Comparative Analysis of a Coaxial Magnetic Gear with a Flux Concentration Rotor and Consequent Pole Rotor Typology

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This paper presents the performance comparison between a flux concentration and triple permanent magnet consequent pole magnetic gear rotor typology with the same 7.5:1 gear ratio. The triple permanent magnet consequent pole magnetic gear is unique in that it can create torque change through two field heterodyning pole combinations. The performance with respect to volumetric and mass torque density is considered. It is shown that the flux concentration typology can operate with a higher mass and volumetric torque density, even when using a low flux concentration ratio rotor.

Index Terms — **Electromagnetic forces, Halbach rotor, radial coupling, finite element analysis**

I. Introduction

Magnetic gears (MG) utilize magnetic field space modulation to create speed amplification without any physical contact [1-3]. As a MG does not rely on current excitation a MG can sustain a very high magnetic airgap sheer stress value. Atallah *et al.* was the first to demonstrate the torque density capabilities of the coaxial MG [1], as shown in Fig. 1. Since then the number of researchers investigating MGs has rapidly increased. In addition to the radial coaxial MG [4] a transverse flux MG [5] and planetary MG [6] typology has been investigated. Both radial and axial [7, 8] types have been studied. The radial coaxial MG typology is currently the most researched. A summary of the different rotor types that have been used in the radial coaxial MG configuration along with their calculated and measured torque density value and outer air-gap shear stress value is shown in Table I. Recently the flux concentration (FC) [9] and triple permanent magnet (PM) consequent pole (CP) typologies have been proposed [10, 11]. The FC typology, as shown in Fig. 2, is able to increase torque by using an additional radial magnet in a type of Halbach arrangement. This can therefore increase the air-gap flux density by focusing the flux. Whilst the triple PM rotor CP typology, shown in Fig. 3, has the potential of creating higher torque due to the addition of the central rotor modulation magnets. This provides an additional torque creation mechanism between the modulation rotor magnets and outer rotor segments. In this paper, these two design typologies are compared for the first time in order to determine the merits of each torque enhancing approach. The objective is to provide a volumetric and mass torque density comparative analysis of each competing typology and then present the mechanical assembly of the best design.

TABLE I.
RADIAL COAXIAL MAGNETIC GEAR ROTOR TYPOLOGIES

Rotor typology	Torque density [N·m /L] Calculated	Torque density [N·m /L] Measured	Gear ratio	Diameter [mm]	Shear stress [kN/m²]
Surface mounted [12]	85.7	60	5.75	140	38.9
Flux focusing [13]	244.5	235.8	4.25	228	129.4
Halbach array [15]	159.2	108.3	4.25	214	54.1
Interior PM [16]	16	12.3	5.5	120	20.9
Flux concentration [9]	154	107	4.25	114	85.3
Triple PM-CP [11]	142.9	-	7.3	184	49.7

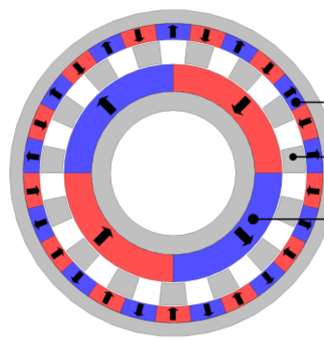


Fig. 1. Cross-sectional view of a 7.5:1 surface mounted magnetic gearbox. The inner rotor as p_1=2 pole-pairs, the outer rotor has p_3=13 pole-pairs and there are n_2 =15 ferromagnetic slots on the central rotor.

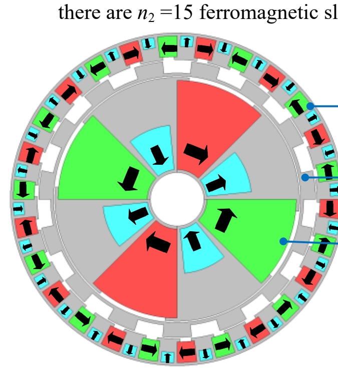


Fig. 2. Flux concentration magnetic gearbox with a 7.5:1 gear ratio. Lamination bridges are used on each rotor to minimize part count. The pole combination is given by (p_1, n_2, p_3) = (2, 15, 13).

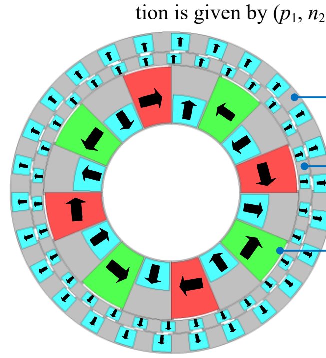


Fig. 3. Consequent pole MG design with a triple PM rotor typology. A 7.5:1 gear ratio. Lamination bridges are used on each rotor to minimize part count. The pole combination is given by (p_1, n_2, p_3) = (4, 30, 26).

II. Pole Selection

The coaxial MG is composed of an inner rotor with p_1 pole-pairs an outer rotor with p_3 pole-pairs and a central modulation rotor with n_2 ferromagnetic segments. In order create maximum continuous torque the poles must satisfy

$$n_2 = p_1 + p_3 \quad (1)$$

For the FC MG rotor the ferromagnetic inner rotor slots, n_1, and outer rotor slots, n_3, are equal to:

$$n_1 = 2p_1 \quad (2)$$

$$n_3 = 2p_3 \quad (3)$$

In contrast, for the CP design, shown in Fig. 3, one has

$$n_1 = p_1 \quad (4)$$

$$n_3 = p_3 \quad (5)$$

In both designs the outer rotor is held fixed and therefore the angular speed relationship is given by:

$$\omega_1 = \frac{n_2}{p_1}\omega_2 \quad (6)$$

where ω_1 and ω_2 is the inner and outer angular speed respectively.

In order to provide a fair performance comparison between the FC and CP designs the pole combinations for both designs were selected to give the same gear ratio. In order to do this the number of outer rotor slots, n_3, was kept constant for both designs this then meant that the inner rotor pole-pair number for the FC design had to be lower. The pole and slot values selected are shown in Table II. The pole values were selected to give a relatively high gear ratio whilst also providing a low torque ripple.

Table II.
Magnetic Gearbox Configuration

Description		Flux concentration	Triple PM rotor consequent pole
Inner rotor	Pole pairs, p_1	2	4
	Slots, n_1	4	8
Modulation rotor	Pole pairs, p_2	-	30
	Slots, n_2	15	30
Outer rotor	Pole pairs, p_3	13	26
	Slots, n_3	26	26
Gear ratio, G_{12}		7.5	7.5

The CP design is unique in that the slots can be used to create torque as well as the magnets. This is due to (4) and (5). For instance, for the design shown in Fig. 3 the inner rotor magnet pole-pairs, p_1=4, will be modulated by the n_2 = 30 ferromagnetic segments and therefore interact with the outer rotor pole-pairs since p_3=n_2-p_1=26. At the same time the modulation rotor's p_2=30 pole-pairs will interact with the stationary outer rotor n_3=26 ferromagnetic slots to give $p_1 = p_2 - n_3$ = 4 pole-pairs. In contrast, the FC typology cannot create torque interactions through the outer rotor slot number since $p_3 \neq n_3$.

Note that in [10, 11] the CP design had a surface mounted PM inner rotor whereas in this analysis the inner rotor has a flux concentration typology. This was determined to create a higher torque density.

III. Parameter Analysis

The fixed geometric and material properties for both designs are given in Table III while Table IV shows the geometry sweep parameters that were considered. The geometric parameters are defined graphically in Fig. 4. The outer MG radii (as well as axial length) have a big impact on the torque performance. Therefore, in order to assess the impact of scaling two different outer rotor radii, r_{o3}, values were studied.

The modulation rotor radial length is defined as

$$l_2 = r_{o2} - r_{i2} \quad (7)$$

where r_{o2} and r_{i2} are the outer and inner radii for the modulation rotor. The angular slot width for both designs was kept equal with the magnet angular width. The FC rotor on both designs is made up of radial and azimuthal magnets that are held in place within a laminated structure with support bridges. The use of a laminated outer rotor with bridges improves the assembly process and results in a less complex design than that presented in [9]. The FC inner rotors radial magnets' radial length, l_{rm1}, has been kept fixed such that

$$l_{rm1} \,/\, (r_{o1} - r_{i1} - 2t_p) = 0.5 \quad (8)$$

similarly, the FC outer rotor radial magnet length, l_{rm3}, has been maintained constant at

$$l_{rm3} \,/\, (r_{o3} - r_{i3} - 2t_p) = 0.5 \quad (9)$$

The use of the additional radial magnets increases the flux concentration since three of the four sides of the ferromagnetic slot has flux flowing from the magnets.

For each parameter selection the volumetric and mass torque density was computed. The active volumetric torque is defined as:

$$T_v = \frac{T_2}{\pi r_{o3}^2 d} \quad (10)$$

and the active mass torque density is

$$T_m = \frac{T_2}{m_s + m_m} \quad (11)$$

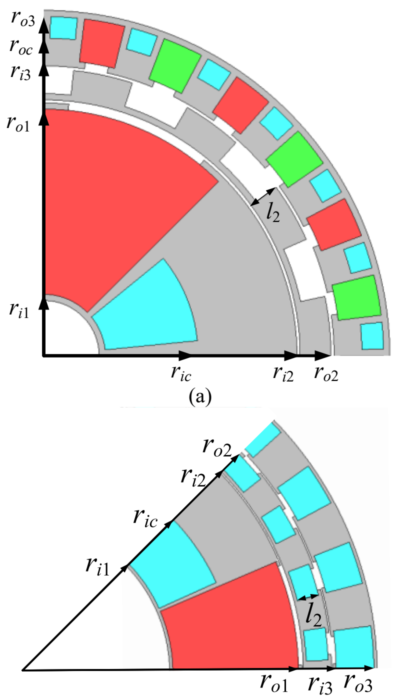
where T_2 = modulation rotor torque, m_s = ferromagnetic steel mass and m_m = magnet material mass.

Table III.
Fixed magnetic gearbox parameters

Parameter	Value
Gear ratio	7.5
Nd-Fe-B magnet grade	N40
Laminated rotor steel grade	M19
Stack length, d	75 mm
Airgap between rotors, g	0.5mm
Magnet retaining lips, t_p	1mm

Table IV.
Geometry Sweep Parameters

Parameter	Sweep range [mm]	
Active region outer diameter, r_{o3}	55	110
Inner rotor inner radius, r_{i1}	5 – 40	20 – 70
r_{i1} sweep step size	5	5
Inner rotor outer radius, r_{o1}	15 – 45	40 – 90
r_{o1} sweep step size	5	10
Modulation rotor radial length, l_2	3 – 13	7 – 22
l_2 sweep step size	0.5 & 1	0.5 & 2



(b)

Fig. 4. Geometric variable definitions for (a) the flux concentration magnetic gearbox and (b) the consequent pole magnetic gearbox.

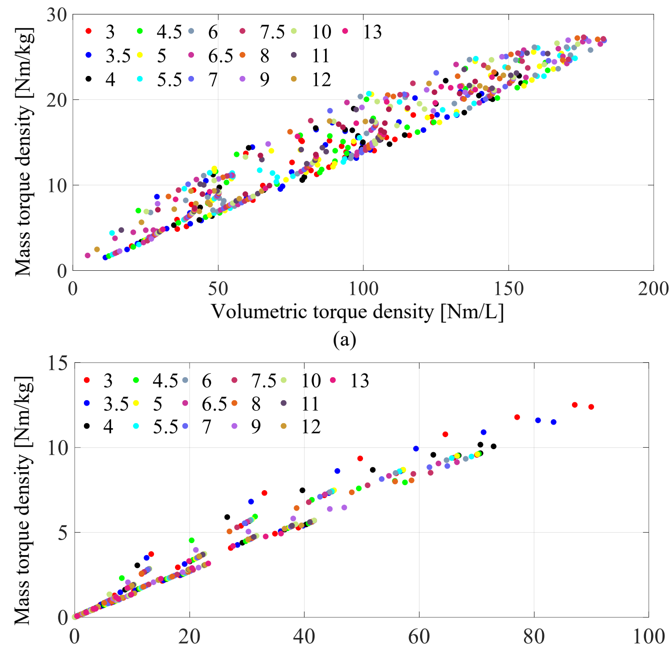
The 2-D finite element analysis (FEA) calculated mass-volumetric performance plots are shown in Fig 4 for the FC and CP designs respectively when $r_{o3} = 55$ mm. It can be noted that the FC design achieves a significantly higher torque density than the CP typology. The best FC MG design was able to achieve an active region torque density that is twice that of the CP design. This indicates that the additional modulation torque created by the central rotor magnets are ineffective at increasing torque relative to the FC design. Table V summarizes the salient design values and performance metrics when the outer radius is r_{o3} = 55mm. The flux concentration ratio for the inner rotor was computed from

$$\Gamma_1 = \frac{2p_1}{\pi}\left(1 - \frac{r_{i1}}{r_{o1}}\right) \tag{12}$$

and for the outer rotor it is

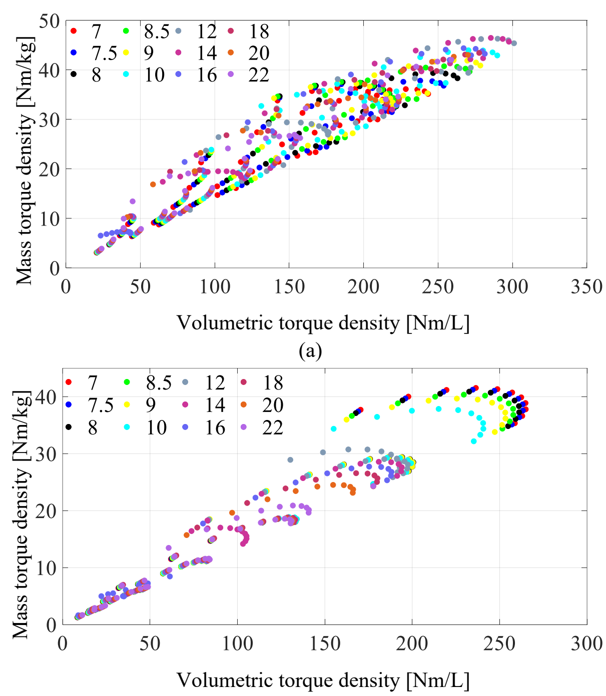
$$\Gamma_3 = \frac{2p_3}{\pi}\left(\frac{r_{o3}}{r_{i3}} - 1\right) \tag{13}$$

Fig. 6 show the mass-volumetric performance plots for the FC and CP designs when the outer radius is doubled to $r_{o3} = 110$ mm. The sweep values used are shown in Table IV. Fig. 6 indicates that the CP performance has dramatically increased, the CP design torque density has increased by 220% while FC design torque density has increased by only 70%. This results in the CP design becoming much more competitive with the FC design. A summary of the best design values for the $r_{o3} =$ 110mm design is shown in Table VI. The CP design benfited from having a higher pole-pair number. However the performance is still not as high as the FC design. The CP requires that magnets be included on the modulation rotor and this will be very difficult to manufacture. For these reasons the authors believe the FC has more potential.



(b)

Fig. 5. (a) Flux concentration and (b) consequent pole magnetic gearbox geometry sweep results with respect to mass and volumetric torque density when the outer rotor radii are r_{o3} = 55mm, different l_2 values are indicated in the legend



(b)

Fig. 6. (a) Flux concentration and (b) consequent pole magnetic gearbox geometry sweep results with respect to mass and volumetric torque density when the outer rotor radii are r_{o3} = 110mm, different l_2 values are indicated on the legend

IV. Practical Design

The 55mm radius design was selected for testing. The FC design was further refined by adding bolt supports as shown in Fig. 7 and Fig. 8. The outer rotor rods are non-magnetic and therefore create a flux barrier. However, there is still significant flux leakage through the lamination bridges, this is shown in Fig. 9. The bridges are needed to make the laminated design simple to assemble. These changes reduced the 2-D FEA calculated torque density by 8% to 168 N·m/L from 183 N·m/L.

TABLE V.
HIGHEST TORQUE DENSITY DESIGN VALUES WHEN r_{o3} = 55MM

Parameter		Flux concentration	Consequent pole	Units
Inner rotor inner radii, r_{i1}		10	10	mm
Inner rotor outer radii, r_{o1}		35	45	mm
Modulator radial length, l_2		7	3	mm
Outer rotor inner radii, r_{i3}		45	52.5	mm
Peak torque, T_2		130.4	64.1	N·m
Volumetric torque density, T_v		183	90	N·m/L
Mass torque density , T_m		26.9	12.4	N·m/kg
Flux concentration ratio	inner rotor, Γ_1	0.91	1.59	-
	outer rotor, Γ_2	1.7	-	-

TABLE VI.
HIGHEST TORQUE DENSITY DESIGN VALUES WHEN r_{o3} = 110MM

Parameter		Flux concentration	Consequent pole	Units
Inner rotor inner radii, r_{i1}		25	30	mm
Inner rotor outer radii, r_{o1}		80	90	mm
Modulator radial length, l_2		12	7	mm
Inner radii of outer rotor, r_{i3}		95	98.5	mm
Peak torque, T_2		858.7	755.7	Nm
Volumetric torque density, T_v		301.2	265.1	Nm/L
Mass torque density, T_m		45.3	37.7	Nm/kg
Flux concentration ratio	inner rotor, Γ_1	0.88	1.70	-
	outer rotor, Γ_2	1.3	-	-

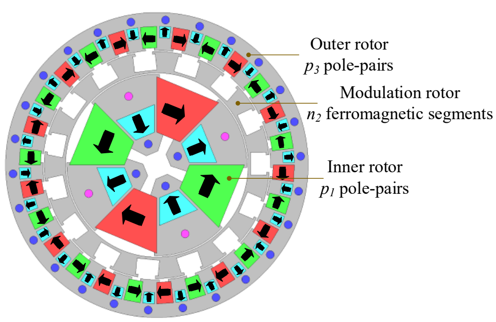


Fig. 7. Flux concentration Halbach magnetic gearbox with supporting rods added. Support rods on outer rotor are made of non-magnetic 316 stainless steel (blue color). Support rods on outer radii side of inner rotor (pink in color) are made of magnetic 416 stainless steel.

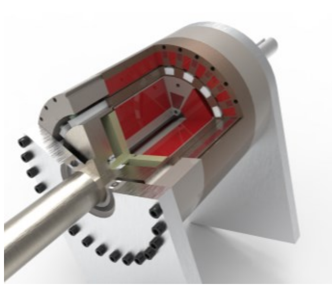


Fig. 8. Assembly drawing for the flux concentration magnetic gearbox with laminated rotor parts.

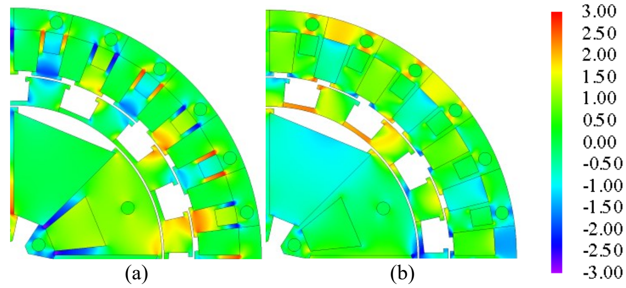


Fig. 9. (a) Radial flux density B_r and (b) azimuthal flux density B_θ for the flux concentration design

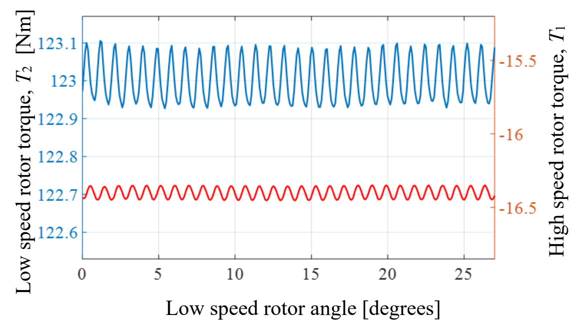


Fig. 10. Torque on both the high speed and low speed rotors

The torque ripple is shown in Fig. 10 at peak load (it is 0.13%). The use of a 75mm axial length will decrease the torque slightly, the reduction in torque due to 3-D edges effects is illustrated in Fig. 11. At a 75mm stack length the torque reduces to 107N·m (150N·m/L). The final design uses 2kg of magnet material and 3.2kg of M19 lamination material.

While a 150Nm/L torque density (at a radius of 55mm) is very high relative to direct-drive motors it still does not meet the comparable rated torque density for off-the shelf mechanical gearboxes. As an example, Table VII shows the performance data for both a cycloidal gearbox (Nabtesco RDS-006E) and planetary gearbox (Anaheim Automation GBPH-1201-NP-007). It can be noted that the volumetric torque density of both is still significantly higher than any published MG design. While the MG has the potential to have a much longer life-rating as well as lower noise and no-backlash further magnetic performance improvements are still needed.

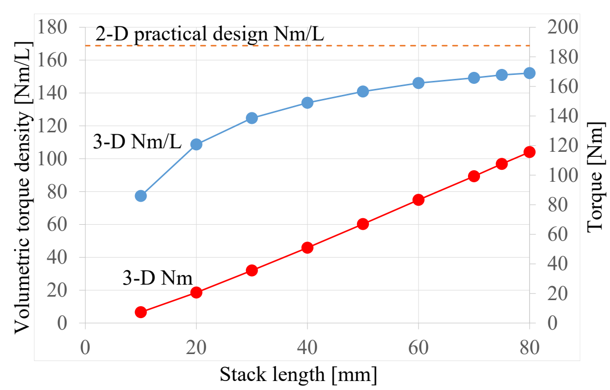


Fig. 11. Impact of axial stack length on performance of the flux concentration magnetic gear.

TABLE VII.
COMMERCIAL CYCLOIDAL AND PLANETARY GEARBOX PARAMETERS

Parameter		Cycloidal Value	Planetary Value	Units
Outer radii		62.75	57	mm
Axial length		83	127	mm
Mass		5.7	4.6	kg
Gear ratio, G_r		54	7	-
Output torque	Rated, T_r	58	285	N·m
	Momentary peak	294	855	N·m
Rated output angular speed, ω_R		30	385	RPM
Rated power ($T_R \cdot \omega_R$)		0.182	11.5	kW
Maximum input speed		3,500	6,500	RPM
Efficiency (at rated power)		85	97	%
Backlash		1.5	≥7	arc-min
Noise level		-	64	dB
Life rating		6,000	20,000	Hours
Volume torque density	Continuous	56.5	219.9	N·m/L
	Peak	286.3	659.6	N·m/L
Mass torque density	Continuous	10.1	65.0	N·m/kg
	Peak	51.6	185.9	N·m/kg
Amount		1,938	752	$US

V. CONCLUSION

A comparison analysis of a FC and CP MG has been presented for the first time. It was shown that the FC design has a significantly higher torque density for small radius designs. However, the CP performance improved significantly when utilizing a larger diameter geometry. As the CP uses magnets within the modulation rotor the CP will be very difficult to manufacture. Therefore, it is believed that the FC design has the greater potential for commercial use.

VI. ACKNOWLEDGMENTS

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