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BY
XIAOXU ZHANG

DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

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by

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DENMARK

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ENGLISH SUMMARY

Applications of the low-speed and high-torque transmissions range from the wind power generation to the ship propulsion. As the fossil energy crisis and environmental issue become increasingly serious, the power transmission system in the low-speed high-torque application is expected to be more electrified. Generally, the electrical-machine-driven low-speed and high-torque transmission system could be classified into the mechanical-geared-drive solution and direct-drive solution. However, the mechanical-geared-drive solution usually suffers from the issues associated with the mechanical contact, such as the need for lubrication, mechanical wear, noise, and vibration. Although the direct-drive solution could operate without a mechanical gearbox, the direct-drive machines rotate at a low speed, which would lead to a bulky size of the torque transmission system. The purpose of this thesis is to propose some new magnetic-geared transmission devices, including coaxial magnetic gears (CMGs) and magnetic-geared machines (MGMs), which could be introduced into the low-speed high-torque applications to solve or avoid the above issues.

Firstly, analytical models of the CMGs and MGMs, based on the subdomain modeling technique, are built up. The magnetic behaviors in them are described by Maxwell equations in terms of the magnetic vector potentials A in 2-D polar coordinates. By applying the interface constraints, the magnetic problems in the CMG could be represented by a coefficient matrix equation. The analytical solution could be achieved by using numerical computation method and shows a good agreement with finite element analysis (FEA). After that, the influence of the key design parameters on the torque capability, the unbalanced magnetic force, the optimization design, and the power factor are investigated. For the CMGs in the high-torque applications, the increased unit capacity may lead to the significant growth of the subdomains number, so that the dimension of the coefficient matrix equation becomes large. As a result, the processing time of the analytical subdomain model is increased sharply, which makes the subdomain technique not present too many advantages over the FEA in terms of the computational efficiency. Therefore, several numerical approaches, such as mathematical derivation of the boundary conditons, are proposed in this thesis to downsize the dimension of the coefficient matrix equation. The computational burden could be then significant reduced.

Secondly, for ease of developing MGMs, this thesis aims at proposing a novel CMG, which will not increase the mechanical complexity after the combination with a permanent magnet (PM) brushless machine. The prominent feature of the proposed CMG is the introduction of a stator with modulating teeth, which play the same role as the modulating pole-pieces in the conventional CMG. The integrated MGM can then be achieved by inserting the armature windings into the stator slots. The configuration, harmonic analysis, and torque capability of the proposed CMG are

studied and compared with the conventional surface-mounted CMG. The operating principle and electromagnetic performance of the proposed MGM are investigated by dividing it into one Vernier PM machine, one PM brushless machine and one proposed CMG. The results show that the developed integrated MGM exhibits good torque capability and high power factor.

Thirdly, a dual-flux-modulator CMG (DFM-CMG), characterized by high torque capability and high PM utilization efficiency, is developed. The DFM-CMG adopts spoke-type outer PM rotor and introduces an auxiliary flux modulator placed outside. The harmonic analysis with detailed theoretical derivation is performed to reveal that the ferromagnetic pole-shoes on the spoke-type outer PM rotor could modulate the flux density distribution as well and create a nested magnetic-gearing effect (flux modulation effect). More useful harmonics are thus generated in the air-gaps to contribute to the torque production. The effect of the auxiliary flux modulator on the magnetic field distribution is also studied by FEA. The observations show that the presence of the auxiliary flux modulator significantly suppresses the magnetic flux leakage. A quantitative comparison among the surface-mounted CMG, spoke-type CMG, and DFM-CMG are made to validate the performance improvement of the DFM-CMG. The presence of the auxiliary flux modulator has been verified to be able to improve the torque production by FEA prediction of 44% growth and experimental test of 41% growth, respectively. Finally, by adding the armature windings into the stator slots of the auxiliary flux modulator, a dual-flux-modulator MGM (DFM-MGM) is achieved. The back electromotive force, torque performance, and power factor of the DFM-MGM are investigated by the FEA and then verified by experimental tests.

DANSK RESUME

Anvendelser af lavhastigheds- og højmomentoverførsler spænder fra vindkraftproduktion til skib fremdrift. Da den fossile energikrise og miljøproblemet bliver mere og mere alvorlig, forventes kraftoverføringssystemet i lavhastighedstog med højt moment at blive mere elektrificeret. Generelt kan det elektriske maskinedrevne lavhastighedssystem og højmomentiske transmissionssystem klassificeres i den mekaniske gear-drive-løsning og direkte-drev-løsning. Imidlertid lider den mekanisk gearede løsning normalt af problemerne forbundet med den mekaniske kontakt, såsom behovet for smøring, slid mellem kontaktflader, støj og vibrationer. Selv om direkte-drev-løsningen kunne fungere uden en mekanisk gearkasse, roterer de direkte drevmaskiner med lav hastighed, hvilket ville medføre en stor størrelse på kraftoverføringssystemet. Formålet med denne afhandling er at foreslå nogle nye koaksiale magnetiske gear (KMG) og magnetisk gearede maskiner (MGM), som kunne introduceres i lavhastighedsspændingsmomentapplikationer for at løse eller kunstigt undgå de ovennævnte problemer.

For det første er KMG analysemodel baseret på subdomæne modelleringsteknik opbygget. De magnetiske opførelser i KMG er beskrevet af Maxwell ligninger med hensyn til de magnetiske vektorpotentialer A i 2-D polarkoordinater. Ved at anvende grænsefladebegrænsningerne kunne de magnetiske problemer i KMG være repræsenteret af en matrixekvation. Den analytiske løsning kunne opnås ved at bruge Matlab og viser en god aftale med finite elementanalyse (FEA). Derefter undersøges indflydelsen af de vigtigste designparametre på drejningsmomentets kapacitet, den ubalancerede magnetkraft og optimeringsdesignet. For KMG i højmomentapplikationerne kan den forøgede enhedskapacitet imidlertid resultere i signifikant vækst af underdomænerne, så dimensionen af matrixekvationen bliver stor. Det er uundgåeligt at øge behandlingstiden for den analytiske underdomænemodel, hvilket gør subdomæneteknikken ikke til stede for mange fordele i forhold til FEA med hensyn til beregningseffektivitet. Derfor lægger denne afhandling vægt på reduktionen af matrixdimensionen og gør forsøg på at få mest muligt ud af grænsefladens begrænsninger for at opnå en signifikant forbedring af beregningsomkostningerne.

For det andet for at lette integrationen af KMG med elektriske maskiner, har denne afhandling til formål at foreslå en ny KMG, som ikke vil øge den mekaniske kompleksitet efter kombinationen med en permanent magnet (PM) børsteløs maskine. Det fremtrædende træk ved den foreslåede KMG er indførelsen af en stator med modulerende tænder, som fungerer som det samme som de modulerende polstykker i den konventionelle KMG. Den integrerede MGM kan så opnås ved at indsætte armaturviklingen i statoråbningerne. Konfigurationen, harmonisk analyse og drejningsmomentskapacitet for den foreslåede KMG studeres og sammenlignes med den konventionelle KMG. Driftsprincippet og elektromagnetisk ydeevne af den foreslåede MGM undersøges ved at dividere den i en vernier-PM-maskine, en PM-børsteløs maskine og en foreslået KMG. Resultaterne viser, at den udviklede integrerede MGM udviser god drejningsmoment og høj effektfaktor.

For det tredje udvikles en dual-flux-modulator KMG (DFM-KMG), der er kendetegnet ved høj drejningsmoment og høj PM-udnyttelse. DFM-KMG vedtager ekttype-ydre PM-rotor og indfører en hjælpefluxmodulator placeret udenfor. Den harmoniske analyse med detaljeret teoretisk afledning udføres for at afsløre, at de ferromagnetiske polsko på den ekstreme PM-rotor af den ekte type kunne modulere også fluxdensitetsfordelingen og skabe en indlejret magnetisk gearingseffekt (fluxmoduleringseffekt). Mere brugbare harmoniske frembringes således i luftgabene for at bidrage til momentproduktionen. Effekten af hjælpefluxmodulatoren på magnetfeltfordelingen studeres også af FEA. På grund af tilstedeværelsen af hjælpefluxmodulatoren undertrykkes fluslækage, og de anvendelige harmonikere forstærkes. En kvantitativ sammenligning mellem den overflademonterede KMG, taletype KMG og DFM-KMG er lavet for at observere præstationsforbedringen af DFM-KMG. Tilstedeværelsen af hjælpefluxmodulatoren er blevet verificeret for at kunne forbedre torqueproduktionen ved FEA med henholdsvis 44% vækst og eksperimentel test med henholdsvis 41% vækst. Endelig opnås en dobbeltstrømningsmodulator MGM (DFM-MGM) ved at tilføre armaturviklingene i statoråbningerne i hjælpefluxmodulatoren. Den bageste elektromotoriske kraft, drejningsmomentets ydeevne og effektfaktor for DFM-MGM undersøges af FEA og kontrolleres derefter af eksperimenteltesten.

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Xiaoxu Zhang

Aalborg Øst, Denmark

August 20, 2017

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CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

1.1.1. BACKGROUND

During the past decades, low-speed and high-torque transmission systems have been widely used in different areas, including the wind power generation [1]-[3], tidal energy system [4]-[7], electric propulsion systems [8]-[10], and so on. Meanwhile, the expansion of the market scale of these application areas drives great development of the low-speed and high-torque transmission technologies. Taking the wind power industry as an example, as the wind power is renewable and produces no planet-warming gas emission, it is believed as a most promising alternative to the fossil fuels in this century. The policy makers in many countries are conscious of the potential economic value of wind energy, and are vigorously advancing its development. Therefore, the wind industry nowadays is becoming one of the fastest developing renewable energy sectors worldwide [11].

According to the Global Wind Market Annual Report 2016, issued by Global Wind Energy Council [12], between the years of 2001 and 2016, the global cumulative installation was growing at an average rate of 22.25%. The increase rate of the annual installation was an average of 15.25%. From only 23.9 GW in 2001, the world cumulative installed capacity multiplied over twenty-fold in the following fifteen years to reach more than 486 GW at the end of 2016. During the year of 2016, around 55GW wind power capacity was integrated to the power grid worldwide. Figure 1-2 and Figure 1-1 show the growth in global cumulative and annual installed wind capacity during the period from 2001 to 2016, respectively.

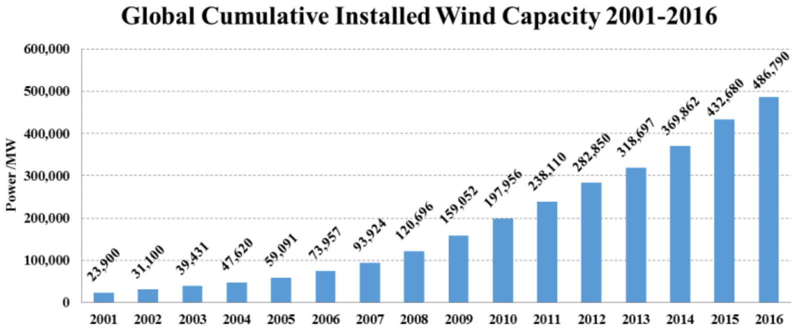


Figure 1-1 Global cumulative installed wind capacity 2001-2016 (Data from [12]).

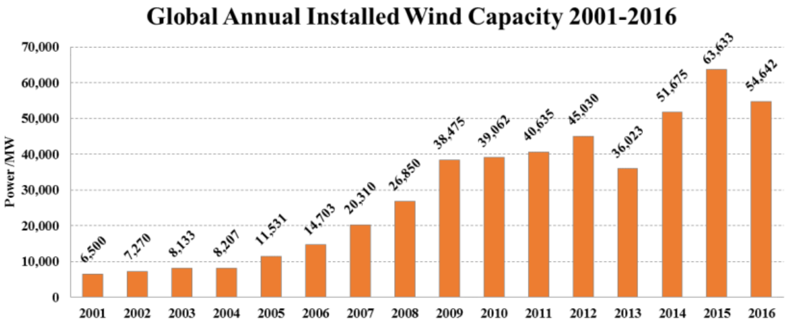


Figure 1-2 Global annual installed wind capacity 2001-2016 (Data from [12]).

By the end of 2016, nine countries had cumulatively installed over 10GW of wind capacity, including China, the United States, Germany, India, Spain, UK, France, Canada, and Brazil, as shown in Figure 1-3. Top ten countries with the annually installed and cumulative wind capacities by the end of 2016 are shown in Figure 1-4. According to the Global Wind Energy Outlook, published by Global Wind Energy Council [13], by the end of 2030, the cumulative wind capacity worldwide might reach over 2,110 GW, and account for more than 20% of global electricity. Besides, the wind industry will then reduce 3.3 billion tonnes of CO_2 emission every year. The annual investment in wind industry could reach about 1.5 trillion Danish Krone. With the increase of wind power capacity and the rapid development of wind industry, the low-speed high-torque transmission system, one of the key subsystem in wind turbines, has been paid special attention to by researchers worldwide. Proper design and performance improvement of low-speed high-torque transmission devices are becoming the research focus in this area.

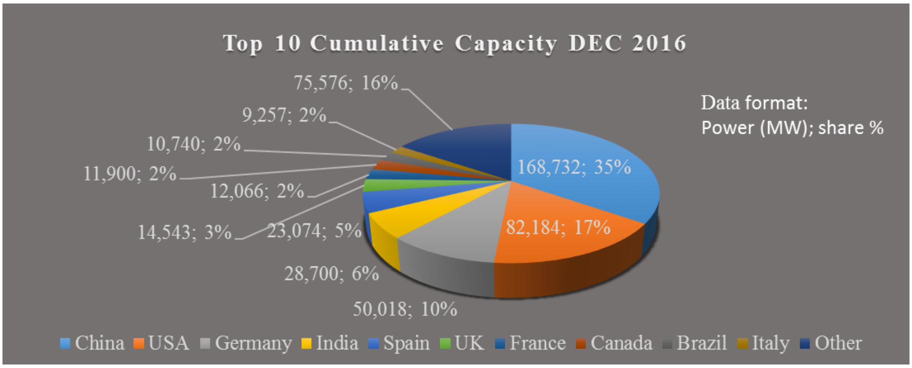


Figure 1-3 Top 10 cumulative wind capacity DEC 2016 (Data from [12]).

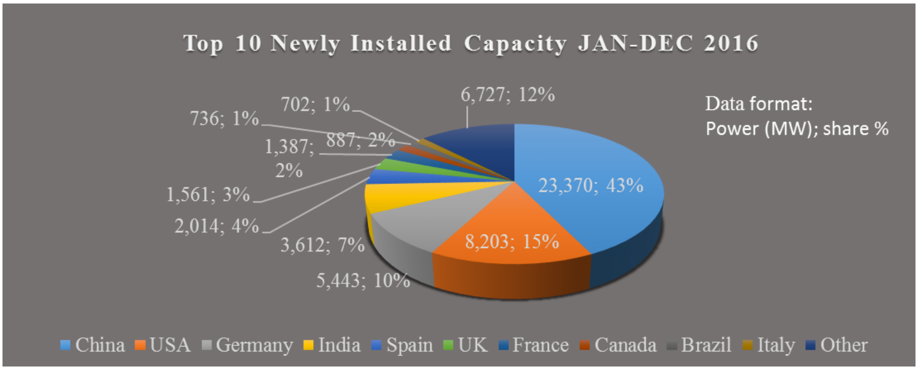


Figure 1-4 Top 10 newly installed wind capacity JAN-DEC 2016 (Data from [12]).

1.1.2. CHALLENGES

In industry applications, induction machines are widely used due to its robustness and low cost. However, they cannot achieve high efficiency in a wide speed range. Generally, their efficiency drops as their rotational speed decreases. Besides, induction machines could not provide excellent smooth torque in low-speed operating conditions [14]. Therefore, for low-speed high-torque applications, it is common to integrate a high-speed induction machine with a mechanical gearbox. The mechanical gearbox functions both as a speed reducer and as a torque amplifier. Several factors should be taken into consideration for matching a mechanical gearbox with an induction motor, including the output torque, speed range, and life cycle. The introduction of mechanical gearbox may lead to a drop in system efficiency, as the friction loss is unavoidable. The loss of the gearbox mainly depends on the number of mechanical stages, rotational speed, and their corresponding type. Normally, the loss of a standard planetary gearbox is around 1-2% per stage. Therefore, at the rated load, the overall efficiency of a three-stage gearbox will be around 94-97% [15]. Moreover, the gearbox is normally selected to be oversized, indicating that the gearbox is always chosen with a higher rated capacity than those average operating conditions. Correspondingly, this will increase system cost and overall weight, and also decrease system efficiency. More importantly, it has been proved that the mechanical gearboxes require frequent maintenance, and are easy to fall into failures, especially for the high-torque applications [16]-[18]. The moving parts in the mechanical gearbox are coupled with each other through metal tooth meshing. This kind of mechanical contact can result in lots of undesired issues, such as friction loss, vibration, acoustic noise, and mechanical fatigue. Figure 1-5 gives the downtime of 36 mechanically geared wind turbines in the offshore wind farm Egmond aan Zee due to the breakdown of subsystems, in the years of 2008 [19] and 2009 [20], respectively. It is clear that the mechanical gearbox and generator are the top two subsystems, which have the biggest impact on the downtime of the wind turbines. In 2008, the breakdown of the mechanical gearbox led to 44,553 hours of downtime, which accounts for 58% of the year-round downtime. Figure 1-6 compares the data from two European surveys about the failure rate and downtime of the wind turbine system [21]. Although the mechanical gearbox failure is not the most frequent, it causes the highest downtime and maintenance cost. Therefore, the reliability of mechanical gearbox is a big concern for the low-speed high-torque applications.

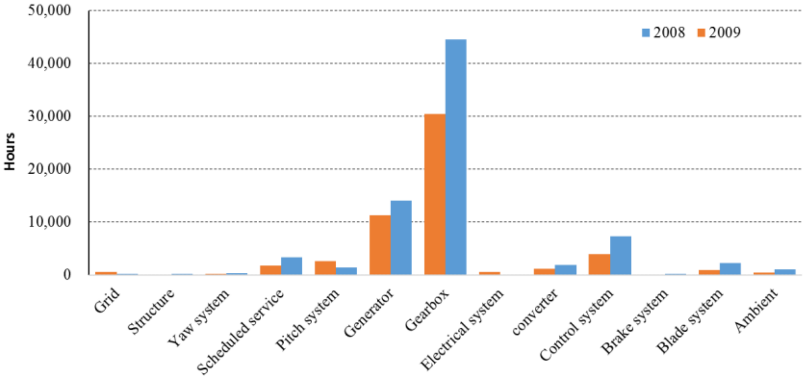


Figure 1-5 The downtime of 36 mechanically geared wind turbines in the offshore wind farm Egmond aan Zee due to the breakdown of subsystems, in the years of 2008 and 2009. (Data from [19] and [20])

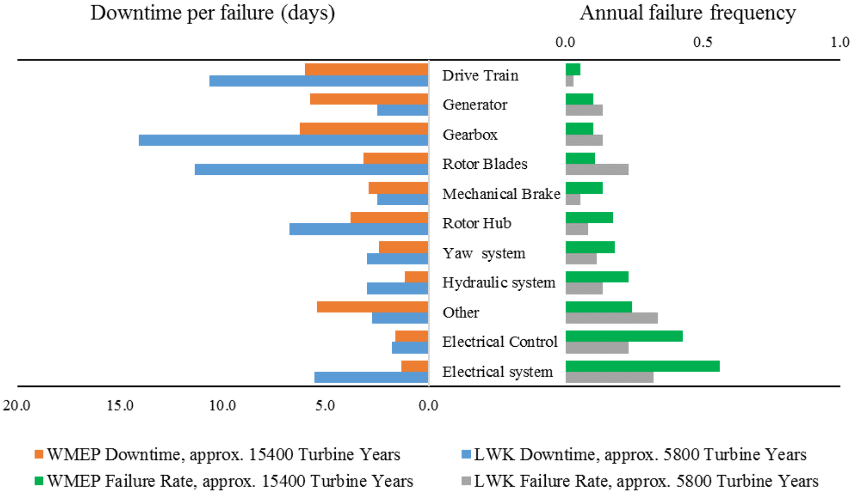


Figure 1-6 The comparison of failure rate and downtime of wind turbines subsystems. (Data from two European surveys [21]).

Direct-drive electrical machine is another option for the low-speed high-torque applications [22], [23]. It could run at a low speed without employing any mechanical transmission elements. The shaft of the electrical machine is directly connected to the prime mover or load, which naturally enables a higher angular stiffness. As the gearbox is not needed in this solution, those problems caused by mechanical contact are avoided, and the maintenance needs and resultant cost are significantly reduced. Besides, the configuration of direct-drive solutions is more straightforward, which not only achieves a higher transmission efficiency and a better system reliability but also greatly reduces the installation complexity and maintenance cost. However, since the size of an electrical machine is proportional to its torque [24], the direct-drive machine for the low-speed high-torque applications normally has a bulky size with a larger diameter in comparison to the electrical machines operating together with gearboxes. With the increase of unit power capacity and the decrease of rotational speeds, the direct-drive machine is becoming larger and heavier, which may bring difficulties to its transportations. Therefore, a trade-off solution was proposed. It adopts a low-speed high-torque machine working together with a single-stage mechanical gearbox, instead of a multi-stage one [25], [26]. The resulting hybrid solution combines the characteristics of both direct-drive and geared systems but makes compromises. Compared to direct-drive solutions, the machine in hybrid solution normally operates in a higher speed range and a lower torque range [27], which results in a significant reduction in the machine cost and weight. However, as a single-stage gearbox is used in this solution, the hybrid solution also has those disadvantages induced by mechanically geared components.

1.1.3. MOTIVATION

Given the above, the electrical machines are normally required to realize low-speed and high-torque operation. A straightforward solution is to use a high-speed low-torque induction machine working together with a multi-stage mechanical gearbox. With the help of mechanical gearboxes, the low-speed high-torque operation of the induction machine is fully achieved. However, those disadvantages related to the mechanical gearboxes make it unattractive to the applications requiring high reliability. Instead of using a multi-stage gearbox, the direct-drive systems directly connect the electrical machine shaft to the prime mover or load. Removing the gearbox obviously eliminates the issues associated with the mechanical contact, thus improving the overall reliability. This type of solution has been characterized by simple structures, which is much less complex than the geared technology, resulting in higher rigidity and easier maintenance. However, the disadvantages of this technical solution lie in the cost and weight. A heavier machine and a higher cost have disqualified direct-drive solutions from being an ideal option in the low-speed high-torque applications. Even though the hybrid system mentioned above could decrease the machine cost and weight, it naturally belongs to the geared solutions. Those problems associated with mechanical gearboxes could also be found in the hybrid systems. Therefore, further research in this area is of great significance.

Magnetic-geared transmission is a promising candidate to the low-speed high-torque applications [28]. The magnetic gear could function as a torque amplifier but require no mechanical contact except bearings. Therefore, a compact topology with high reliability and high torque density could be potentially achieved. However, the magnetic-geared transmission is still at its early-stage development. The purpose of this thesis is to propose some new magnetic-geared transmission devices, including magnetic gears and magnetic-geared machines, which are expected to provide a different way to solve or avoid the above issues in the low-speed high-torque applications.

1.2. STATE-OF-THE-ART

Magnetic-geared transmission devices are a kind of mechanism, which could employ magnetic field coupling to transmit power, torque, or forces while changing the forms of motion (speed or direction), or even the types of motion (rotary motion or linear motion). The first appearance of the magnetic-geared transmission device can be tracked back to the early period of the 20*th* century. In 1901, a power transmitting device was proposed by an American inventor [29]. This device consists of one small driving wheel and one big driven wheel. The driving wheel has 14 steel teeth evenly distributed on its peripheral surface, and the teeth are wound by coils and could be magnetized when the coils are energized. The driven wheel with the same profile of teeth on its peripheral surface sits next to the driving wheel in the same plane. When the coils on the driving wheel are energized, the two wheels are coupled by the magnetic field. The driven wheel will spin when the driving wheel rotates. Henceforth, the magnetic-geared transmission technique came into the vision of the research in the field of power transmission and attracted increasing attention [30]-[35].

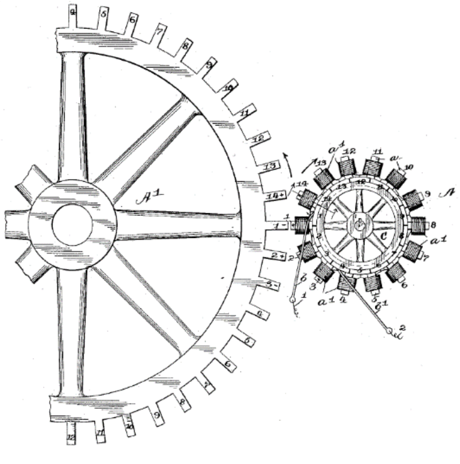


Figure 1-7 First magnetic-geared device [29].

For a long time, the performance of the magnetic-geared transmission devices depended on the properties and availability of the permanent magnet (PM) material. Especially after the emergence of the rare earth magnet material, the torque capability of the magnetic-geared transmission devices is becoming increasingly better [36]. In this thesis, the magnetic-geared devices are classified into the magnetic gears (MGs) and magnetic-geared machines (MGMs).

1.2.1. MAGNETIC GEAR

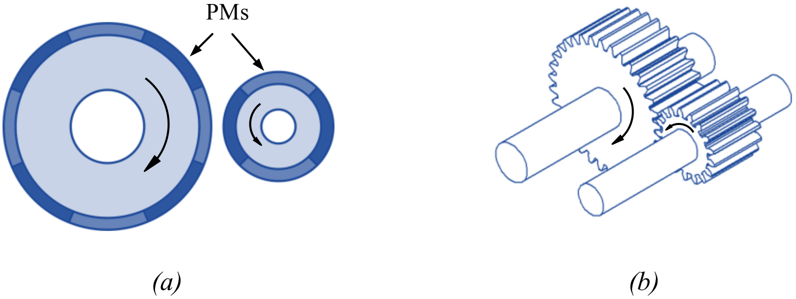
From the point view of the operational principle, the MGs could be further divided into the non-flux-modulated MGs and the flux-modulated MGs [37].

1.2.1.1 Non-Flux-Modulated Magnetic Gear

The non-flux-modulated MGs are normally derived from the conventional mechanical gearboxes by replacing the steel teeth with PMs. The operating principle is therefore changed from the tooth meshing to magnetic field coupling.

Magnetic spur gear

The magnetic spur gears have been paid lots of attention at the early-stage development of the magnetic-geared transmission devices [30], [32], [38]-[40]. As shown in Figure 1-8, the magnetic spur gear has two rotors with surface-mounted PMs. The two rotors have different outer diameters and different pole-pair numbers of PMs, which are very analogous to its mechanical spur gearbox. The gear ratio of this magnetic spur gear is the ratio of pole-pair numbers of two PM rotors. Stable torque transmission could be achieved between two PM rotors by magnetic field coupling. However, the area of interaction between the two PM rotors is very small, which means only a small portion of PMs is effectively involved in the torque transmission. Therefore, the torque density and PM utilization of the magnetic spur gear are very poor.

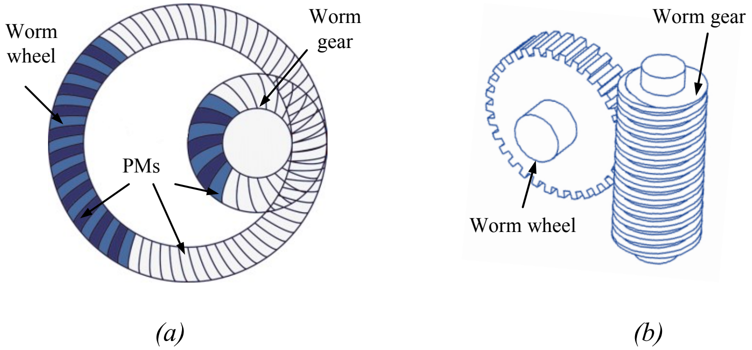


(a) *(b)*

Figure 1-8 The spur gears, (a) magnetic spur gear, (b) mechanical counterpart.

Magnetic worm gear

Similarly, the magnetic worm gear, as shown in Figure 1-9, is also a derivative of the mechanical gearbox [41]-[43]. The structure and design method of the magnetic worm gears were studied in [41]. Stable torque transmission with a gear ratio of 3:1 could be achieved by the prototype, but its torque density is approximate to 1.7 kNm/m^3, which is not comparable to that of its mechanical counterpart. In [42], another magnetic worm gear with a higher gear ratio of 33:1 was proposed and then analyzed. It could deliver a maximum torque of 11.5 Nm, which gives a torque density of 2.3 kNm/m^3 [43]. Poor PM utilization efficiency may account for the low torque density.

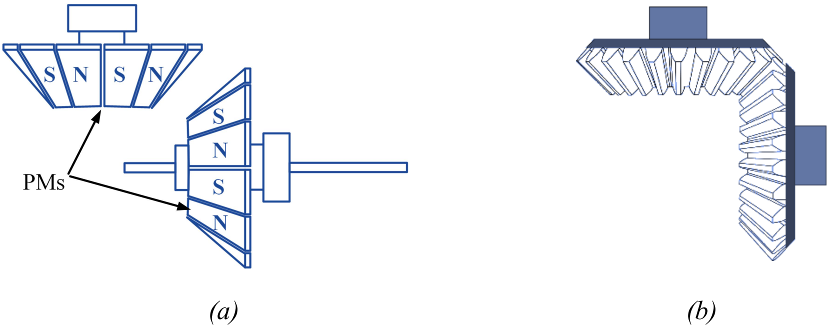


(a) *(b)*

Figure 1-9 The worm gears, (a) magnetic worm gear, (b) mechanical counterpart.

Magnetic perpendicular gear

Studies of the magnetic perpendicular gears, shown in Figure 1-10, were made in [44], which shows the magnetic field coupling strength relies on the PM pole-pair number, the magnetically coupled area, and distance between the two PM rotors. Like the magnetic spur gear, the studied magnetic perpendicular gear cannot achieve good performance in terms of the torque density, because only a small portion of PMs could contribute to the torque generation at any given time.

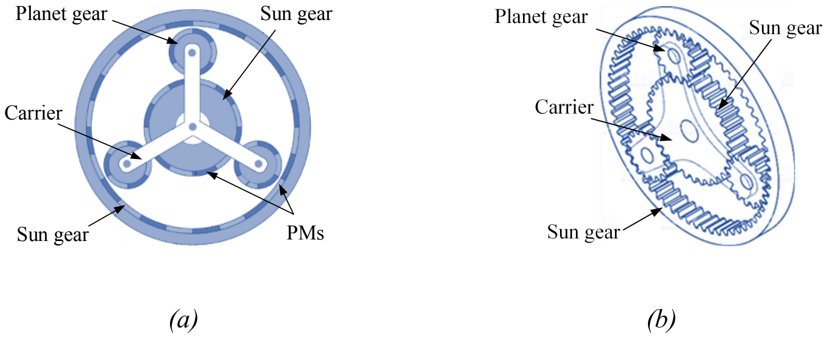


(a) *(b)*

Figure 1-10 The perpendicular gears, (a) magnetic perpendicular gear, (b) mechanical counterpart.

Magnetic planetary gear

A magnetic planetary gear with the rare-earth PMs was proposed and analyzed in [45]. Like its mechanical counterpart, it consists of three planet gears, one sun gear, one ring gear, and one carrier, as shown in Figure 1-11. It can be observed that more PMs are involved into the magnetic field coupling in comparison to the above MGs. Consequently, a simulated torque density of 48.3 kNm/m^3 could be achieved, which is much higher than the above MGs. It is worth noting that the number of magnetic planet gears has a decisive effect on the torque capability. In [46], a hybrid-type magnetic planetary gear with less amount of PMs was proposed. A torque density of 9 kNm/m^3 was measured on a proof-of-concept prototype.



(a) *(b)*

Figure 1-11 The planetary gears, (a) magnetic planetary gear, (b) mechanical counterpart.

Magnetic cycloid gear

Magnetic cycloid gear, also known as magnetic harmonic gear [48], is a kind of MGs characterized by the high gear ratio and high torque density, as shown in Figure 1-12. By employing rare-earth PMs, an active torque density up to 150 kNm/m^3 could be achieved, which benefits from a good PM utilization efficiency [48], [49]. However, its high-speed rotor and low-speed rotor rotate eccentrically, causing unbalanced magnetic force on its shaft. Therefore, the magnetic cycloid gear is normally made by multi-stage topology so as to cancel the unbalanced magnetic force from each other, which results in a complex structure.

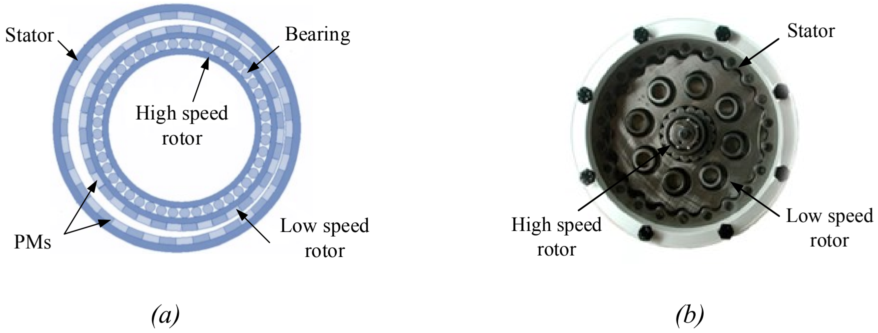
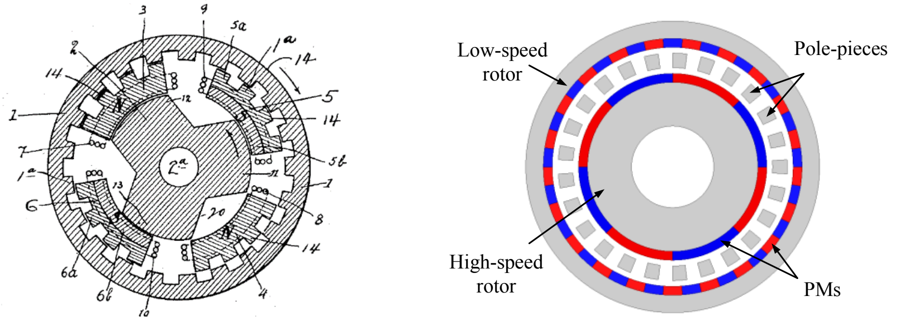


Figure 1-12 The cycloid gears, (a) magnetic cycloid gear, (b) mechanical counterpart [50].

In addition, the research about magnetic trans-rotary gear was also made in [51] and [52]. Although the above MGs could achieve contactless torque transmission, apart from the magnetic cycloid gear, they normally have a poor PM utilization efficiency and thus low torque density, which is not comparable to their mechanical counterparts. Therefore, the above MGs have not gained too much development.

1.2.1.2 Flux-Modulated Magnetic Gear

The operation of the flux-modulated MGs relies on the flux modulation effect or magnetic gearing effect, which could reorganize magnetic field distribution in the air-gaps by modulating the air-gap permeance. The first flux-modulated MG could be tracked backed to 1916 [30], as shown in Figure 1-13 (a). It consists of three main components made by laminated electrical steel sheets, i.e., a slotted outer rotor, an inner rotor with three salient poles, and a flux modulator with four pieces of slotted iron cores. Coils are wound around the slotted iron core to build the magnetic field. The flux modulator is located between two rotors to modulate the magnetic field distribution so that two rotors could be magnetically coupled to transfer power and torque. Because of the coaxial arrangement of the three components, most of the teeth on this MG could be involved in the torque transmission at any given moment. However, although this flux-modulated MG has a relatively effective topology, the flux-modulated MGs had received very little attention until the year of 2001. A milestone paper proposed a surface-mounted PM coaxial MG (CMG) based on the flux modulation principle, as illustrated in Figure 1-13 (b) [53]. Its topology is similar to the one shown in Figure 1-13 (a). Two rotors are mounted with different pole-pair numbers of PMs, and a flux modulator made by ferromagnetic pole-pieces is sandwiched between two PM rotors. Due to the presence of the flux modulator, the air-gap permeance is no longer uniform, so that the magnetic field distribution excited by the PMs is reorganized and then modulated. Moreover, in order to mediate the differential between the pole-pair numbers of two PM rotors, the pole piece number of the flux modulator is required to equal the sum or the absolute substance of the pole-pair numbers of two PM rotors. Most worthy of mention is that, because of the coaxial arrangement, all of the PMs in this surface-mounted CMG could contribute to the torque transmission simultaneously, which results in a high torque density of exceeding 100 kNm/m^3. The performance of this CMG is comparable with that of the mechanical gearboxes [54]-[56]. Since then, the concept of flux-modulated MG has attracted extensive attention and gained great development.



(a) *(b)*

Figure 1-13 Flux-modulated MGs, (a) first flux-modulated MG [30], (b) a new flux-modulated CMG.

Surface-mounted coaxial magnetic gear

Great efforts have been made to improve the performance of the above surface-mounted CMG. The influence of the pole-piece profile, PM volume, and PM arrangement on the torque capability was investigated in [57] and [58]. An analytical model was developed to predict the magnetic field distribution in CMG [59]. The gear ratio of the CMGs for wind turbines and marine turbines was discussed in [60] and [61] , respectively. The studies in [62] show that the outer PM rotor with large pole-pair number suffers from the large magnetic flux leakage on the both end sides, which has a negative impact on the torque capability. The problem of the cogging torque in the surfaced-mounted CMG was formulated and then verified by measurements on a prototype in [63]. In order to decrease the cogging torque and iron loss, and to increase the torque density, a surface-mounted MG with Halbach PM arrays was proposed and studied in [64], as shown in Figure 1-14 (a). Because of the Halbach magnetization, the proposed gear shows a 13% growth of torque density and up to 67% decrease of cogging torque. From the perspective of material and cost, a comparative study between the CMGs with different magnet materials was presented in [66]. Reference [67] explored the possibility of replacing ferromagnetic material by the bulk high-temperature superconductors (HTS), as shown Figure 1-14 (b). The results show the bulk HTS could not only ensure the expected flux modulation effect but also suppress the unexpected end-effects. Because the magnetic field coupling is not as stiff as the steel tooth meshing, the CMGs tends to suffer long-lasting oscillation when the load and speed change [68]. In order to suppress this undesirable transient oscillation, a passive method and a positive method were investigated in [69] and [70], respectively. The design aspect of rotor eccentricity was also theoretically studied in [71].

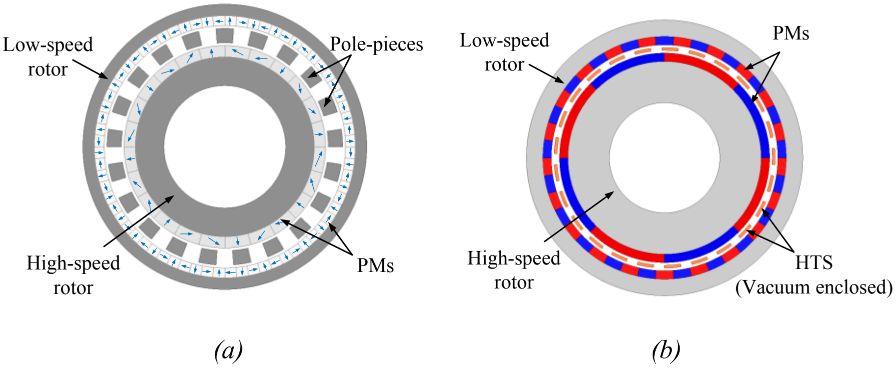


Figure 1-14 Derivatives of surface-mounted CMGs, (a) with Halbach PM arrays, (b) with bulk HTS pole-pieces.

With different design considerations, several derivatives of the surface-mounted CMG were developed. In order to improve the mechanical integrity and cut down the cost, a new topology with buried PMs on the outer rotor was proposed in [72], as shown Figure 1-15 (a). But its torque density is decreased because of the less PM consumption on the outer PM rotor. Figure 1-15 (b) gives a CMG with interior PMs on the inner rotor. For the sake of a higher torque density, a novel CMG was proposed by introducing an extra set of PMs into the space between the stationary ferromagnetic pole-pieces, as illustrated in Figure 1-15 (c). Its achieved torque density is 20% higher than the conventional surface-mounted CMG with the same size. References [75] and [76] developed a new CMG by substituting free-spinning magnetized cylinders for the ferromagnetic pole-pieces, as shown in Figure 1-15 (c). The presence of the spinning cylinder brings the benefits of the lower cogging torque and 60 % increase of the torque density.

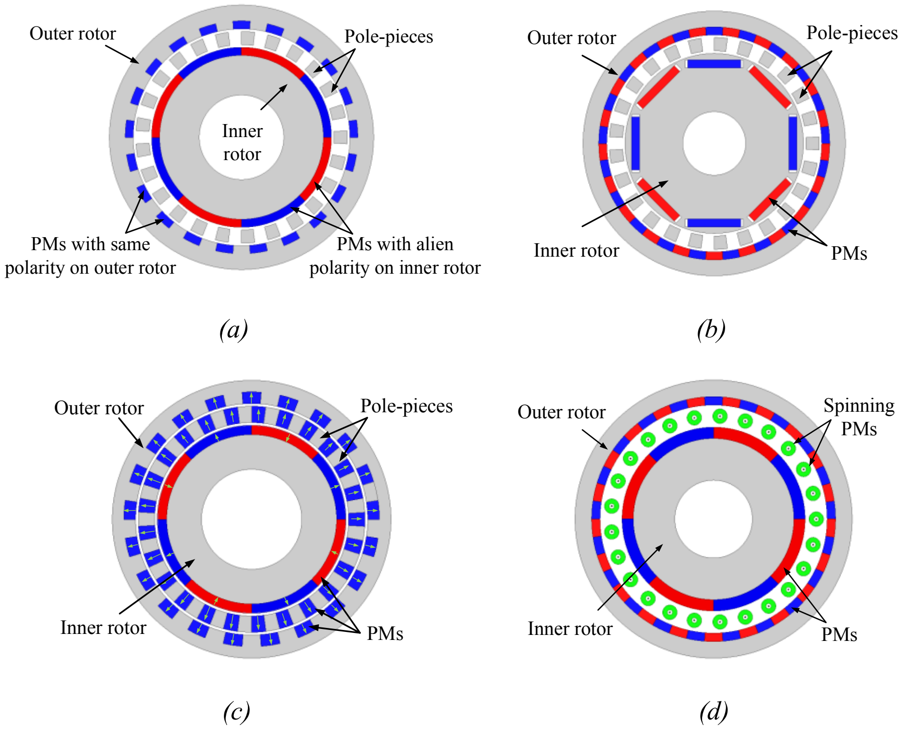
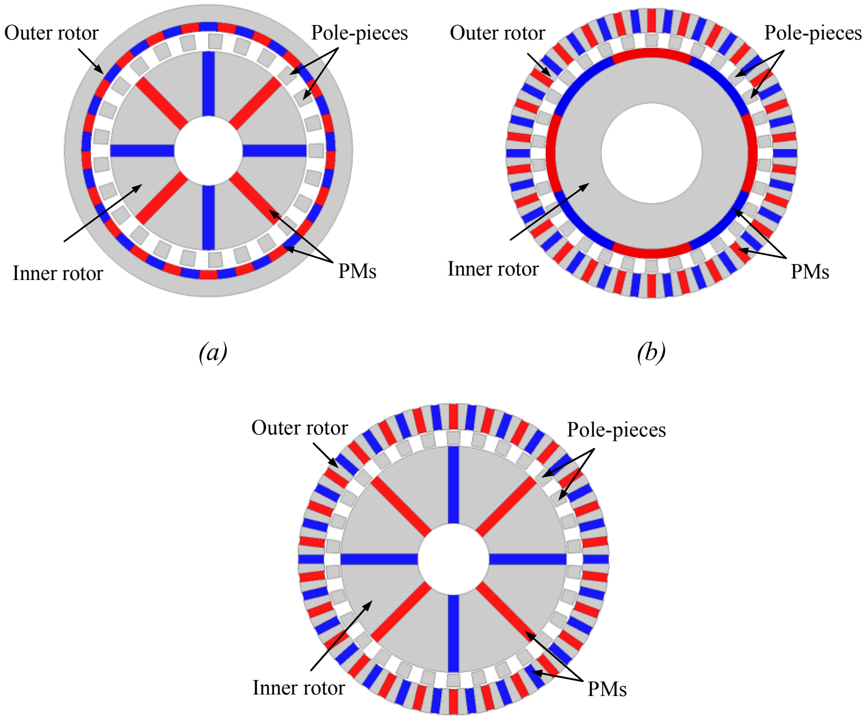


Figure 1-15 Derivatives of surface-mounted CMG, (a) with buried PMs on outer rotor, (b) with interior PM rotor, (c) with triple PM layers, (d) with spinning PM cylinders between two PM rotors.

Spoke-type coaxial magnetic gear

In order to further increase the torque density, the flux-focusing technique was introduced to the flux-modulated CMGs by employing spoke-type PM arrangement. A CMG with a spoke-type inner PM rotor was proposed and could achieve a torque density of 92 kNm/m^3 [77], as shown in Figure 1-16 (a). Figure 1-16 (b) shows a CMG with a spoke type outer PM rotor, which could offer a 25% growth of torque density over the conventional surface-mounted one [78]. CMGs with two spoke-type PM rotors were well studied in [79]-[81]. Figure 1-16 (c) shows a spoke-type CMG with a measured torque density of 151.2 kNm/m^3, but the corresponding ratio of the torque to the PM mass is only 44.6 Nm/kg [79]. With the help of parameter sweep analysis, a CMG with two spoke-type PM rotor could achieve an active region torque density up to 239 kNm/m^3 [82].



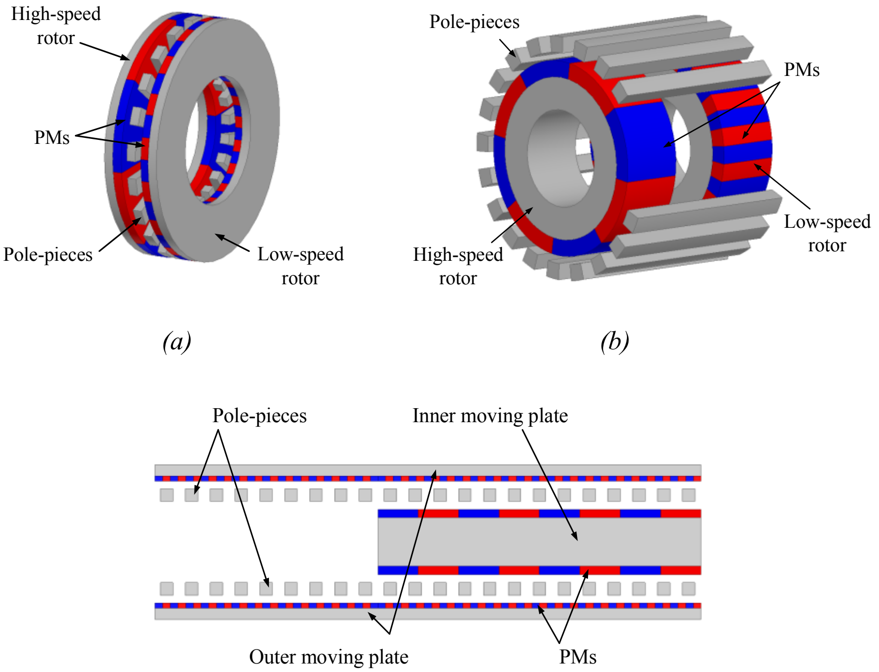
(a) *(b)*

(c)

Figure 1-16 Spoke-type CMGs, (a) with spoke-type inner PM rotor, (b) with spoke-type outer PM rotor, (c) with two spoke-type PM rotors.

Other variants of coaxial magnetic gear

Apart from the radial flux topology, the flux-modulated MGs could be built in other different forms, such as axial flux layout [83]-[85], transverse flux topology [86], and linear layout [87], [88], as presented in Figure 1-17. Because this Ph.D. project mainly focuses on the radial flux topology, we will not go into details about the non-radial-flux CMGs.



(a) *(b)*

(c)

Figure 1-17 Non-radial-flux CMGs, (a) axial flux layout, (b) transverse flux topology, (c) linear topology.

1.2.2. MAGNETIC-GEARED MACHINE

The MGM is a kind of machine, which integrates a MG with a brushless PM machine. The simplest integration method is to connect a MG and a brushless PM machine in series by sharing a common shaft, which is in line with the topology of the traditional mechanically geared machine. Currently, this kind of magnetic-geared motor is commercially off-the-shelf by a German company GEORGII KOBOLD [89]. However, this topology cannot offer a high torque density solution because of its cascaded structure. For the sake of high torque density, the possibilities of developing MGMs with coaxial structure have been explored. According to the number of the air-gaps, the coaxial MGMs could be divided into the three-air-gap topology, two-air-gap topology, and one-air-gap topology.

1.2.2.1 Three-air-gap topologies

The three-air-gap MGM is the most prominent topology, which incorporates an outer rotor brushless PM machine within the bore of a surface-mounted CMG [91]-[93]. As shown in Figure 1-18, this MGM has four components: the gear outer PM rotor, the stationary pole-pieces, the motor outer PM rotor, and the motor inner stator. Three air-gaps are formed to separate the four components from each other. The subtlety of this topology is that a common rotor is shared by the gear part and motor part, namely the outer rotor of the PM motor or the inner rotor of the CMG. The common rotor has two PM rings mounted on its inner and outer surfaces, respectively. From the perspective of magnetic coupling, the three-air-gap MGM can be made into the magnetically coupled topology or magnetically decoupled topology [94], [95], as shown in Figure 1-19. For the magnetically coupled topology, the magnetic flux could travel from the motor stator all the way to the outer rotor of the CMG by passing through all three air-gaps, while there is no magnetic connection between the motor part and MG part for the magnetically decoupled topology. As can be observed in Figure 1-18 and Figure 1-19, because of the magnetic coupling, the iron core of the shared PM rotor could be thinner or even be eliminated. Therefore, the magnetically coupled one has a more compact topology and higher torque density.

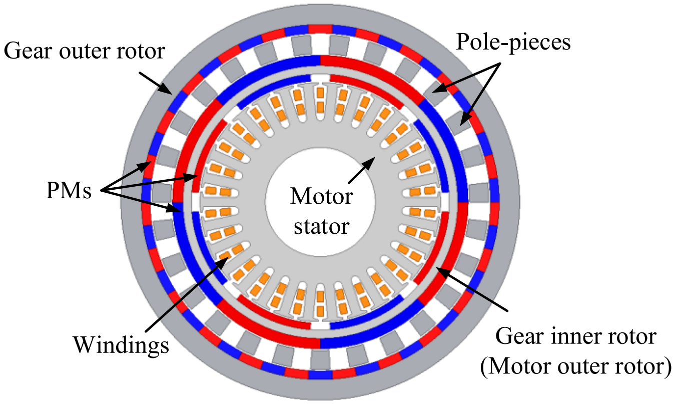


Figure 1-18 Three-air-gap MGM.

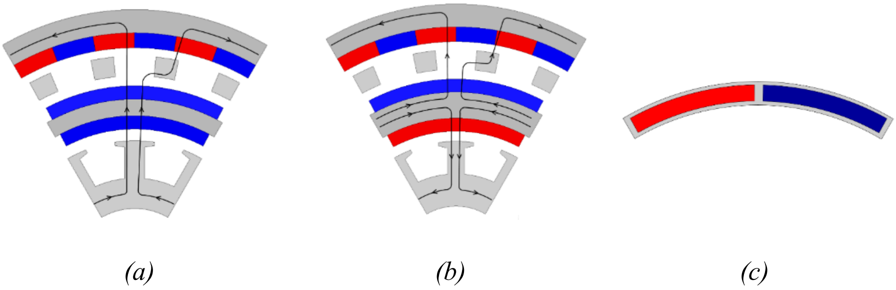


Figure 1-19 Two possible topologies for the three-air-gap MGM, (a) magnetically coupled topology, (b) magnetically decoupled topology, (c) variant of the magnetically coupled rotor.

The possibilities of the application of three-air-gap MGM in wind power generation and electrical traction have been well studied in [91], [92], [96], and [97]. The loss in the three-air-gap MGM is theoretically determined in [96]-[99]. The results show that the loss and efficiency are very sensitive to the profiles of the outer rotor and pole-pieces, and mechanical design. High-efficiency performance could be achieved by optimization design.

1.2.2.2 Two-air-gap topologies

There is a wide range of possibilities to build a two-air-gap MGM. The most successful topology is named Pseudo Direct Drive (PDD®), which is registered as a trademark by MAGNOMATICS, a spin-out from the University of Sheffield [100]. The PDD MGM, as shown in Figure 1-20, has three parts: an outer stator with a PM ring mounted on the tooth surface, a high-speed PM rotor, and a low-speed rotor with several ferromagnetic pole-pieces. Two air-gaps are formed to partition three parts from each other. The design aspects of the PDD MGM, such as torque matching between the gear part and the machine part [102], winding configuration [103], [104], cogging torque [105], slip protection [106], and dynamic performance [107]-[109] have been well studied.

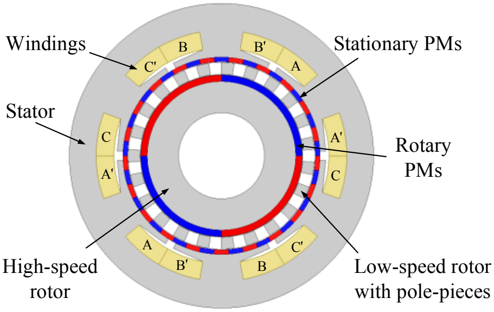


Figure 1-20 Pseudo Direct Drive® MGM.

In order to obtain a compact topology, a two-air-gap MGM was developed by inserting the armature windings into the space between the pole pieces of the surface-mounted CMG [110]-[114], as shown in Figure 1-21. From the point of view of the thermal conduction, the configuration with sandwiched armature windings makes it hard to dissipate the thermal energy resulting from the winding loss, which would heat up the PMs on two PM rotors and then increase the risk of the demagnetization. Moreover, the topology also brings the difficulties to the mechanical design and assembly.

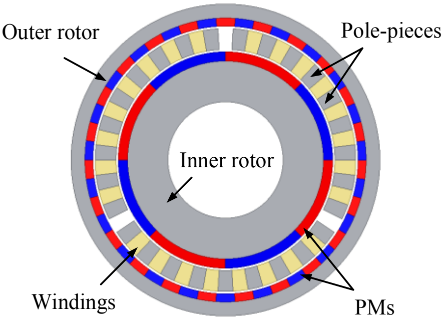


Figure 1-21 One two-air-gap MGM with sandwiched armature windings.

Another available two-air-gap topology is featured by using only one PM ring. It can be developed by replacing the inner PM rotor of the CMG with an armature-wound stator [115]-[118], or built by replacing the outer PM rotor of the CMG with an armature-wound stator [119]-[126], as shown in Figure 1-22. However, owing to the reduction of PM usage, the torque density, and power factor of those topologies are normally not comparable to the aforementioned two-PM-ring topologies.

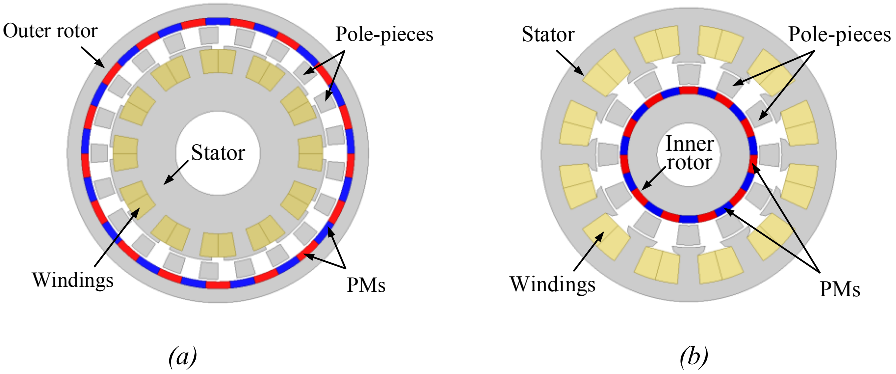


Figure 1-22 Two-air-gap MGMs with one PM ring, (a) with inner stator, (b) with outer stator.

The fourth available two-air-gap MGM was proposed by replacing the two PM rotors of the CMG with two armature-wound stators [127], as shown in Figure 1-23. Consequently, there is no PM material used in this topology, and thus its torque capability is not attractive.

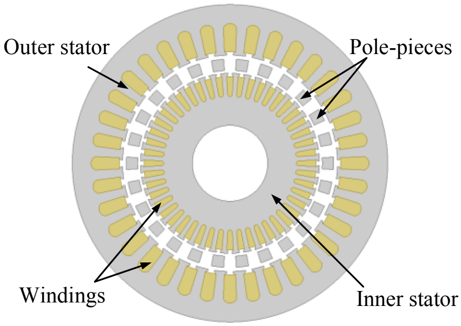


Figure 1-23 A two-air-gap MGM without using PM material.

1.2.2.3 One-air-gap topologies

Vernier PM machines, as one kind of magnetic-geared device, have attracted a great deal of attention due to its simple structure of one air gap. One available topology is very similar to the traditional PM brushless motor, as shown in Figure 1-24 (a). However, the pole-pair number of its armature windings is different from that of the PM rotor [128]-[133]. Its stator tooth number is required to equal the sum of pole-pair numbers of the armature windings and outer PM rotor. So that the magnetic gearing effect can be achieved to mediate their pole-pair number differential. Figure 1-24 (b) presents another Vernier machine with flux-modulation poles on the stator teeth [134]-[138]. Similarly, the number of those flux-modulation poles is equal to the sum of pole-pair numbers of the armature windings and PM rotor. Vernier hybrid machine is another variant by adopting a ferromagnetic rotor with salient poles [139]-[141]. PMs are attached on the stator bore, as illustrated in Figure 1-25. Magnetic gearing effect can be also achieved by employing a suitable combination of PM pole-pair number and salient pole number. However, in the aforementioned Vernier machines, for the sake of the magnetic gearing effect, the number of the ferromagnetic stator teeth, flux-modulation poles, or salient poles are normally very close to the pole-pair number of the PM ring. A considerable amount of magnetic flux leaks around ferromagnetic pole and adjacent PMs, resulting in a low power factor. Several efforts have been made to increase the power factor [142], [143]. Since the Vernier machine uses one PM ring, its torque density is not comparable to the aforementioned two-PM-ring MGMs.

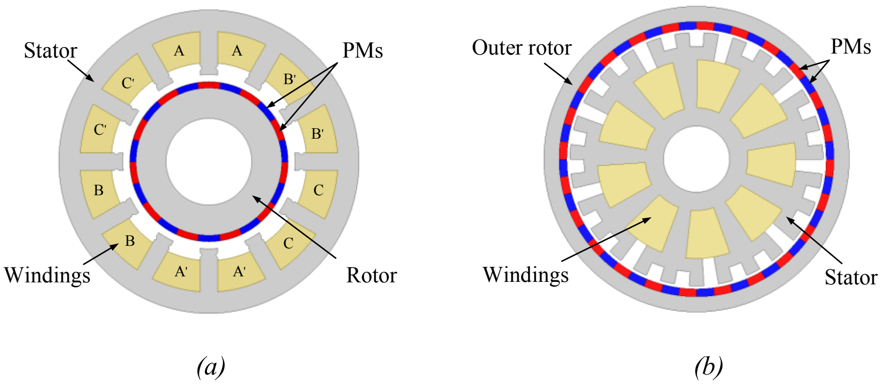


Figure 1-24 Vernier machines, (a) with flux-modulation teeth, (b) with flux-modulation poles on the stator teeth.

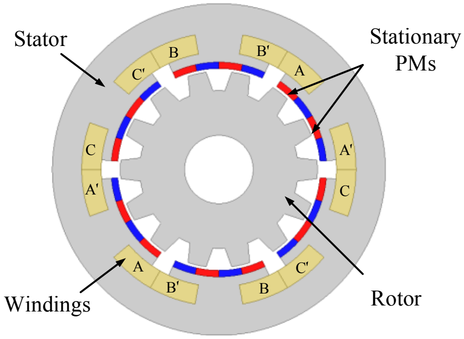


Figure 1-25 Vernier hybrid machine.

A one-air-gap MGM with two PM rings was proposed in [144] and [145]. One PM ring is located on the rotor, and the other one is buried on the stator bore. In order to insert the armature windings, the stator yoke and teeth are manufactured separately. Compared to the aforementioned Vernier machines, it can achieve higher torque density and power factor as a result of more usage of PM material, but it has a more complex mechanical structure.

Apart from the radial-flux topologies, the MGM could be built in other different forms, such as the axial-flux layout [146], [149], the linear layout [150], [151], and the trans-rotary layout [152], [153]. Since this Ph.D. project mainly focuses on the radial-flux topologies, we will not go into details about the non-radial-flux MGMs.

Through the above analysis, it can be concluded that the magnetic-geared technique has gone through a great development in the past years. More and more topologies and possibilities have been coming up, which makes the MGs and MGMs the promising devices for the low-speed high-torque applications. However, it is also found that the high-performance of some MGs and MGMs are achieved at the expense of using a large amount of PM material and complex structures. Therefore, the PM utilization efficiency of the dominating magnetic-geared devices is relatively poor. Nevertheless, this issue was rarely mentioned in the above research work. The low PM utilization efficiency seems to be a big obstacle on the way to practically apply them in the low-speed high-torque transmission systems. Another concern is the magnetic flux leakage on the outer PM rotor. Since the outer PM rotor normally has a large pole-pair number and is located next to the flux modulator, a big portion of magnetic flux tends to leak between outer rotor PMs and ferromagnetic pole-pieces. This magnetic flux leakage cannot contribute to the torque production but increase the loss in the magnetic-geared devices. Little attention has been paid to the suppression of the magnetic flux leakage on the outer PM rotor. Therefore, there are still a lot of opportunities and strong demands in this research field.

1.3. RESEARCH OBJECTIVES AND METHODOLOGY

1.3.1. RESEARCH OBJECTIVES

As aforementioned, for the low-speed high-torque applications, the faults in the mechanical gearboxes and the bulky size of direct-drive electrical machines have escalated the demands for a compact and reliable solution. In this Ph.D. project, the possibilities of applying the magnetic-geared transmission technique in the low-speed high-torque transmission systems are discussed. The insights on the built-in attributes of the magnetic-geared devices are expected to be obtained. Based on the above literature review, this project will lay emphasis on the issues of the mechanical complexity, PM utilization efficiency, and magnetic flux leakage in the magnetic-geared devices. New topologies are proposed to solve the above issues and make the magnetic-geared transmission technique more attractive to the low-speed high-torque applications.

Specific objectives

- To develop analytical models for CMGs and MGMs to theoretically study the flux modulation effect and their working principle.
- To investigate the influence of key design parameters of CMGs on the performance, and to carry out optimization design with emphasis on the torque capability and cost.
- To qualitatively and quantitatively study the unbalanced magnetic force in CMGs and MGMs.
- To develop a time-efficient analytical solution for the CMGs with a large

pole-pair number.

- To investigate the power factor of a flux-modulated machine.
- To propose a new CMG with the convenience of integrating the PM brushless machines.
- To propose a more reasonable topology for CMG to suppress the magnetic flux leakages on the outer PM rotor and improve the torque capability and PM utilization efficiency.
- To develop a MGM with high torque capability and high PM utilization efficiency.

1.3.2. METHODOLOGY

The methodology employed in this project is illustrated in Figure 1-26.

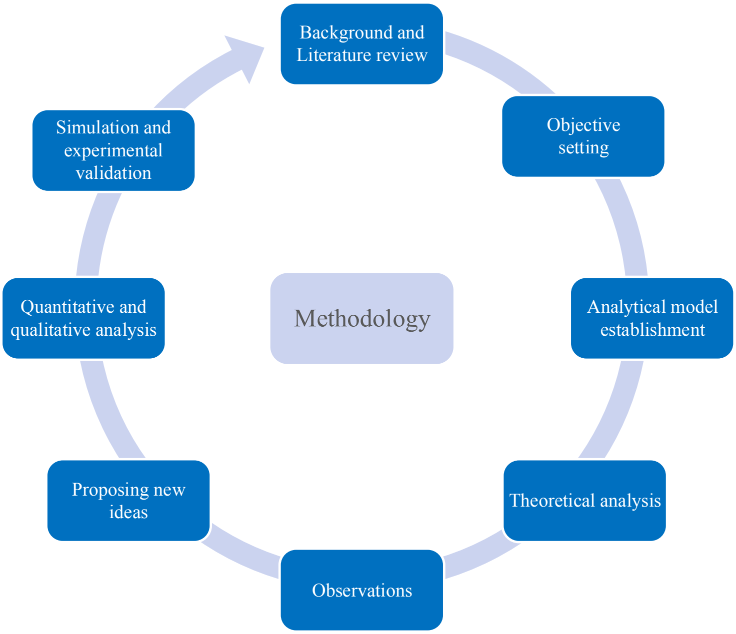


Figure 1-26 The methodology of this Ph.D. project.

Background and literature review: Low-speed and high-torque transmission system is widely used in different areas. It is found the two popular drivetrains, namely, mechanical drivetrain solution and direct drivetrain solution, may suffer from the mechanical issues and size issues, respectively. Therefore, the magnetic-geared drivetrain, featured by high reliability and high torque density, is set as the topic of this research. The development of magnetic-geared transmission technique is then overviewed.

Objective setting: Based on the fact of the low PM utilization efficiency and non-negligible magnetic flux leakage in the magnetic-geared devices, this Ph.D. project is aiming to develop new CMGs and new MGMs to overcome the aforementioned issues.

Analytical model establishment: The subdomain modeling technique is used to build the analytical model for CMGs and MGMs. The magnetic field distribution can be obtained by solving the analytical model. Then, the working principle and flux modulation effect is studied by performing harmonic analysis of the magnetic field. Finite element analysis (FEA) is employed to verify the correctness of the developed analytical model.

Theoretical analysis and observations: The influence of key design parameters on the torque capability is investigated through the parametric sweep. Multi-objective optimizations, based on particle swarm algorithm, are used for optimization design. Then, the unbalanced magnetic force in CMGs and MGMs is studied based on the air-gap relative permeance theory. The power factor of the MGM is also studied by using the classical synchronous machine theory. Some observations about the built-in attributes of CMGs and MGMs are summarized.

Proposing new ideas, and quantitative and qualitative analysis: Based on the above fundamential research, a good understanding and a few insights of the conventional CMGs and MGMs could be achieved. Several new ideas are proposed to work towards the established objectives. Quantitative and qualitative analysis are then performed to intially verify the proposed new ideas.

Simulation and experimental validation: The static and dynamic characteristics of the proposed CMGs and MGMs are predicted by FEA. The predicted performance is finally validated by the measurements on proof-of-concept prototypes.

1.4. THESIS OUTLINE

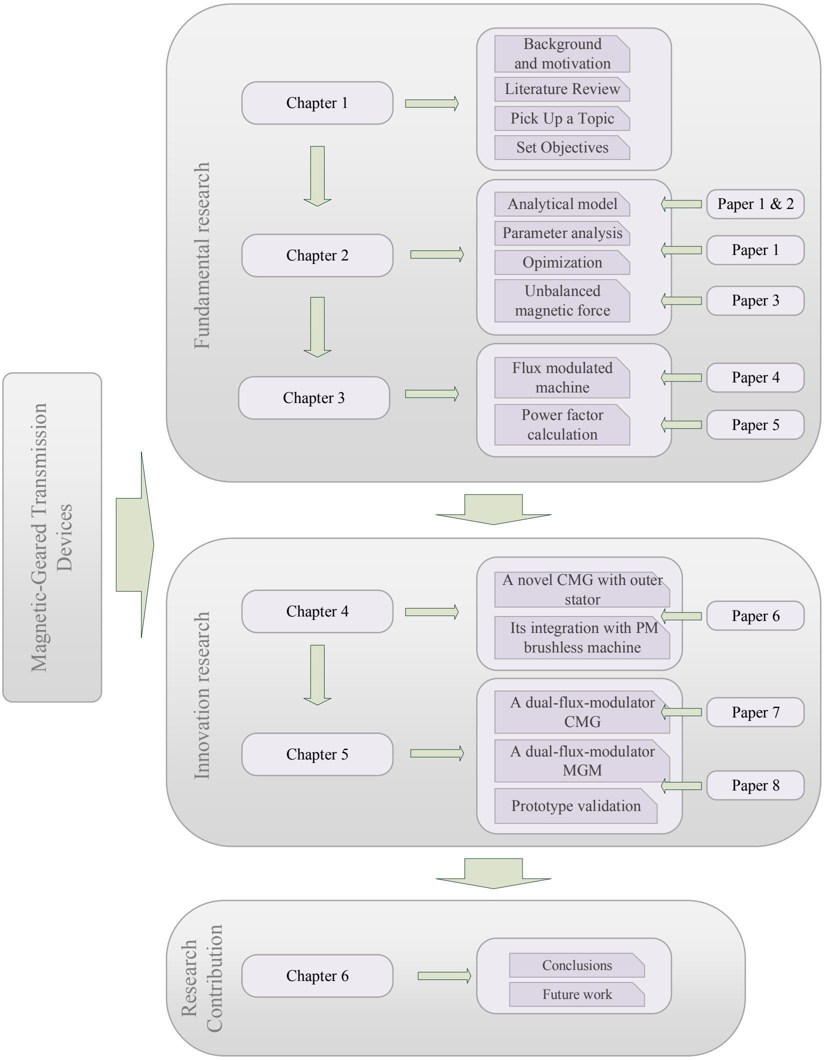


Figure 1-27 Thesis outline.

This thesis consists of six chapters based on a collection of eight papers. The thesis outline and relationships are shown in Figure 1-27. The fundamental research of the magnetic-geared devices are conducted in the first three chapters, while the innovation research are presented in Chapter 4 and Chapter 5. Conclusions are drawn in Chapter 6.

Chapter 1 Introduction

The background and motivation of this Ph.D. project are first presented. Recent developments of MGs and their integrations with PM brushless machines are then summarized, which activates the conduction of this research. The research objectives as well as the research methodology, are also pinpointed. The thesis outline and list of publications are given in the end.

Chapter 2 Analytical Analysis of the Coaxial Magnetic Gear and Magnetic-Geared Machine

An analytical modeling method based on subdomain technique is developed to accurately calculate the magnetic flux distribution and magnetic forces in CMGs. The influence of key design parameters on the torque density is investigated with the assistance of the developed analytical model. A global optimal design is then accomplished. In order to increase the computational efficiency of analytical model with a large number of subdomains, several numerical approaches are proposed to downsize the coefficient matrix of the magnetic problem. Their correctness is verified by the FEA. Finally, the unbalanced magnetic force in CMGs and MGMs are investigated in analytical ways, and some observations about the built-in attributes of CMGs and MGMs are summarized.

Chapter 3 Analysis of A Flux-Modulated Permanent Magnet Brushless Machine

A flux-modulated PM brushless machine, which is characterized by a two-air-gap one-PM-ring topology, is studied in this chapter. A fast analytical approach to calculate the magnetic flux distribution in the flux-modulated PM brushless machine is developed. The magnetic behavior in the studied machine is described by partial differential equations in terms of magnetic vector potentials. Based on the fact that the flux-modulated PM machine has a low power factor, this chapter studies this issue in theory, and an analytical method is developed to explore the possibilities of improvement.

Chapter 4 A Novel Two-Air-Gap Coaxial Magnetic Gear and Its Integration with Permanent Magnet Brushless Machine

In this chapter, a novel two-air-gap CMG is proposed to alleviate the contradiction between high performance and complicated structure. A slotted stator is introduced and located in the outermost layer to replace the role of pole-pieces in CMGs. The teeth number of the stator is required to equal the number of pole-pieces in the conventional CMG, so that the desired flux modulation effect could be also achieved. Its integration with PM brushless motor could be easily implemented by inserting the armature windings into the stator slots. The mechanical structure experiences no changes after the integration. The developed MGM shows good performances in terms of the torque capability and power factor.

Chapter 5 A Novel Dual-Flux-Modulator Magnetic Gear and Magnetic-Geared Machine

This chapter proposes a novel dual-flux-modulator CMG (DFM-CMG) featured by high torque capability and high PM utilization efficiency. The DFM-CMG adopts spoke-type outer PM rotor and introduces an auxiliary flux modulator placed on the outermost layer. The harmonic analysis with detailed theoretical derivation is performed to reveal that the ferromagnetic pole-shoes on the spoke-type outer PM rotor could modulate the flux density distribution as well and create a nested magnetic-gearing effect. The influence of the auxiliary flux modulator on the magnetic flux leakage, flux distribution, and torque density is also studied in this chapter. A comprehensive comparison among the proposed CMG, the conventional surfaced-mounted CMG, and a spoke-type CMG is conducted to show the performance improvement achieved by the proposed topology. A prototype is built to verify the theoretical analysis and simulation results. A novel dual-flux-modulator MGM (DFM-MGM) is then developed in this chapter by inserting the armature windings into the auxiliary flux modulator. The operating principle and electromagnetic performance of the developed MGM are investigated by dividing it into one Vernier PM machine, one PM brushless machine, and one CMG. Its no-load back electromotive force, torque transmission, power factor, loss, efficiency, and unbalanced magnetic force are studied. Finally, the predicted performance of the proposed DFM-MGM is validated by the measurements on a proof-of-concept prototype machine.

Chapter 6 Conclusion and future works

This chapter summarizes the obtained observations, findings, and results in this research project, and discusses further work in the end.

1.5. LIST OF PUBLICATIONS

Journal papers

[1] X. Zhang, X. Liu, C. Wang, and Z. Chen, “Analysis and design optimization of a coaxial surface-mounted permanent-magnet magnetic gear,” *Energies*, vol. 7, no. 12, pp. 8535–8553, Dec. 2014.

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[1] X. Zhang, X. Liu, and Z. Chen, “Analytical calculation of magnetic field in a flux-modulated permanent-magnet brushless machine”, in *Proceeding of 18th International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1353-1359, Pattaya, Thailand, Oct. 2015.

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CHAPTER 2. ANALYTICAL ANALYSIS OF THE COAXIAL MAGNETIC GEAR AND MAGNETIC-GEARED MACHINE

2.1. INTRODUCTION

This chapter is devoted to theoretical study of the working principle of CMGs and MGMs, and analytical prediction of their performance. This chapter is based on a collection of three papers.

Paper 1 first develops an analytical model for the CMGs based on the subdomain modeling technique. The flux modulation effect is considered by dividing the flux modulator into several dependent subdomains. The magnetic behavior in each domain is described by the magnetic vector potential A. The interaction between different domains is represented by applying the boundary constraints. Then the magnetic flux distribution in CMGs could be obtained by solving a matrix equation. The analytical solution shows a good agreement with the FEA. Then, the influence of the key design parameters on the torque density is investigated. Some useful observations are summarized. The optimization with emphases on torque capability and material cost is carried out in the end.

Paper 2 investigates the computation burden of the CMG subdomain model in the high-torque application. The CMG usually shows a big size with a large pole-pair number when it is scaled up for high-torque applications, which results in a significant increase of the subdomain number. Therefore, the dimension of the matrix equation to be solved will be large, which makes the analytical calculation very time-consuming. In order to rectify this situation, this paper explores the possibilities of downsizing the matrix dimension. Several numerical approaches are proposed and the computation burden could be then significantly reduced. Their correctness is verified by the FEA.

Paper 3 studies the unbalanced magnetic force shown in some CMGs and MGMs. The essential reasons for this issue are theoretically investigated by two analytical methods. The first analytical model is developed by using the air-gap permeance theory. The magnetic behaviors associated with the unbalanced magnetic force could be identified. Some observations are summarized, and the design criteria of avoiding unbalanced magnetic force are then proposed. In order to quantitatively calculate the magnetic force exerted on the two PM rotors, the second analytical model based on the subdomain technique is developed. The spatial distribution of the magnetic force in several MGM designs is calculated. Two analytical methods could arrive in the same results, which are also verified by FEA.

2.2. PAPER 1

Analysis and Design Optimization of a Coaxial Surface-Mounted Permanent-Magnet Magnetic Gear

by

Xiaoxu Zhang, Xiao Liu, Chao Wang and Zhe Chen

The paper has been published in

Energies, Vol. 7, No. 12, pp. 8535-8553, Dec. 2014.

2.3. PAPER 2

Fast Calculation of Magnetic Field Distribution in Magnetic Gear for High Torque Application

by

Xiaoxu Zhang, Xiao Liu, Zhanfeng Song, and Zhe Chen

The paper has been published in

Proceeding of 22nd International Conference on Electrical Machines (ICEM), pp. 1742-1748, Sep. 2016.

2.4. PAPER 3

Investigation of Unbalanced Magnetic Force in Magnetic Geared Machine Using Analytical Methods

by

Xiaoxu Zhang, Xiao Liu, and Zhe Chen

The paper has been published in

IEEE Transactions on Magnetics, Vol. 52, No. 7, Jul. 2016.

Article number: 8203304

CHAPTER 3. ANALYSIS OF A FLUX-MODULATED PERMANENT MAGNET BRUSHLESS MACHINE

3.1. INTRODUCTION

This chapter is devoted to the study of a flux-modulated PM brushless machine, which is a kind of MGMs characterized by a two-air-gap one-PM-ring topology. This chapter is based on a collection of two papers.

Paper 4 develops an analytical model for the flux-modulated PM brushless machine. The magnetic behavior in the studied machine is described by partial differential equations in terms of magnetic vector potentials. The partial differential equations are then solved by applying the boundary constraints. With the knowledge of the magnetic vector potential, the magnetic flux distribution in the air-gaps could be easily calculated. FEA is employed to verify the correctness of the developed model.

Paper 5 studies the power factor of the flux-modulated PM brushless machine in theory. An analytical method is first developed to fast calculate the power factor of this machine. The reasons behind the low power factor performance are then investigated. Some efforts are made to study the effect of key design parameters on the power factor performance. Finally, an optimization is performed to explore the possibility of improvement.

3.2. PAPER 4

Analytical Calculation of the Magnetic Field Distribution in a Flux-Modulated Permanent-Magnet Brushless Motor

by

Xiaoxu Zhang, Xiao Liu, and Zhe Chen

The paper has been published in

Proceeding of 18th International Conference on Electrical Machines and Systems (ICEMS), pp. 1353-1359, Oct. 2015.

3.3. PAPER 5

Analytical Investigation on the Power Factor of a Flux-Modulated Permanent-Magnet Synchronous Machine

by

Xiaoxu Zhang, Xiao Liu, Jinlin Liu, and Zhe Chen

The paper has been published in

IEEE Transactions on Magnetics, Vol. 51, No. 11, Nov. 2015.

Article number: 8110704

CHAPTER 4. A NOVEL TWO-AIR-GAP COAXIAL MAGNETIC GEAR AND ITS INTEGRATION WITH PERMANENT MAGNET BRUSHLESS MACHINE

4.1. INTRODUCTION

The chapter presents a novel two-air-gap MGM based on the work published in Paper 6.

Paper 6 proposes a new CMG with an outer stator (or outer flux modulator), with the emphasis on the convenient integration with PM brushless machines. The slotting of the stator plays the same role of the pole-pieces in the conventional CMG to modulate the magnetic flux distribution. The ferromagnetic pole-shoes on the spoke-type outer PM rotor provide the magnetic path for two PM rings, which allows the outer stator to be effectively coupled with two PM rotors. Therefore, the differential between the pole-pair numbers of two PM rotor could be moderated by the stator, and the stable torque transmission could be achieved. Its integration with PM brushless motors could be easily implemented by inserting the armature windings into the stator slots. The harmonic analysis and torque capability of the proposed CMG are studied in this paper. The working principle and electromagnetic performance of the developed MGM are also investigated.

4.2. PAPER 6

A Novel Coaxial Magnetic Gear and Its Integration with Permanent-Magnet Brushless Motor

By

Xiaoxu Zhang, Xiao Liu, and Zhe Chen

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Article number: 8203304

CHAPTER 5. A NOVEL DUAL-FLUX-MODULATOR COAXIAL MAGNETIC GEAR AND MAGNETIC-GEARED MACHINE

5.1. INTRODUCTION

This chapter explores the possibilities of suppressing the magnetic flux leakage in CMGs and MGMs, and then improving the PM utilization efficiency. One new CMG and one new MGM, featured by two-flux-modulator topology, are proposed in this chapter based on a collection of two papers.

Paper 7 proposes a novel DFM-CMG with high torque capability and high PM utilization efficiency. An auxiliary flux modulator is introduced to the outermost layer of a CMG with spoke-type outer PM rotor. Consequently, the outer PM rotor is sandwiched between two flux modulators, which brings the benefits of significant reduction of the magnetic flux leakage. The harmonic analysis with detailed theoretical derivation is performed to reveal that the ferromagnetic pole-shoes on the spoke-type outer PM rotor could modulate the flux density distribution as well and create a nested magnetic-gearing effect. The influence of the auxiliary flux modulator on the magnetic flux leakage, flux distribution, and torque density is also studied in this paper. A comprehensive comparison among the proposed CMG, the conventional surfaced-mounted CMG, and a spoke-type CMG is conducted to show the performance improvement achieved by the proposed topology. A prototype is built in the end to verify the theoretical analysis and simulation results.

Paper 8 develops a novel DFM-MGM by inserting the armature windings into the auxiliary flux modulator of the DFM-CMG. The operating principle and electromagnetic performance of the developed MGM are investigated by dividing it into one Vernier PM machine, one PM brushless machine and one CMG. Its no-load back electromotive force, torque transmission, power factor, loss, efficiency, and unbalanced magnetic force are studied. Finally, the predicted performance of the proposed DFM-MGM is validated by the measurements on a proof-of-concept prototype machine.

5.2. PAPER 7

A Novel Dual-Flux-Modulator Coaxial Magnetic Gear for High Torque Capability

by

Xiaoxu Zhang, Xiao Liu, and Zhe Chen

This paper has been submitted to
IEEE Transactions on Energy Conversion, 2017.

5.1. PAPER 8

A Novel Magnetic-Geared Machine with Dual Flux Modulators

by

Xiaoxu Zhang, Xiao Liu, and Zhe Chen

This paper has been submitted to
IEEE Transactions on Industrial Electronics, 2017.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1. CONCLUSIONS AND CONTRIBUTIONS

With the increasing demand for the low-speed high-torque applications, such as the wind power generation, wave energy harnessing, and marine propulsion, the magnetic-geared transmission has been paid wide attention in recent years due to its contactless mechanism, high torque density, and high reliability. Great efforts on the development of magnetic-geared transmission devices have been made by both industry and academia. Currently, the capability of the MGMs could be up to 10 MWs [154], which is very suitable for the next-generation offshore wind power system. However, compared to the industrial-proven mechanical-geared solution and direct-drive solution, the magnetic-geared transmission technique still has a long way to go. The main contributions of this Ph.D. project are as follows,

- Analytical models have been developed and verified by FEA to provide clear insights into the magnetic behaviors in the flux-modulated CMGs. The developed models allow the performance index, such as torque density, to be expressed as a function of geometrical parameters, which brings the convenience to the optimization designs. Some interesting observations have been summarized
    a) For a given gear ratio, larger pole-pairs of the two PM rings are preferred;
    b) The ratio of pole-piece width to pole pitch ratio, and the ratio of length to pitch are preferred to be around ½;
    c) The torque capability is more sensitive to the volume of the inner rotor PMs than that of the outer rotor PMs ;
    d) The torque capability is more sensitive to the outer air-gap length than to the inner air-gap length.
- This project has enlarged the application range of the subdomain modeling technique to the high-torque application. By making the most of boundary conditions and periodicity, and conducting mathematical transformations, the matrix dimension of unknown coefficients has been downsized from $(16N+2Q+2Q*K) \times (16N+2Q+ 2Q*K)$ to $(2Q+2Q*K)/c \times (2Q+2Q*K)/c$. The computational cost of the CMG design for high-torque applications is significantly decreased.

- The issue of the unbalanced magnetic force in CMGs and MGMs has been theoretically studied by two different analytical methods. Three kinds of magnetic behaviors have been identified to probably contribute to the unbalanced magnetic force. The unbalanced magnetic force can be zero if the design satisfies two criteria, namely gcd($2p_i$, N_s)>1 and gcd(p_i, p_o)>1. Two developed analytical methods could arrive in the same results, which have also been verified by FEA.

- An analytical model based on the subdomain technique has been developed for a flux modulated machine. The FEA has been employed to verify the developed model. The power factor of a flux-modulated PM brushless machine has been studied in a theoretical way. Based on the developed analytical model, a rapid method has been developed to calculate the power factor of the flux-modulated PM machine. The flux density in the inner air gap excited by the PM rotor has been found to be relatively low, which accounts for its low power factor performance. The influence of key design parameters on the power factor has also been investigated, and then the optimization has been made to improve the power factor. The results show that the power factor of the studied MGM could be improved by 20% when compared with the initial design.

- For ease of developing MGMs, a new CMG with external flux-modulating stator has been proposed. The slotting of the stator has been verified to be able to modulate the magnetic flux distribution excited by both PM rotors. Stable torque transmission could be achieved, and its torque density of 84 kNm/m^3 is slightly lower than the conventional CMG of 91 kNm/m^3. Although the proposed CMG could not achieve best torque capability, it can be easily integrated with a PM brushless machine. The corresponding MGM could be accomplished by directly inserting armature windings into the stator slots. Some efforts have been made to investigate the performance of the developed MGM.

- A novel CMG with two flux modulators has been proposed in this project. Due to the presence of the auxiliary flux modulator, the magnetic flux leakage on the outer PM rotor could be suppressed and the useful harmonics are thus amplified. With the same amount of consumed PMs, the torque capability of the proposed CMG shows a 73% growth over the conventional surface-mounted CMG, and a 44% growth over the conventional spoke-type CMG. The proposed topology has been prototyped and verified by experiments.

- A DFM-MGM has been designed, analyzed and prototyped. Compared to the traditional MGMs, the stator of the proposed MGM could not only be used to accommodate the armature windings, but also function as additional flux modulator to enhance the magnetic gearing effect. Moreover, the location of the stator enables it to be part of the magnetic path for the magnetic flux excited by either inner rotor PMs or outer rotor PMs, so that the armature windings could be coupled with all of the PMs in the proposed machine to achieve the electromechanical energy conversion. High torque capability and high PM utilization efficiency could be thus achieved.

As concluded above, this Ph.D. thesis has made efforts to investigate the built-in attributes of the conventional CMGs and MGMs. Two novel CMGs and two MGMs with different features have also been proposed, which enriches the possibilities of the magnetic-geared devices. The research work conducted in this project is expected to motivate more people to work in this field and then drive the further development of the magnetic-geared devices together.

6.2. FUTURE WORK

Although many aspects of the proposed CMGs and MGMs have been investigated in this thesis, there is plenty of room for improvement. Additionally, the magnetic-geared transmission is still an unproven technology for industry application. Lots of issues are worthy to be further studied. Based on the achievement and findings of above research, several research perspectives are listed as follows,

- The nonlinearity of magnetic materials has not been taken into account in the above developed analytical models. The developed analytical model is unable to accurately predict the loss in CMGs and MGMs. There is still room for improvement of the analytical models.

- The end effect, vibration and noise, and mechanical strength of the modulation pieces are interesting topics to be discussed.

- The topology proposed in Chapter 4 is planned to be prototyped and then validated by experimental tests.

- For the ease of manufacture and assembly, the proof-of-concept prototypes were built in this project with several compromises, such as the modulation pole pieces and pole shoes on the spoke rotor made by a whole piece of steel instead of being laminated by electrical steel sheets, the pole shoes longer than the PMs mounted on them for easy assembly. Those trade-offs worsen the performance of the proposed machines. A better mechanical structure design is expected in the future to ensure the electromagnetic performance.

- The slotting of the modulating pole-pieces and stator results in significant flux density variations in the PMs and ferromagnetic cores. Therefore, the eddy-current loss in PMs and ferromagnetic cores is expected. In order to avoid the risk of PM demagnetization, it is necessary to accurately calculate these loss and resultant temperature rise.

- Since the two PM rotors in CMGs and MGMs are coupled by the magnetic field without physical contact, torsional oscillations may occur between two PM rotors when the load or speed are suddenly changed. The dynamic performance and control strategy need to be further investigated.

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APPENDICES

Prototype Construction and Testing

1. Part Manufacturing

Figure A-1 End cover

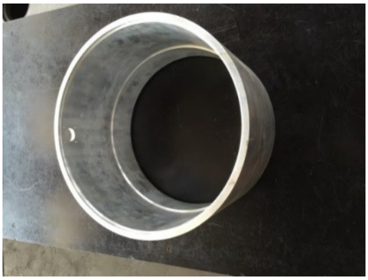

Figure A-2 Housing

Figure A-3 Inner rotor shaft

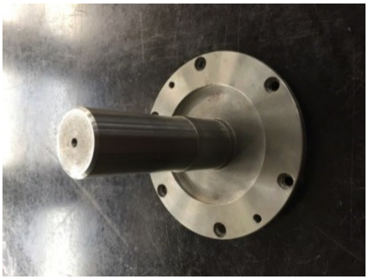

Figure A-4 Outer rotor shaft

Figure A-5 Stator steel lamination

Figure A-6 Pole-shoes

Figure A-7 Flux modulation pole-piece

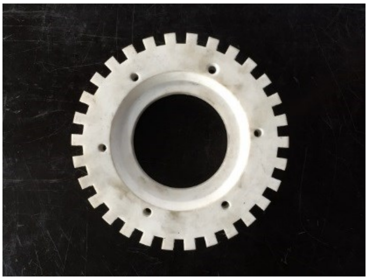

Figure A-8 Pole-piece end supportor

Figure A-9 Outer rotor PMs

Figure A-10 Inner rotor PMs

2. Assembly

Figure A-11 Inner rotor without PMs

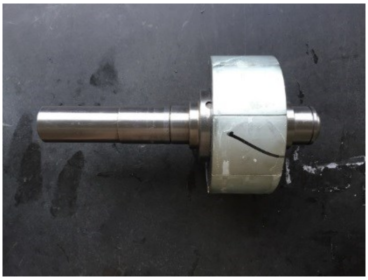

Figure A-12 Inner rotor with PMs

Figure A-13 Flux modulator

Figure A-14 Outer rotor without PMs

Figure A-15 Stator with armature windings

Figure A-16 Armature windings

Figure A-17 Spoke-tpye CMG

Figure A-18 Proposed MGM

3. Experimental Rig

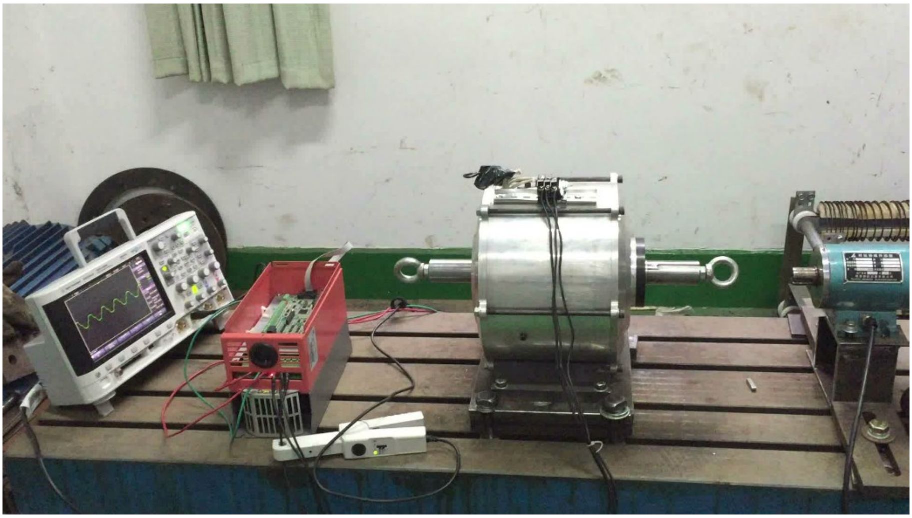

Figure A-19 No-load test

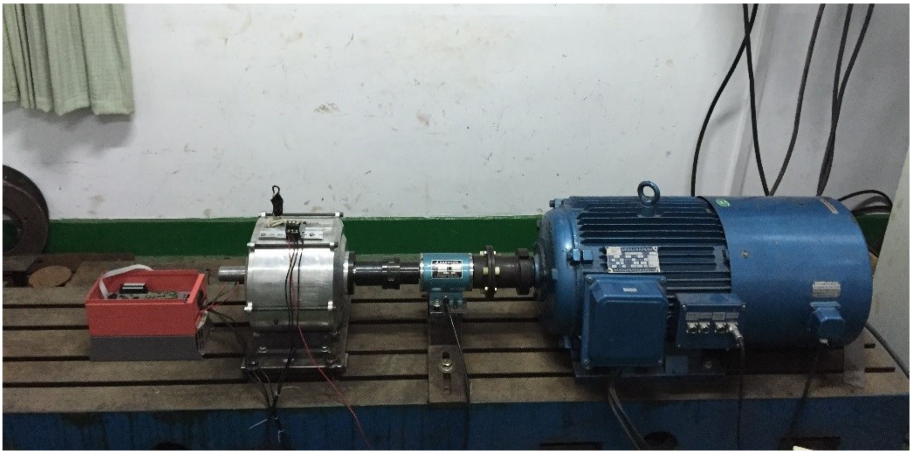

Figure A-20 Load test

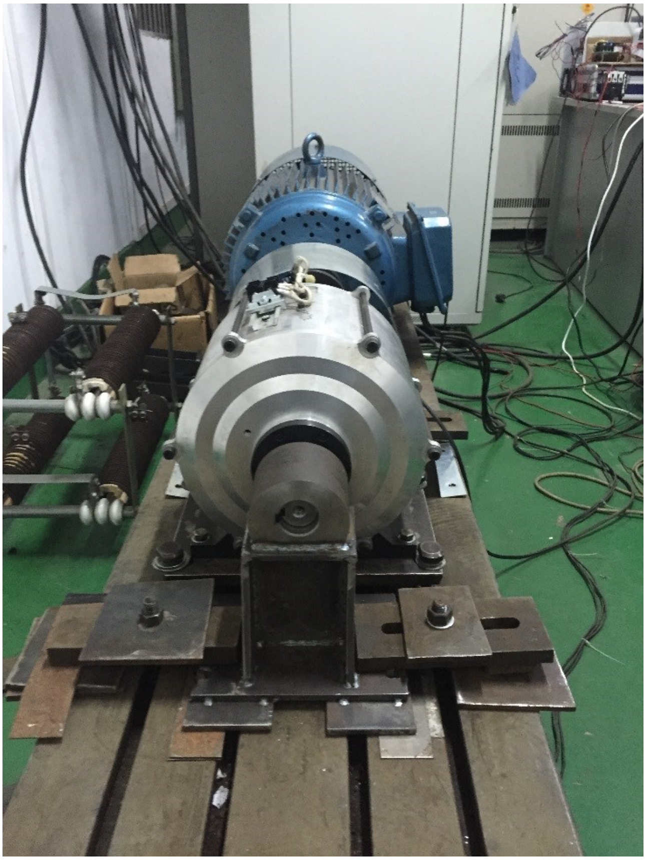

Figure A-21 Stall torque test

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