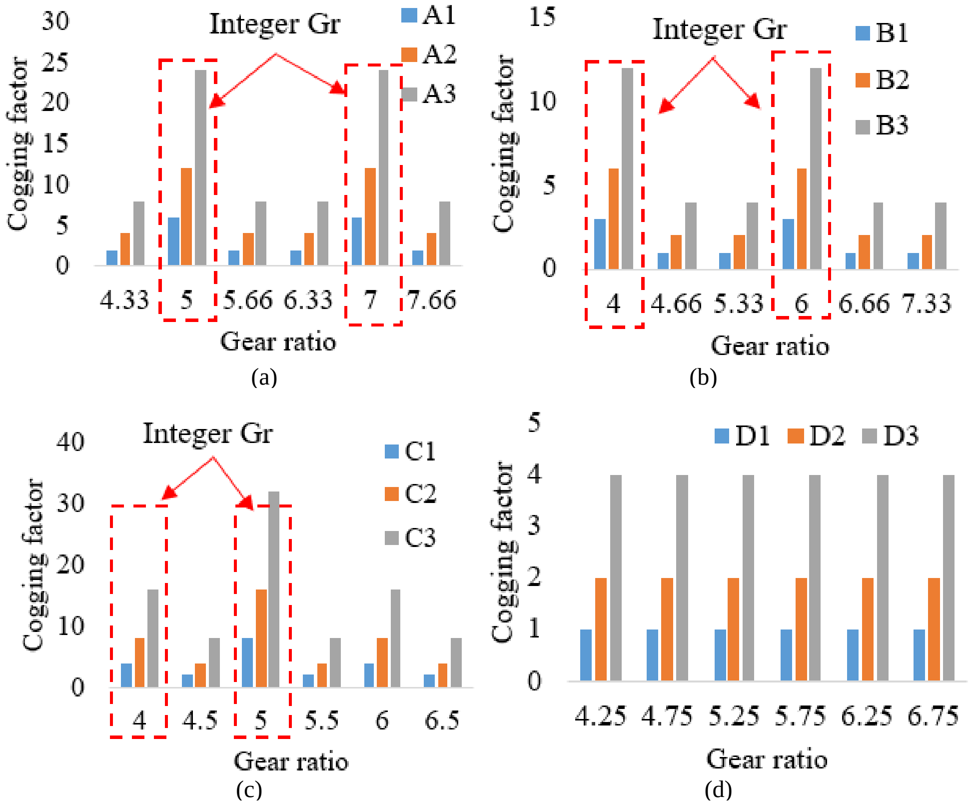


Figure 3. Cogging factor versus the gear ratio in three CMG combinations (a) set A, (b) set B, (c) set C, (d) set D

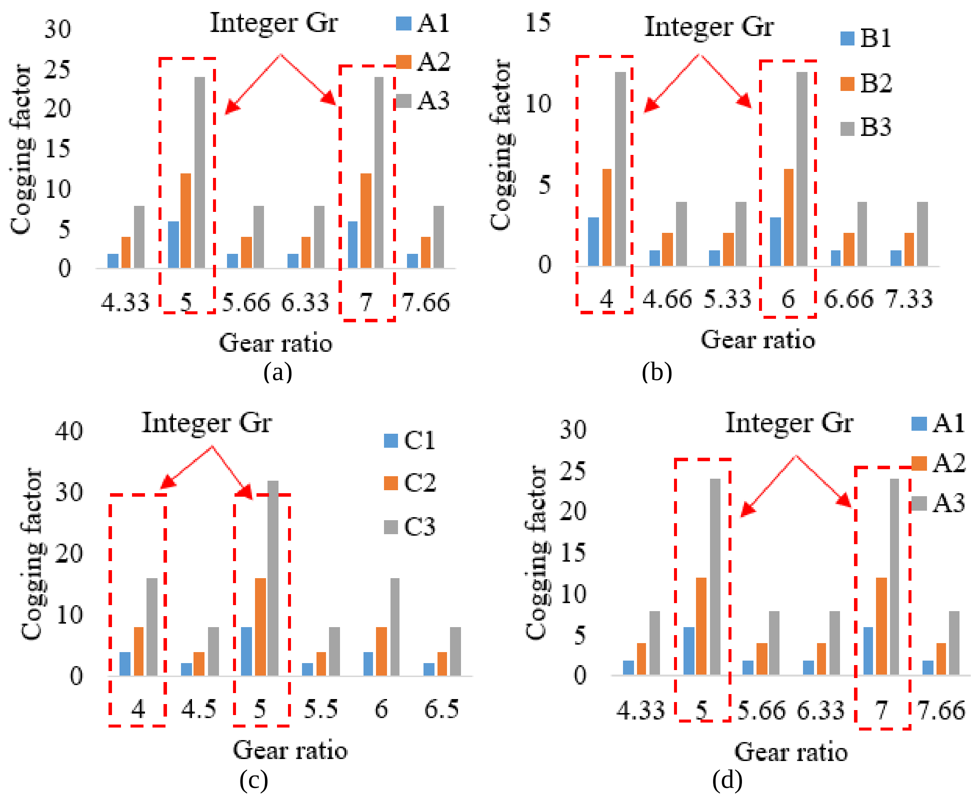
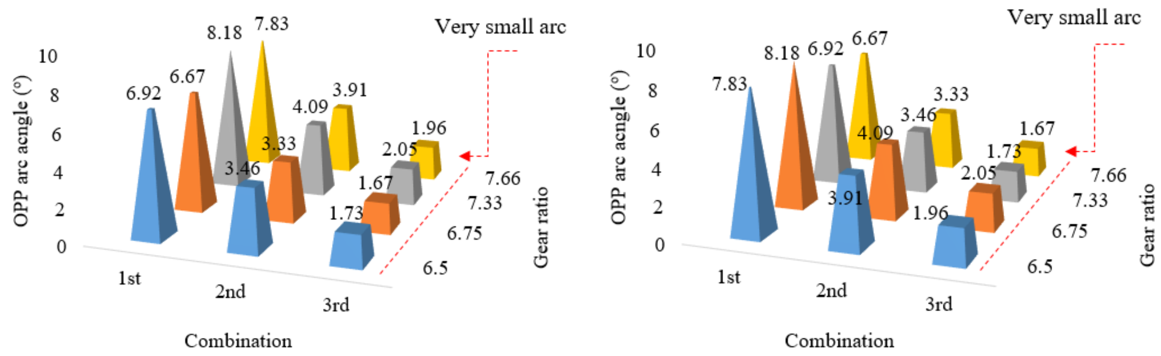
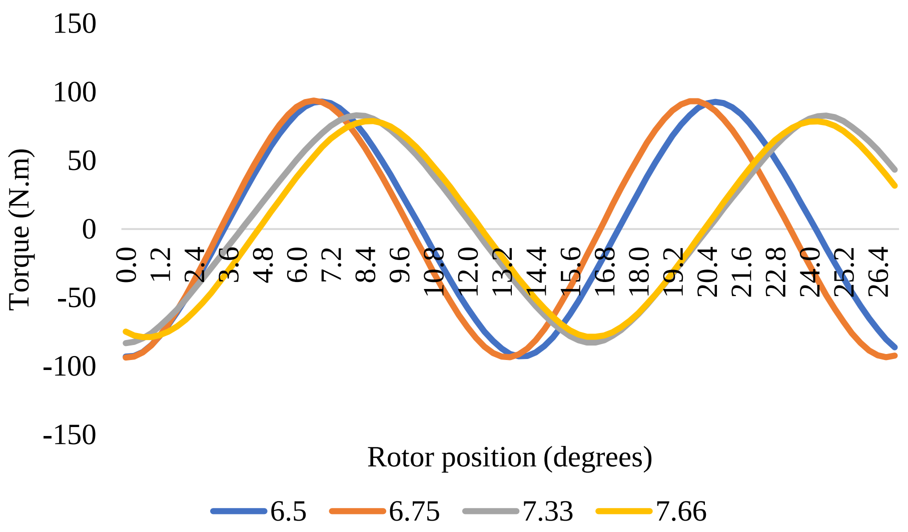


Figure 4. Cogging factor versus the gear ratio in three RPMG combinations (a) set A, (b) set B, (c) set C, (d) set D

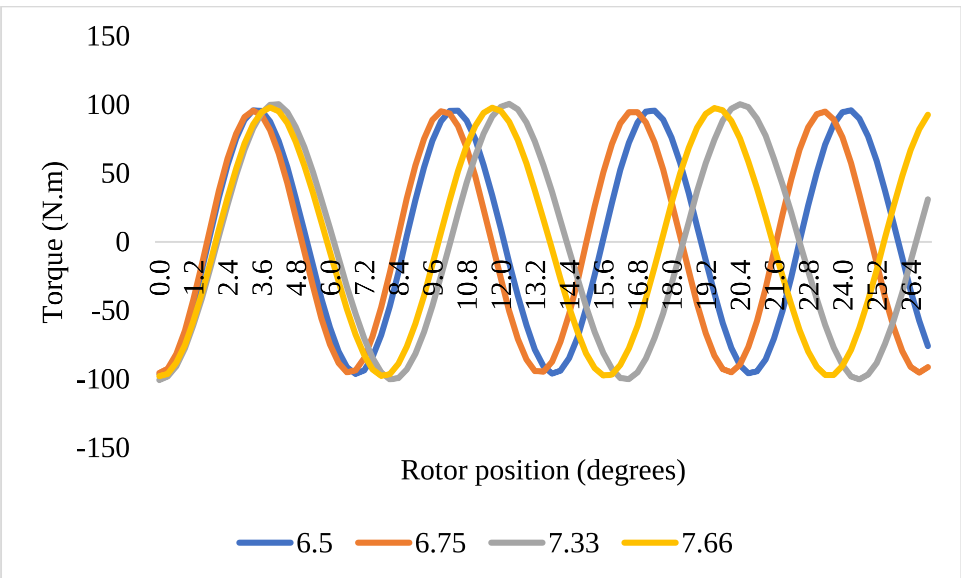


(a) (b)

Figure 5. OPP arc angle in all three combinations at different gear ratios for (a) CMG and (b) RPMG



(a)



(b)

Figure 6. Cogging torque in CMG in the (a) 1st and (b) 2nd combination

Figure 6 shows the result of the cogging torque simulated in CMG for the 1st and the 2nd combinations. Meanwhile, figure 7 illustrates the result of the cogging torque simulated in RPMG for the 1st and 2nd combinations. In the previous calculation, it is observed that the f_c values double from the 1st to the 2nd combination. However, the cogging torque value from the simulation did not increase as much as the f_c value. Literature [CITE] revealed that the f_c in the equation in (1) is based on the PM machine. Unlike PM machines, CMG and RPMG have no slots and winding which would increase the air gap flux density when energized. Therefore, the cogging torque in CMG and RPMG will always produce the same maximum torque as when both rotors are in the synchronization state. It is affirmative that CMG and RPMG cogging torque values cannot be interpreted in a similar way to the PM machine. The graph also demonstrates that the higher the pole's number, the higher the cogging torque frequency is. Higher torque can also be observed in the RPMG instead of the CMG, notably in the 2nd combination.

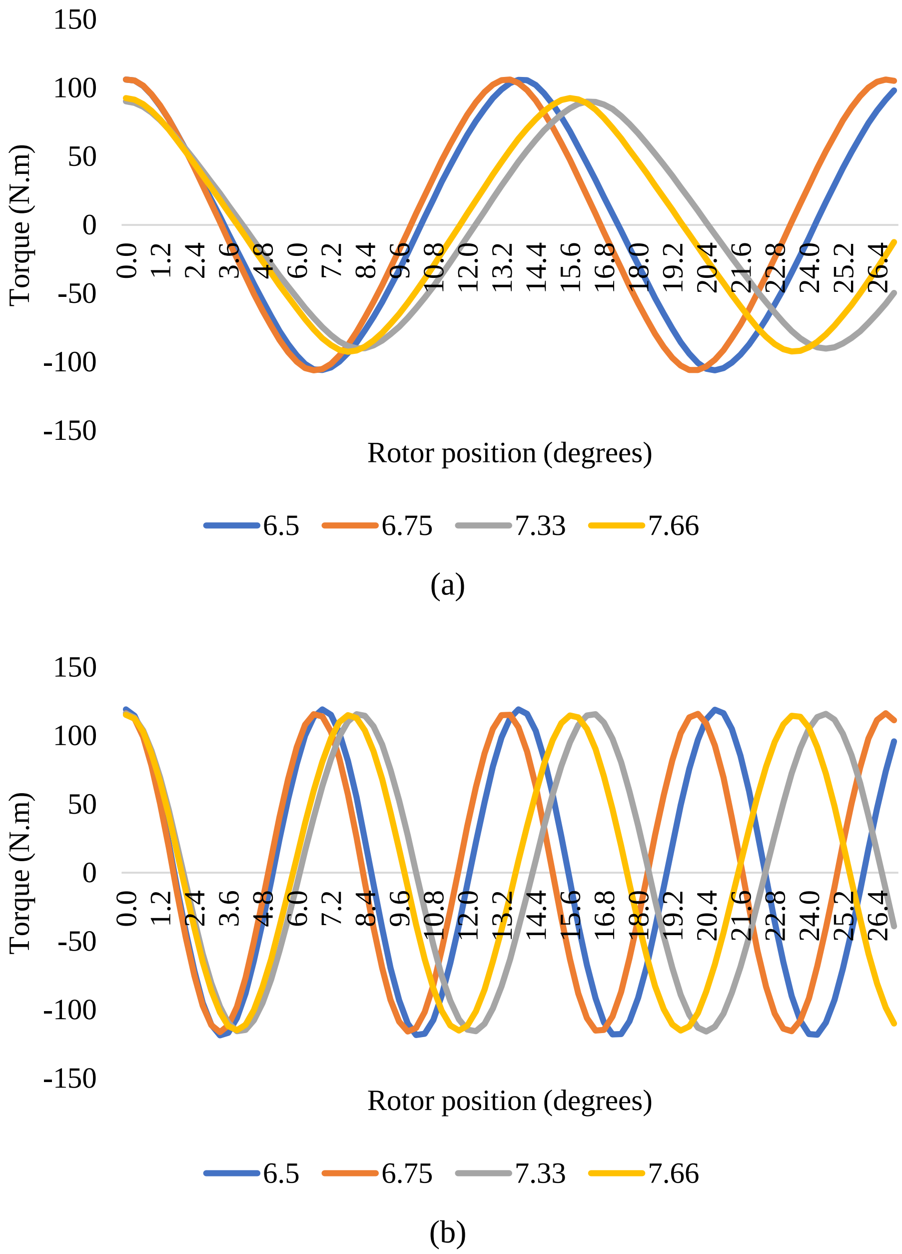


Fig. 7. Cogging torque in RPMG in the (a) 1st combination and (b) 2nd combination

4. Conclusions

This research investigates the torque characteristic in several pole pair combinations of CMG and RPMG. The gear ratio equations are initially derived for both CMG and RPMG. Based on these equations, four sets of pole pair combinations are determined. The cogging factor is calculated in each combination. The result shows that the integer gear ratio registered a high cogging factor across all the sets compared to the non-integer gear ratio. In the non-integer gear ratios, a lesser cogging factor is observed in the lower pole pair combination, especially in D1. Both RPMG and CMG have the same cogging factor value when compared within the same ratio. To determine the cogging factor significance towards the cogging torque, the 1st and 2nd combinations in each set are simulated. The cogging torque in the 2nd combination is 6% higher than in the 1st combination for RPMG and 13% higher in CMG. The simulation result shows that the rate of increase in cogging factor does not directly relate to the increase of cogging torque in the simulation. These results confirm that the cogging factor is not a suitable method to determine the rate of cogging torque in CMG and RPMG. An improved cogging factor needs to be developed for CMG and RPMG.

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Authors' Contributions

E. Sulaiman and A. A. Rahman carried out the study and wrote up the article. Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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