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Concentric Magnetic Gear Structure Review

***Abstract**. The paper presents the evolvement of magnetic gear structure from its inception up to the year of 2023. The output performances (power and torque) of all the structure will be tabled and analyzed in this paper. Among several structures researched in MG, Concentric Magnetic Gear (CMG), is the most researched structure due to its high utilization of the magnetic field compared to other structure. Since many structure evolved from CMG, a classification tree derived from CMG is presented. The classification tree provides an overview of the state of the art in CMG design.*

***Streszczenie.** artykule przedstawiono ewolucję konstrukcji przekładni magnetycznej od jej powstania do roku 2023. W artykule zostaną zestawione i przeanalizowane parametry wyjściowe (moc i moment obrotowy) wszystkich konstrukcji. Spośród kilku struktur badanych w MG, koncentryczna przekładnia magnetyczna (CMG) jest najczęściej badaną strukturą ze względu na wysokie wykorzystanie pola magnetycznego w porównaniu z innymi strukturami. Ponieważ wiele struktur wyewoluowało z CMG, przedstawiono drzewo klasyfikacyjne wywodzące się z CMG. Drzewo klasyfikacyjne zawiera przegląd stanu techniki w projektowaniu CMG. (**Przegląd struktury koncentrycznego przekładni magnetycznej**)*

Keywords: Magnetic gear, Hybrid-excited, finite element
Słowa kluczowe: Przekładnia magnetyczna, wzbudzana hybrydowo, element skończony

Introduction

Gears and gearboxes are used regularly for torque transmission in many applications including in automotive sector. It is one of the main component in a drive system. Mechanical gear has high torque over volume ratio, but it suffers from inherent problems such as friction, noise, heat, vibration and reliability problems. Mechanical gear requires contact to transmit torque and motion. Due to the engagement of toothed wheel of gears, regular maintenance is required especially on the lubricant and wear and tear. Manual differential gear in the transmission system recommend at least every 2 years of lubricant change. In automatic transmission and continuous variable transmission (CVT), the lubrication has to be change at least once a year [1]. Without proper lubrication, contact friction would result in gear fatigue and vibration [2]. The research on Magnetic Gears (MGs) is currently very active, primarily due to their ability to achieve contactless torque and rotation transmission [3] . Unlike mechanical gears that rely on physical contacts to transfer torque, which can result in issues like vibration-induced noise, tooth wear and potential tooth failure [4], MGs do not have these problems. They offer advantages such as no wear, no friction, no fatigue and do not require lubrication. Furthermore, MGs can be customized for specific mechanical properties like stiffness or damping. They also have the ability to protect structures and mechanisms against overload. Another advantage is their suitability for through-wall transmission without the need for joints or sealing [5]. As a result, the higher reliability and stability of MGs could potentially lead to them replacing mechanical gears in the near future. MGs have found increasing use in robotic applications that require high operating speeds and step-less speed control, such as electric vehicles and robot joints [6].They are also being studied and developed for aerospace and renewable energy applications that demand precise power transfer[4] [5][7]. This paper is divided into three sections. The first section presents the evolution of the design structure of MGs before the high density rare earth material were discovered up to the realization of Concentric Magnetic Gear (CMG). The second section summarized all the structures and compare the characteristic of all the structure that has been reviewed. The third section conclude and propose the structure that can be enhanced in the coming years.

Magnetic Gear Structures in The Past

Numerous studies have been conducted on Magnetic Gears (MGs) since the 1990s, addressing the challenges faced during their development. The lack of finite element software posed a significant hurdle in creating effective MGs fifty years ago. Initially, MG designs were directly inspired by traditional mechanical gears, with the idea of replacing teeth and slots with the north and south poles of permanent magnets (PMs) [8]. However, the limited availability of rare-earth PMs at that time resulted in poor torque density and became a key design challenge. Over time, researchers began exploring different structures to overcome this limitation [9]. In 1968, a patent was filed for the design of a planetary magnetic gear. This design featured inner magnet pole pairs, outer magnet pole pairs, and permeable bars positioned at varying radii along a common axis. Figure 1 illustrates the structure of the planetary magnetic gear [10]. The magnetic field of the inner magnet pole pair was modulated through the permeable bar, generating a magnetic flux density corresponding to the rotation of the inner magnet. The outer magnet pole pair then interacted with this modulated field, resulting in rotation of the outer magnet. Unfortunately, the patent did not provide any simulation or experimental data [10].

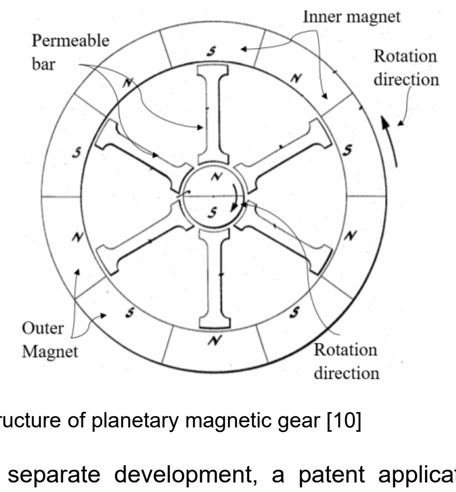


Fig. 1. Structure of planetary magnetic gear [10]

In a separate development, a patent application was filed for the structure of the spur magnetic gear. Figure 2(a) depicts the diagram of the patented spur-type magnetic gear from 1970. The smaller rotor is intended for motor attachment, while the larger rotor is connected to the output. The rotors rotate in opposite directions. The permanent magnet (PM) poles are arranged alternately in both rotors to generate attractive and repulsive forces, which drive the gear's motion [11]. Simulation results for this structure indicated a torque density of 18 kN.m/m3 [12]. An alternative design for the spur magnetic gear is illustrated in Figure 2(b), where the inner rotor is positioned inside the outer rotor, and the gear rotates along the inner side of the outer rotor [13].

a) b)

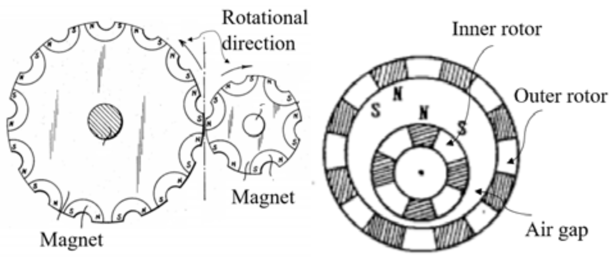


Fig. 2. Structures of spur magnetic gear: (a) external spur [11] and (b) internal spur [13]

In 1993, the worm structure of the magnetic gear was developed. This structure resembles a mechanical worm gear but without physical contact between the two rotors. Figure 3(a) displays the structure of the worm magnetic gear published in 1993 [14]. The input rotor, referred to as the worm, consists of a yoke and teeth. The teeth form a spiral line along the body of the yoke and are made of alternating pole magnets. The output rotor, called the worm wheel, also features teeth made of alternating pole magnets in the radial direction. Unlike the spur type, the attractive and repulsive forces of the toothed PM act perpendicular to the surface of each rotor. The maximum achieveable output torque was 11.5 Nm at 1400 rpm. Another research study estimated that the worm magnetic gear could only achieve a torque density of 2.3 kN.m/m3 [15]. In 1980, another intriguing design was presented, as depicted in Figure 3(b)[16]. In contrast to the previous concept, the authors applied the principle of reluctance torque for torque transfer and rotation. This design comprises an inner rotor with teeth, a transfer block, and an outer rotor with teeth. The transfer block remains stationary at all times. According to the authors, when the inner rotor deviates from its equilibrium state, the outer rotor attempts to rotate and align its teeth to establish a flux path, similar to the working principle of a reluctance machine. The transfer block serves as the flux source, which can be supplied by a PM or a DC coil. Although the experimental results yielded an output torque of 106 N.m, the gear efficiency was only 34.6 % at 2500 rpm. During the late 19th century, numerous structures resembling the planetary MG, spur MG, worm MG, and reluctance MG were extensively studied. However, the limited availability of high-power-density PMs during that era posed a significant challenge, resulting in low torque density for these design architectures. Towards the end of the 19th century, the discovery of rare-earth neodymium-iron-boron (NdFeB) permanent magnets (PMs) sparked new interest among machine designers. They began exploring the use of NdFeB PMs in magnetic gear designs, resulting in the simulation and verification of a spur magnetic gear structure. This design achieved a torque density of 30 kN.m/m3 when extrapolated, with the smallest air gap measuring 0.5 mm [15][17]. The pursuit of high-performance magnetic gears continued, leading to the publication of a high-performance coaxial magnetic gear design in 2001 [18]. In a coaxial magnetic gear, the input rotor and output rotor share the same centre point. The torque and rotation transfer between the rotors are based on the flux modulation principle. Figure 4(a) illustrates the structure of a coaxial magnetic gear, also known as a concentric magnetic gear (CMG), utilizing the flux modulation principle. It consists of three concentric components: stationary ferromagnetic pole pieces (FMPs), an inner pole pair (IPP) and an outer pole pair (OPP). Both the IPP and OPP rotors are composed of surface-mounted PMs and a yoke [18]. The magnetic field of the inner rotor is modulated through the stationary FMPs. Later publications reported about the fabrication of a CMG prototype [16][19]. According to the authors, this prototype achieved a transmitted torque density of up to 100 kN.m/m3 and 97 % gear efficiency at 1500 rpm [19][20]. Another variation of the CMG structure was proposed in [20] as illustrated in Figure 4(b). This structure was designed to be more practical for fabrication compared to the earlier CMG structure [15]. The inner rotor PMs in this design are of a spoke type rather than surface-mounted, allowing for the use of rectangular PMs instead of arc-shaped ones. The torque density achieved by this structure was 92 kN.m/m3. The initial prototype demonstrated an efficiency of 81 % at 1500 rpm, with the authors suggesting that efficiency could reach 96 % with proper optimization.

a) b)

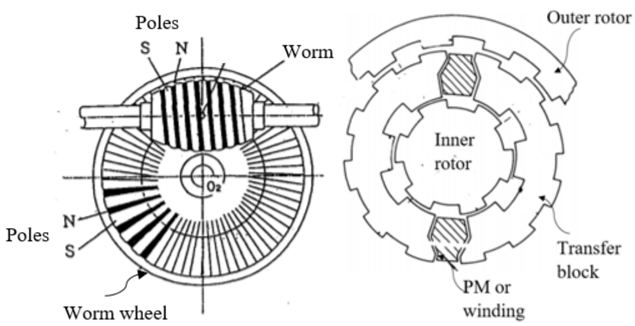


Fig. 3. Structure of (a) worm magnetic gear [14] and (b) reluctance magnetic gear [16]

a) b)

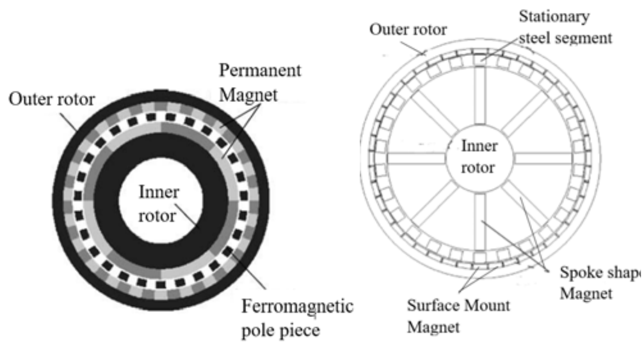
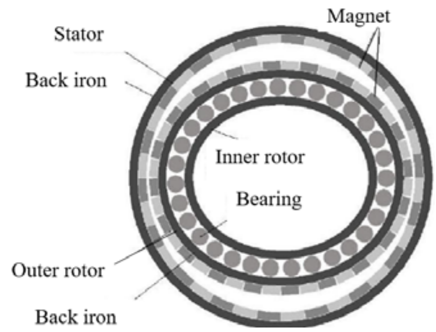


Fig. 4. Structures of CMG: (a) surface-mounted rotor [18] and (b) spoke rotor [15]

Two additional CMG structures, namely harmonic and planetary magnetic gears, are illustrated in Figure 5(a) and Figure 5(b). In a harmonic magnetic gear, an inner rotor with a profiled shape deforms the outer rotor through sliding contact when it rotates. This deformation generates time-varying space harmonics in the air gap region. Simulation results indicated that the harmonic structure achieved a torque density of 100 kN.m/m3 at a high gear ratio of 20:1

without any ripple. However, its implementation in physical hardware has been put on hold due to the requirement for flexible low-speed rotors and potential vibrations resulting from the asymmetrical structure [21]. A planetary magnetic gear (PMG) consists of four primary components: a ring gear, a sun gear, planet gears and a carrier to which the planet gears are attached. Among these gears, anyone can be designated as the output, while the remaining gears function as driving gears. Torque transfer occurs only when the two driving gears are correctly set. The authors in [12] reported a torque density of 100 kN.m/m3 for this configuration. However, assembling this structure is quite challenging since it necessitates two identical driving forces to generate torque at the output shaft [22]. As a result, no further development has been observed regarding this particular topology.

a)



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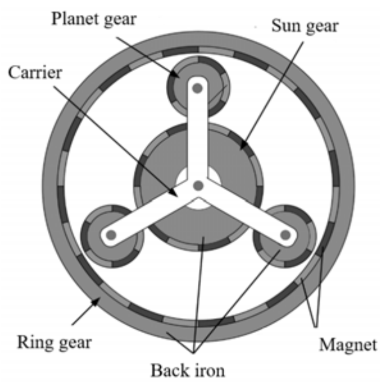
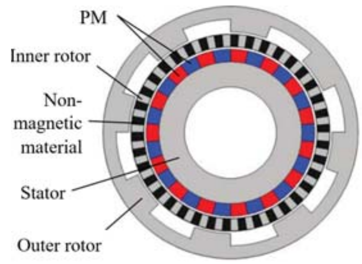


Fig. 5. Structures of CMG: (a) harmonic MG [21] and (b) PMG [22]

The application of reluctance torque in magnetic gears is not a new concept. Over the past decade, several researchers have explored methods for transferring torque and rotation utilizing the working principle of reluctance machines. The general advantage of reluctance machines lies in the absence of permanent magnet material on the rotating part, thereby mitigating the weaknesses associated with PM rotors. Figures 6(a), (b), and (c) showcase three different structures of reluctance magnetic gears (RMG) [6, 23, 24]. Although these structures demonstrated improved rotor robustness, the achieved torque density values for all RMG configurations remained below 60 kN.m/m^3. In 2007, a magnetic-geared outer-rotor-PM (MGORPM) brushless machine was introduced as in [25]. This machine falls under the category of magnetically geared machines (MGMs), which differ from conventional magnetic gears as they integrated the motor with the magnetic gear. The inner rotor of the MGORPM rotates due to its interaction with the armature winding, similar to a typical permanent magnet (PM) motor. On the other hand, the outer rotor rotates at a higher torque and lower speed, following the gear ratio, which resembles the working principle of concentric magnetic gears (CMGs). The structure of an MGORPM brushless machine is illustrated in Figure 7. As stated by the authors, when the stator was supplied with a three-phase voltage rated at 36 V/220 Hz, the inner rotor achieved a rotational speed of 4400 rpm. The primary motivation behind this design was to enhance torque for driving heavy loads, such as in motorcycle applications

a)



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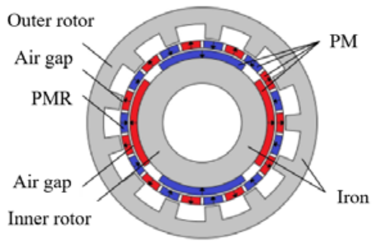

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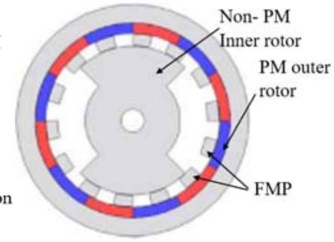

Fig. 6. RMG structures: (a) stationary inner pole pair [41], (b) stationary PM ring [50] and (c) stationary pole pieces [51]

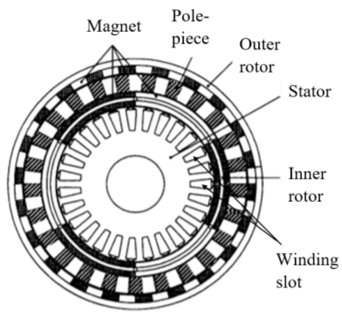

Fig. 7. Structure of magnetic-geared outer-rotor-PM brushless machine [54]

In the subsequent year, a different MGM structure was developed as in [26]. The operating principle of this structure bears similarities to the previous design [25]. However, there is a notable difference: the inner rotor PM is substituted with an armature winding. Figure 8 illustrates the configuration of the magnetically geared outer rotor machine. This structure offers several advantages, including reduced reliance on rare-earth PMs and the capability to regulate the strength of the inner magnetic field. In [27]. A magnetic geared machine (MGM) design was introduced in 2012. Figure 9 presents an exploded view of this MGM. When an alternating current (AC) passes through the armature coil, the inner rotor will commence rotation based on the frequency of the magnetic field generated by the stator. Simultaneously, the outer rotor, which composed of FMPs (Flux Modulation Poles), will also rotate due to the influence of both magnetic sources [45].

Notably, unlike the structures described in [25] [26] is that in [27],the FMPs are employed as the rotor components.

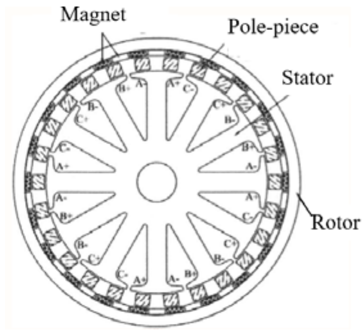

Fig. 8. Structure of magnetically geared outer rotor [55]

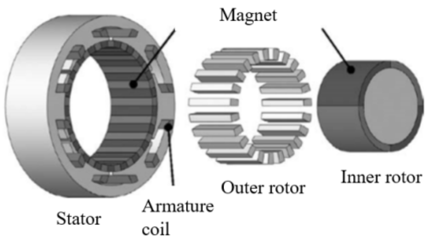

Fig. 9. Exploded view of magnetically geared machine parts [56]

In the subsequent year, [23] presented two modified CMG (Concentric-Pole Magnetic Gear) models. The inner rotor of these models comprises a yoke and surface-mounted PMs in a salient shape. The middle component consists of PM poles which are separated by a flux barrier. The structures of these models are depicted in Figures 10(a) and (b). In the first model, all PMs are magnetized tangentially, while in the second model, the PMs in the middle component are magnetized radially. However, according to the Finite Element Method (FEM) simulation results, both models exhibited lower torque density compared to that of CMGs.

a) b)

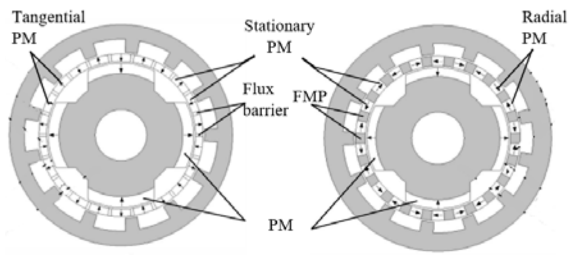

Fig. 10. Structures of CMG with stationary PMs: (a) Model 1 and (b) Model 2 [23]

Meanwhile, a cycloidal magnetic gear with a flux-focusing rotor was presented in 2015 [29]. The magnets in this structure are azimuthally directed, and steel poles are placed between each magnet. The torque density from the magnetostatic analysis in the study showed a very high torque density of 291 kN.m/m3. However, the inner gap rotor moves in an orbit path, which may results in heavy vibration. Figure 11 displays the cycloidal magnetic gear structure. Other study regarding this structure can be found in [24][25].

Compared to CMGs, Axial magnetic gears (AMGs) have unique advantages, including creating uniform and adjustable air gaps, safe separation of primary and secondary shafts, simple mechanical structure, high torque density, and simple assembly [26]. Axial topology can be a better choice if the machine is designed with high number of poles [27] and the outer diameter of the machine is limited by the application demands [28]. In aerospace, pharmaceutical, food and chemical industries, it is necessary to use AMGs due to the need to separate primary and secondary shafts [29]. Figure 12 illustrates the structure of axial magnetic gear. The improved structure of CMG produce a high torque of 291kN.m/m3. However, the torque ripple is higher than 20% at the low speed rotor and higher than 60% at lower speed rotor [30]. Other research on AMG can be found in [31][32][33].

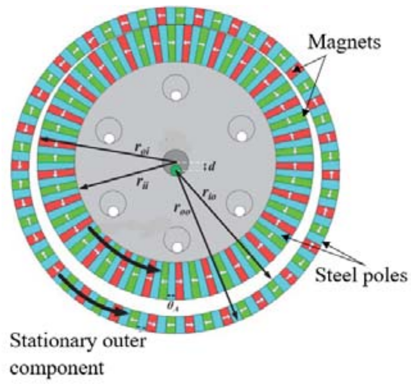

Fig.11. Structure of cycloidal magnetic gear [57]

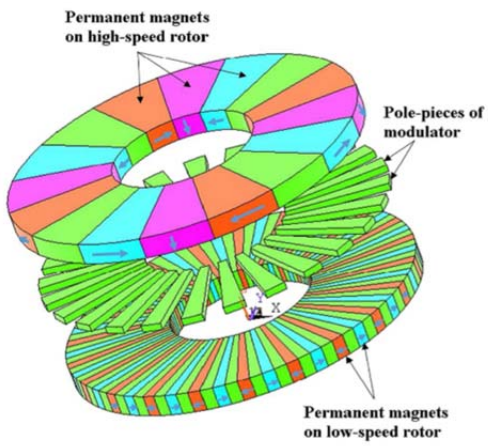

Fig. 12. Axial Magnetic Gear [30]

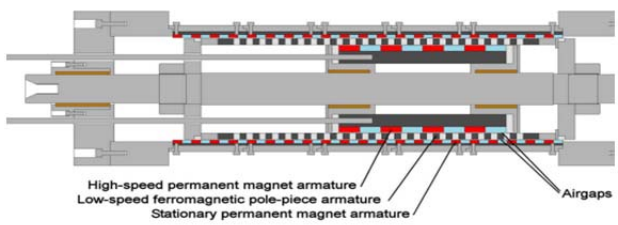

Fig. 13. Structures of linear magnetic gear [37].

A transverse-flux-type MG has also been studied and analyzed by a few researchers [34][35][36]; this type has advantages over the conventional structure. However, the torque density for the transverse-flux MG is lower than that of the radial-type MG, as studied by Bomela [35], primarily due to the leakage in flux [36]. Since a linear magnetic gear exhibits inherent overload protection, when the output armature is subjected to a load force which is larger than the pull-out force, it will slip harmlessly, thereby preventing physical damage to the magnetic gear and the systems connected to it. This feature is very important for aerospace applications. A 3.25 ratio linear magnetic gear has been presented and compared in [37]. The force density produced in [37] is 300 kNm/m^3. Figure 13 displays the structure of linear magnetic gear. This study found that spacing between the pole-piece rings has a significant effect on the transmitted force.

Today's electric vehicle motor spin at around 12,000 rpm. Electrical motors for up to 20,000 rpm are being develop for the next milestone and machines reaching 30,000 rpm are under test. However, higher speeds requires gearboxes of greater manifold. A single stage parallel gear pair has limited ratio of 10:1. Beyond this ratio, the gear size will become too large in dimension and costly. It is more practical to consider multi-stage gear train to produce higher gear ratio [38][39]. A two-stage magnetic gear was designed in 2019. Vernier machine (VM) was used as the first stage, and CMG was used as the scond stage. The resultant ratio from these gears are 34. Figure 14 shows the two-stage magnetic gear [40]. The torque density was not revealed in this publication. Another two-stage magnetic gear was publlished in the same year to be applied to a 1kW wind turbine generator. Two CMGs were coupled to produce 10 gear ratio. The author found out that the best combination to yield the highest power density and efficiency are 2.5 and 4 for stage 1 and 2 respectively. Figure 15 shows the structure of two-stage magnetic gear using CMGs.

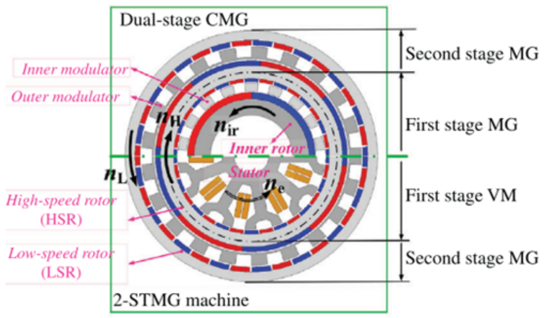

Fig. 14. Structures of two-stage gear VM with CMG

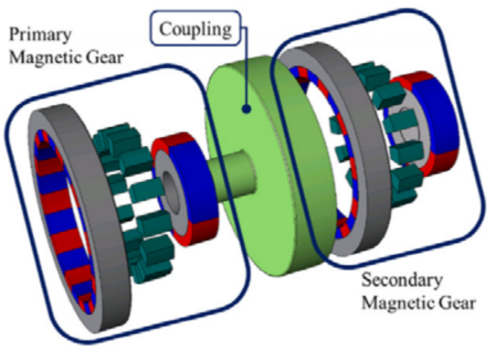

Fig. 15. Structures of two-stage gear VM with CMG

The shape of PM can influence the performance of the torque transfer of MG. However, its selection can also be tricky when the cost is considered. Three PM shapes used in MG are surface mount shape, rectangular shape and spoke shape. These three shapes can be found in different types of MG such that in CMG, HMG, Cycloidal and RMG [25][41][42][43][44][45]. Surface mount shape produces the highest torque when compared to its counterpart mainly due to the minimum flux leakage. However, this PM shape is difficult to make thus will cost more that the rectangular shape and spoke shape. Figure 16 demonstrates three PM shapes used in MG [25][42][43]. Rectangular PM is more affordable than surface mount PM but the magnetic field density is not uniformly distributed inside the air gap. Buried PM setup provide better robustness than the surface mount PM and rectangular PM. However, the flux needs to takes longer path to reach the air gap, thus reduce the magnetic field inside the air gap.

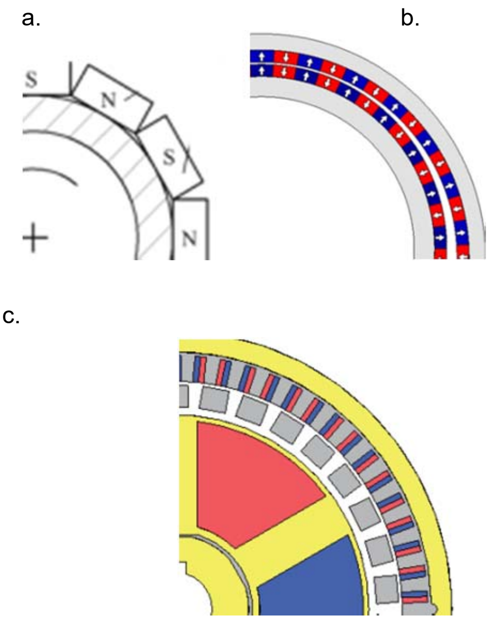

Fig. 16. a) Structures of buried PM in CMG, b) surface-mount PM on cycloidal CMG, c) rectangular PM on RMG

Summary of Magnetic Gear Structures

The features, torque density and efficiency of the magnetic gears discussed thus far are summarized in Table 1. The summary highlights that CMGs with surface-mounted rotors demonstrate the highest torque density along with high efficiency. Reluctance structure, cycloidal structure and axial structure could produce high toque density. However, it has its own weakness and not practical to develop. The exceptional performance of CMGs has made this structure particularly intriguing for further research. Figure 11 illustrates the various structural investigations conducted on CMGs. The highest torque density can be achieved using Halbach array arrangement on the PM. On the other hand, the highest efficiency that can be achieved is by reluctance magnetic gear. To accomplish high torque density and high efficiency, theoretically, the CMG should be hybrid-excited to reduce the loss of eddy current on the PM thus giving a better trade-off between the torque density and the gear efficiency.

CMG Optimal Parameters

The determination of magnetic gear design parameters started with identifying the gear ratio for its application. The gear ratio of a CMG depends on the ratio between the pole pairs of the inner rotor and outer rotor. A lower number of pole pairs means a simpler design and fabrication. Furthermore, as the number of pole pairs increases, the size of the poles becomes smaller. A smaller PM pole size is difficult to build and costs more. Unlike other electrical machine that can use power electronics to minimize the torque ripple [46], a general guideline that assists machine designers in filtering high-cogging-torque pole pair combinations is to use the least common multiple (LCM) method. Based on Equation (2.1) the higher the LCM values, the lower the cogging factor, f_c, is:

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

where p is the number of pole pairs on either the OPP or IPP. If the stationary part is changed from the FMPs to the IPP or OPP, then the term n_s is replaced with the new stationary part.

CMG parameter study is performed depending on its objectives, such as to increase torque density, reduce harmonics, increase efficiency, increase mechanical robustness or reduce material cost. In one paper, a multi-objective optimisation was achieved through differential evolution to limit the computational effort. The proposed strategy employs a fast semi-analytical model initially to identify the optimal region in the Pareto front. The study concluded that the inner yoke width was the most influencing parameter for achieving optimised specific torque [47]. In another study, magnetomotive force (MMF) and the permeance theory were used to analyse the ratio of air slot opening to pole pitch (c_o), ratio of magnet-arc to PM pole pitch (α) and PM thickness (h_m) in regard to the generated torque [48]. The paper also investigated pole-piece shapes of radial slots, parallel-tooth slots and parallel slots. The authors recommended that c_o and α should be equal to 0.5 and 1, respectively, to achieve the highest torque. The result also showed that the radial-slot shape produced the highest torque compared with the parallel-tooth and parallel slots. A minimum boundary for the outer rotor yoke thickness was suggested to avoid heavy saturation, especially when h_m increased, which could result in reduced torque density and a potential increase in iron losses.

Tab le 1. Summary of features, torque density and efficiency of various types of magnetic gears

Magnetic Gear Type	Rotor shape	Torque density	Efficiency
Spur [15], [45]	Surface-mounted	Mid = 30 kN.m/m^3	96%
Coaxial CMG [18]	Surface-mounted	High = 100 kN.m/m^3	97%
Coaxial CMG [15]	Spoke	High = 92 kN.m/m^3	96%
Worm [15], [18]	Skew	Low = 2.4 kN.m/m^3	90%
Reluctance [58]	Salient	High = 91.3 kN.m/m^3	32.50%
Cycloidal [57]	Surface-mounted	High = 291kN.m/m^3	99%
Axial MG [30]	Surface-mounted	High =291kN.m/m^3	~83%

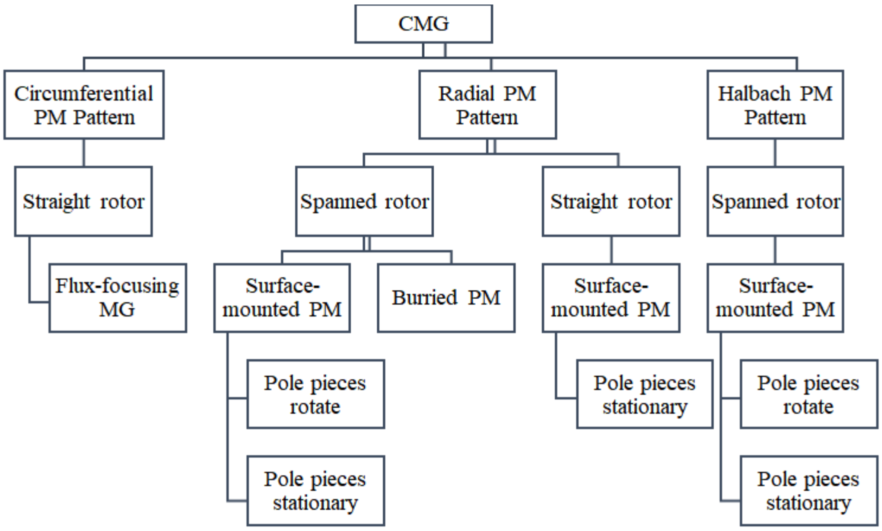

Fig. 13. Previous structural studies on CMG

A fast analytical model of iron losses in the ferromagnetic parts of a magnetic gear was proposed in [49]. The proposed 2D magneto-static analytical linear model was based on the resolution of both the Laplace equation and Poisson's equation, coupled with the permeance network, in order to determine the magnetic field distribution in pole pieces. In this paper [49], iron losses in the FMPs were higher than the losses that occurred in either the outer or inner yoke. The higher losses in the FMPs were due to the amount of magnetic field experienced from the inner and outer PMs, unlike that at the outer or inner yoke. An analytical model for the CMG was developed and optimised using a particle swarm optimisation algorithm in [50]. Torque density and material cost were set as the optimisation objectives in this paper. The authors demonstrated that both objectives can be achieved simultaneously by the optimised design. The torque density and torque-to-PM ratio achieved from the optimised design were 124 kN.m/m^3 and 128 N.m/kg, respectively.

On the other hand, the deterministic optimisation method (DOM) algorithm was performed by changing the design sensitivity parameters in one sequence directly, part by part, and repeated until the design obtained the highest performance of torque and the lowest torque ripple [51], [52], [53]. The variables were the pole piece radial width, outer yoke radial width and inner yoke radial width, labelled as *W1*, *W2*, and *W3*, respectively. The parameter study variables are depicted in Figure 17. The parameter study of each of the variables is considered to be completed either when the torque condition was satisfied or when magnetic saturation was reached. The PM's volume was maintained throughout this process. According to one of the studies, the *W2* parameter contributed up to 23% increase in torque density, while the *W2* and *W3* parameter combination added 111% of torque density to that of the initial design. The final torque density reported in this paper was 364.5 kN.m/m^3 [51].

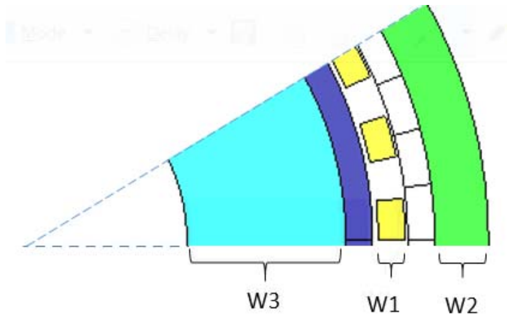

Fig. 17: Parameter study variables in CMG [51]

Conclusion

Magnetic gear is the future for transmission system in many applications. This paper reviewed several structures that has been designed in the past 30 years. CMG structure shows that it has the highest potential to produce the highest output torque with a high transmission efficiency. The author predicted that the direction of the future MG structure will be derived from CMG. Although there are other structures that could match the performance of CMG such as axial structure, the efficiency and torque ripple are under par while realization of the structures are very complex and impractical. On the other hand, cycloidal magnetic gear in order to operate, cycloidal structure with a non-uniform air gap is required which resulted in large non-symmetric radial forces. The paper also outlined the optimal parameters in terms of ratio for each CMG components to produce the highest torque density. The performances of CMG derived structure will be even more improved and will be of real interest, especially in the field of transportation and aeronautics in the coming years

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