# Recent Developments and Comparative Study of Magnetically Geared Machines

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(Invited)

*Abstract*—**This paper overviews the recent developments and various topologies of magnetically geared (MGd) machines. Particularly, current design trends and research hotspots of this kind of MGd machines are emphasized, with the aid of statistic summary of the published papers. According to different evolutions from a magnetic gear (MG), four mainstreams of MGd machines are extracted and compared in terms of both mechanical complexity and electromagnetic performance. By virtue of their inherent features, such as high torque density and multi-power port, the feasibility of MGd machines for applications, where continuously variable transmission (CVT) and power split are demanded, is also described.**

*Index Terms*—**Field modulation, magnetic gear, multi-port, permanent magnet.**

## I. INTRODUCTION

THANKS to the development of high-energy permanent magnet (PM) materials in last decades, PM machines exhibit high torque density and efficiency, and have now been widely used for various applications at different power and speed levels [1-3].

For those applications with low-speed and high-torque requirements, e.g. electric/hybrid electric vehicles (EV/HEVs), wind power generation etc., the mainstream system solution consists of a conventional medium-speed electrical machine and mechanical transmission mechanisms [4]. However, the system is inevitably accompanied with drawbacks brought by the mechanical transmission components, such as strict lubrication and maintenance demand, high vibration and noise, short lifecycle and so on. Therefore, research on high torque density PM machines has aroused great attention from both academia and industry, aiming to eliminate the transmission devices and directly drive the system. To date, numerous novel PM machine topologies toward high torque density have been developed, such as axial-field, Vernier, transverse-flux, and stator-PM machine etc. [5-8]

In the past decade, a new class of high-torque density PM machines has become one of the hottest research topic of electrical machines. The machines are originally derived from a contactless magnetic gear (MG) [4], and can be termed as magnetically geared (MGd) machines [9-12]. As shown in Fig.1, the most important feature of MGd machines is that they work based on magnetic gearing effect/air-gap field modulation, and can be regarded as the integration of a conventional machine and a contactless MG. By inheriting the merits of contactless torque/speed transmission from the MG, as well as compact volume from the conventional medium-speed machine, MGd machines are capable of directly driving the low-speed systems with high torque density and reliability, thus becoming promising candidates for many applications.

Unlike the conventional electrical machines with one electrical port and one mechanical port, most MGd machines can have more than one mechanical port, providing additional degrees of freedom [13-15]. The multi-port characteristic of MGd machines makes them possible to achieve specific functions, such as continuously variable transmission (CVT) and power split, which are inherently suitable for HEVs and wind power generations, Fig. 1.

Owing to the diverse integration methods of MG and conventional machine, numerous topology variants belonging to the family of MGd machines have been proposed, and some of them are investigated aiming at specific applications. This paper overviews the recent developments of MGd machines. Based on the provided design parameters and performance of various MGd machines in the published papers (more than 60 papers), some design trends and research hotspots are summarized in terms of (a) size constraints and gear ratio; (b) output power and speed; and (c) torque density. In addition, according to different evolutions from MG, various MGd machine topologies can be mainly categorized into four types, which are mechanically coupled, Pseudo, mechanically and magnetically coupled, and partitioned stator machines, respectively. Their detailed performances are then compared including torque density, PM volume, rotor number, mechanical structure, heat dissipation and topology diversity.

This paper is organized as follows. Section II describes the configuration and working principle of a MG. Breakdown of different MGd machine types is introduced and various topologies are reviewed in Section III. Statistic summary of MGd machines is reported in Section IV. Section V compares the performance of different MGd machines, with their potential utilization for HEVs/wind power generation also highlighted. The conclusions are then given in Section VI.

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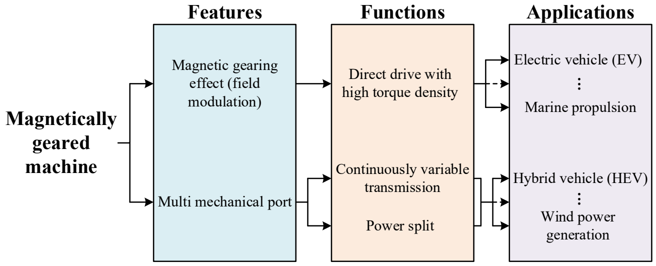


Fig. 1. Characteristics and applications of MGd machines.

## II. MAGNETIC GEAR AND MAGNETIC GEARING EFFECT

### A. Magnetic Gears (MGs)

With reference to various mechanical gears, different MG topologies can be easily developed by simply replacing the teeth of mechanical gear with PM poles. However, most of them have poor torque density due to the insufficient utilization of PMs. Hence, MGs have not attracted much attention till a novel coaxial MG is proposed [4], which gets rid of the concept of mechanical gear and largely improves the torque density (>100kNm/m$^3$).

As shown in Fig. 2, the MG consists of three components: a high-speed element, a low-speed element, and a magnetic modulation ring. Both high-speed and low-speed elements are made of PMs but with different pole-pair numbers, and the magnetic modulation ring consists of a certain number of ferromagnetic iron pieces. Normally, the magnetic modulation ring locates between the other two elements, aiming to effectively modulate the PM fields, and the positions of the other two PM elements can be swapped (see Fig. 2).

The basic configuration of a MG is expressed as [4]

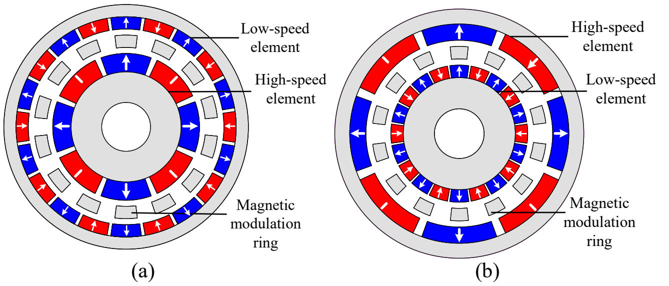
$$N_m = p_h + p_l \tag{1}$$

$$N_m\Omega_m = p_h\Omega_h + p_l\Omega_l \tag{2}$$

where $N_m$ is the number of iron pieces of the modulation ring, $\Omega_m$ is its mechanical angular velocity; $p_h$ is the pole-pair number of the high-speed element, $\Omega_h$ is its mechanical angular velocity; $p_l$ is the pole-pair number of the low-speed element, $\Omega_l$ is its mechanical angular velocity.

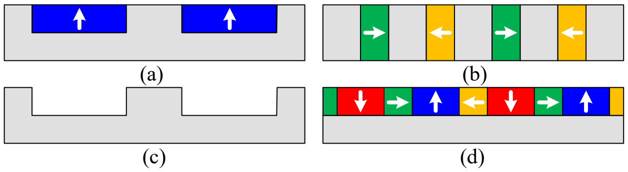
From (2), it is clear that all three components of the MG can be rotating and thus the gear ratio (speed ratio) $G_r$ of any two movable components can be freely adjusted by controlling the speed of the other component, which is so-called continuously variable transmission (CVT); alternatively, any one of the three components can be fixed at standstill and thus the MG has a constant $G_r$ between the other two components, which is always used for speed/torque conversion, similar to a conventional mechanical gear.

Many studies have been conducted to further improve the performance of the MG: (a) for high/low-speed element, apart from the surface-mounted PM (SPM) rotor structure, other structures can be used to improve the torque density or reduce the PM volume [16-19], such as consequent-pole PM (CPM), interior-PM (IPM), pure reluctance, and Halbach PM rotor, etc. as shown in Fig. 3; (b) the pure reluctance rotor structure of the magnetic modulation ring can be replaced by CPM or IPM structure, thus providing additional excitation and boosting the torque [20]; (c) the radial-field type can be changed to the axial-field or transverse-flux type, and the shape of iron pieces can be modified to enhance the field modulation and mitigate the flux leakage [21]. Up to now, the maximum torque density of a MG with various torque-boosting techniques adopted has already reached over 250kNm/m$^3$, making its competitive for practical applications [22].



(a) (b)

Fig. 2. Typical MGs. (a) MG with low-speed element outside. (b) MG with high-speed element outside.



(a) (b) (c) (d)

Fig. 3. Different rotor structures. (a) Consequent-pole PM rotor. (b) Interior-PM rotor. (c) Pure reluctance rotor. (d) Halbach PM rotor.

### B. Magnetic Gearing Effect/Air-gap Field Modulation

For conventional electromagnetic devices with two sets of excitation sources, a steady average force/torque can be generated only when the pole-pair number and rotational speed of the fields produced by the two sources are identical. However, for a MG, the average torque can be produced by two PM excitation sources with different pole-pair numbers and rotational speeds. More specifically, the torque production is resulted from the indirect interaction instead of the direct interaction of the two sources since the field provided by any PM source is firstly modulated by iron pieces so as to match the pole-pair number and speed of the other PM source. This phenomenon can be termed as magnetic gearing effect [12] and/or air-gap field modulation [23].

Based on energy conservation, the torques of the MG should match

$$T_m + T_h + T_l = 0 \tag{3}$$

$$T_m\Omega_m + T_h\Omega_h + T_l\Omega_l = 0 \tag{4}$$

where $T_m$, $T_h$, $T_l$ are the magnetic torque of the modulation ring, high-speed element, and low-speed element of the MG, respectively.

For most low-speed and high-torque applications, the high-speed element is always connected to the prime mover, either the low-speed element or modulation ring is used to drive the load while the remaining one is fixed. The magnetic gearing effect can then be defined by the gear ratio $G_r$, which reflects the capability to amplify the torque, as

$$G_r = \frac{T_l}{T_h} = -\frac{\Omega_h}{\Omega_l} = \frac{p_l}{p_h} \ or \ G_r = \frac{T_m}{T_h} = \frac{\Omega_h}{\Omega_m} = \frac{N_m}{p_h} \tag{5}$$

By way of example, Fig.2 shows the MG with $N_m$=14, $p_l$=10, and $p_h$=4. When the modulation ring is fixed, the torque of the high-speed PM rotor is amplified by 2.5 times while it is amplified by 3.5 times when the low-speed PM rotor is fixed.

## III. VARIOUS MAGNETICALLY GEARED MACHINES

Although MG has high torque density, it is simply a passive transmission part without any electrical output port or input port. For the sake of practical application, its integration with electrical machines needs to be well considered. Instead of being a simple replacement of a mechanical gear, numerous artful integration methods aiming at compact system volume have been proposed, which greatly enriches the development of this new class of electrical machine, i.e. MGd machines.

As shown in Fig. 4, most MGd machines can be directly derived from a MG and are the focus of this paper. In addition, many existing machine topologies, such as stator-PM machines [24, 25], variable flux reluctance machines (VFRMs) [26], Vernier machines [27], and fractional-slot PM machines [28] etc., have now been re-recognized and/or proven to work based on magnetic gearing effect. Since these machines have been well analyzed and reviewed, they will not be included in this paper.

According to different evolutions from a MG, MGd machines can be mainly categorized into four types, which are mechanically coupled machines (Type 1), Pseudo machines (Type 2), mechanically and magnetically coupled machines (Type 3), and partitioned-stator machines (Type 4), respectively. For Type 1, the subordinate MG and electrical machine can be easily identified since they are just mechanically coupled without changing their original structures. In contrast, other three types have more compact integration between the MG and electrical machine, as shown in Fig. 5. More detailed introduction and review of each type will be given below.

### *A. Type 1: Mechanically Coupled Machines [9, 29-49]*

The basic concept of mechanically coupled machines, Fig. 6, is that a MG and a conventional electrical machine are physically connected by sharing the same rotor [9]. When the machines operate in motor mode, one of the PM rotor (normally the high-speed element) of the MG is shared by the machine and driven by the armature field, then the speed/torque conversion can be achieved by setting the other PM rotor and/or magnetic modulation ring as output rotor. Ideally, the subordinate MG and machine are magnetically decoupled since the magnetic field of the machine does not cause flux distortion in the MG and vice versa [9].

According to the different relative positions of the MG to the machine, mechanically coupled machines can be further classified into MG-outside machine, Fig. 6(a) [9], MG-inside machine, Fig. 6(b) [29], and MG-sandwiched machine (one MG with both PM rotors shared by other machines) [30]. It should be noted that the number of the connected MG and/or machine can be larger than 1, i.e. the cascade level of the mechanically coupled machines can be improved. Apart from PM machine, the subordinate machine can be induction machine, and reluctance machine etc. [31-33].

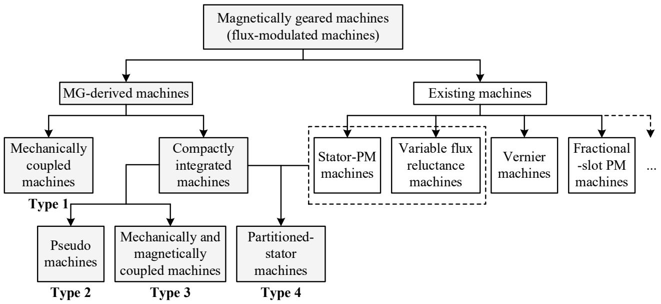


Fig. 4. Breakdown of different types of MGd machines.

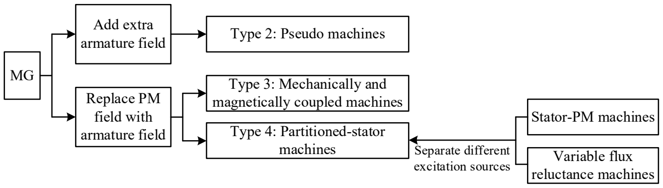


Fig. 5. Breakdown of different types of compactly integrated MGd machines.

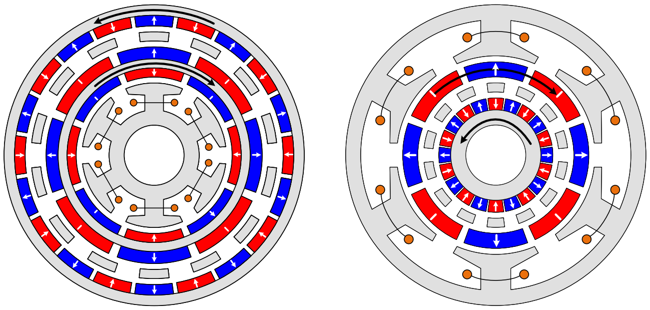

(a) (b)

Fig. 6. Type1: mechanically coupled machines. (a) MG-outside. (b) MG-inside.

Mechanically coupled machines always have high torque density due to their good space utilization ratio, and they have been investigated and applied for certain applications, such as EV, and wind power generation [34-46]. In addition, as many as three rotors with one of the speeds controllable also make these machines capable of achieving CVT [47, 48]. Some techniques can be used to further improve the machine performance, such as adopting different PM structure [49], Fig. 3, and eliminating the yoke of the shared rotor [46], Fig. 6(b). For the machine shown in Fig. 6(b), although the fields of the subordinate MG and machine are actually coupled, it is still regarded as a mechanically coupled machine when considering the similarities in machine structure, as compared with Fig. 6(a).

### *B. Type 2: Pseudo Machines [10, 50-57]*

To drive the high-speed rotor of the MG, another approach is to add an extra set of armature winding on the low-speed element, Fig. 7(a), the evolved machine is termed as Pseudo machine [10]. The added armature winding can be either fractional-slot concentrated winding or integer-slot distributed winding, it produces additional rotating field with the same pole-pair number of the high-speed rotor, thus controlling its rotational speed and direction. Since the PMs of the low-speed element are mounted on the inner surface of the fixed stator, the magnetic modulation ring and the high-speed rotor rotate in the same direction under a fixed speed ratio of $G_r$. Basically, the Pseudo machine can be regarded as the combination of a MG with fixed low-speed element and a SPM machine with large air-gap. In [10], it shows that the Pseudo machine can have a high torque density of 60kNm/m$^3$ even with a small current density of 2A/mm$^2$, then it has also been investigated for assorted applications, such as wind power generation and flight control surface actuation etc. [50-54]. Other PM rotor structures applied to Pseudo machine are also investigated [55].

In terms of the placement of armature winding, it can be also placed on the magnetic modulation ring [56, 57], Fig. 7(b). In this case, the modulation ring is fixed with additional integer-slot distributed winding adopted, the low-speed PM rotor and high-speed PM rotor rotate in reverse under a fixed speed ratio of $G_r$.

### *C. Type 3: Mechanically and Magnetically Coupled Machines [11, 58-70]*

The rotating magnetic field produced by the PM rotor of the MG can be replaced by employing a stator equipped with multi-phase sinusoidal excited windings, from which the mechanically and magnetically coupled machines are derived [11]. As shown in Fig. 8 (a), the inner PM rotor of the MG is replaced by the armature winding. In terms of the low-speed PM rotor and the magnetic modulation ring, either one or all of them can be rotating. When the modulation ring is stationary, the machine is similar to a conventional outer-rotor machine but with dual air-gaps. For certain slot/pole number combinations, it is possible to remove the air-gap between the stationary modulation ring and wound stator by merging them into one stator with multi-tooth structure, Fig. 8(b), which is identical to a typical Vernier machine. Hence, the inherent relationship between the Vernier machine and MGd machine is revealed [27], as shown in Fig. 4. Different winding types and rotor structures have also been investigated [58].

By swapping the positions of the PM rotor and wound stator, the inner-rotor MGd machines have also been proposed [59-61], which are easier to assemble for most applications. Besides, by setting both inner PM element and magnetic modulation ring as rotor, the machine can achieve functions of power split and CVT, which are suitable for HEVs [62-65]. The related manufacture issues and control strategies are also analyzed [66-68].

Further, both PM rotors of the MG can be replaced by the wound stator, eliminating the PM usage so as to reduce the machine cost [69, 70]. Of course, this will lead to torque reduction.

### *D. Type 4: Partitioned Stator Machines [12, 71-82]*

Another type of MGd machine, i.e. partitioned stator (PS) machine, is newly developed based on the synergies of MGs and stator-PM machines [12], as shown in Fig. 9 (b). The PS machine can be directly evolved from the stator-PM machine by separating the winding and PMs to two stators, Fig. 9. The PS machine always has improved torque density, thanks to the removal of space conflict between the winding and PM. Based on this concept, all kinds of stator-PM machines, including double salient PM (DSPM), flux reversal PM (FRPM), and switched flux PM (SFPM) machines, can be easily converted to PS machines [71-77]. The difference among various PS machines lies in the pole-pair number, PM structure and relative angular position to the wound stator of the PM stator. For instance, the PM stator of the PS-FRPM machine is of SPM structure, Fig. 9(b), while that of the PS-SFPM machine is of IPM structure, Fig. 10(b). The PS-DSPM machine also has IPM structure but with different pole-pairs of the PS-SFPM machine [74], which will not be shown here.

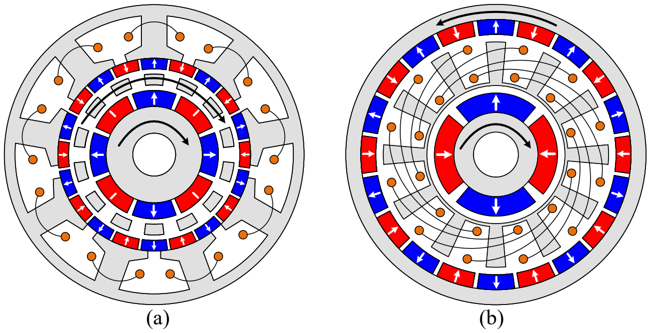

(a) (b)

Fig. 7. Type 2: Pseudo machines. (a) Outer-stator. (b) Sandwiched-stator.

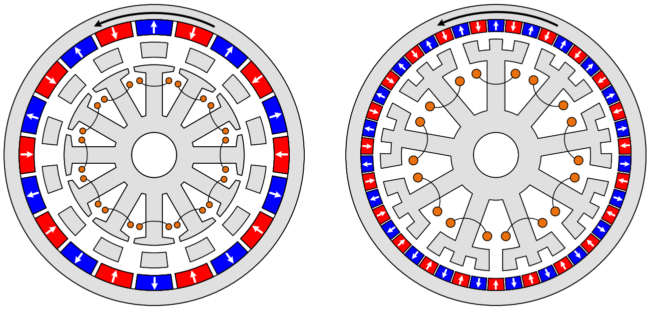

(a) (b)

Fig. 8. Type 3: mechanically and magnetically coupled machines. (a) Dual air-gap. (b) Single air-gap (Vernier machine).

By comparing Type 4 (PS machines), Fig. 9(b), with Type 3 (mechanically and magnetically coupled machines), Fig. 8(a), it is found that they share many similarities in machine structure, i.e. a PM element, a wound stator, and a magnetic modulation ring. The working principle of Type 4 and their stator-PM counterparts are then analyzed from the new perspective of air-gap field modulation, from which the inherent magnetic gearing effect is revealed [77]. It should be noted that for Type 4, only modulation ring can be rotating while the modulation ring and/or the PM element can be rotating for Type 3.

The electromagnetic performance of various PS machines are compared [78]. Results show that in order to achieve high torque, the number of poles of the PM stator is always equal to the number of teeth of the wound stator, which is determined by the configuration of the original stator-PM machine. Besides, the control performance of PS machines is analyzed [79]. Results show that the reluctance torque of PS machines is negligible, which is similar to stator-PM machines.

Since the PMs of stator-PM machines are stationary, they can be completely replaced by dc-field excitation, as shown in Fig. 11(a). The machines are termed as variable flux reluctance machines (VFRM) or wound field switched flux (WFSF) [26]. Correspondingly, PS-VFRM machines with improved torque

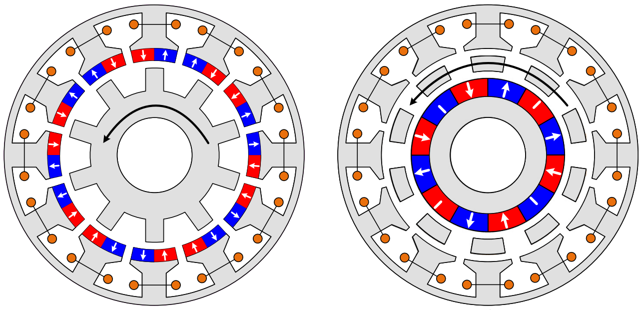

(a) (b)

Fig. 9. FRPM machine and its PS counterpart. (a) FRPM. (b) PS-FRPM.

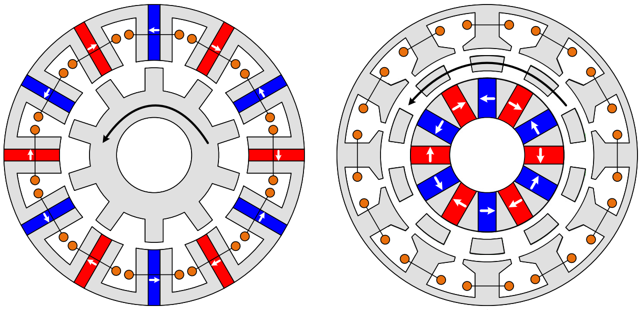
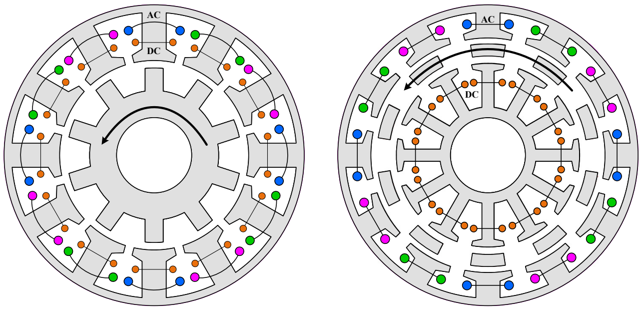

(a) (b)

Fig. 10. SFPM machine and its PS counterpart. (a) SFPM. (b)PS-SFPM.



(a) (b)

Fig. 11. VFR machine and its PS counterpart. (a) VFRM. (b) PS-VFRM.

density have also been proposed, Fig. 11(b), which are suitable for low-cost applications [80, 81].

## IV. DESIGN TRENDS AND RESEARCH HOTSPOTS

Due to the attractive features of high torque density, multi-power port, and diverse topology possibilities, MGd machines have become one of the hottest research topics in electrical machine. Up to now, various MGd machine topologies have been proposed, and new topology variants are still emerging. In addition to the theoretical analysis, detailed issues of MGd machines for practical applications have aroused more and more attention.

To provide a visualized overview of the research status of MGd machines, more than 60 related papers are reviewed in this paper [9-12, 29-93]. Based on the provided design parameters and performance from these papers, some design trends and research hotspots are summarized in terms of size constraints, gear ratio, output power, speed, and torque density.

### *A. Size Constraints and Gear Ratio*

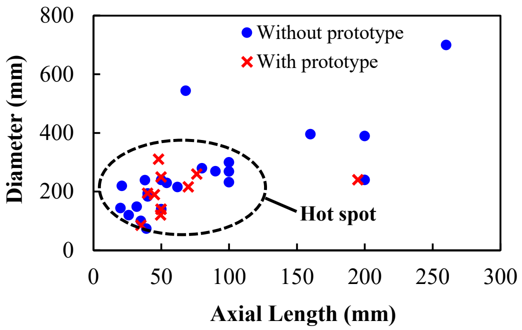


Fig. 12. Statistic summary of size constraints of the MGd machines.

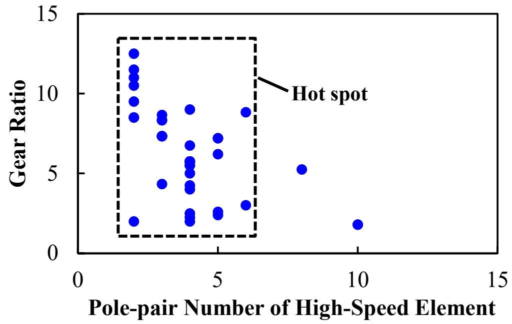


Fig. 13. Statistic summary of gear ratio of the MGd machines.

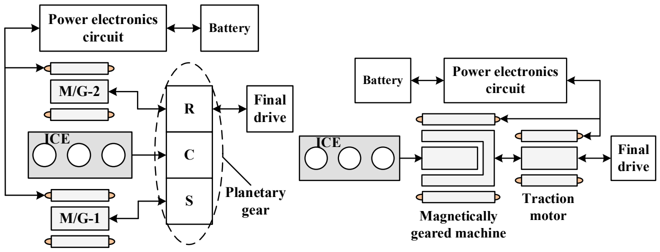
Fig. 12 shows the statistic summary of size constraints of the MGd machines. As can be seen, most published papers focus on the machines with relatively small size constraints (diameter $D$<400mm, axial length $l$<150mm) since most of them are proposed just as theoretical solutions for practical applications, and only some small prototypes are made to verify the concept.

Fig. 13 shows the adopted gear ratios of the MGd machines. For most papers, the pole-pair number of the high-speed element ranges from 2 to 6, corresponding to the small size constraints shown in Fig. 12. In terms of the gear ratio $G_r$, it is related to the requirement of specific applications. In general, a large $G_r$ is helpful to improve the torque density. However, the flux leakage may become severe when $G_r$ is too large, which will impair the torque density. From Fig. 13, the hotspot of $G_r$ ranges from 2 to 12.

### *B. Output Power and Speed*

For MGd machines, they are inherently suitable for low-speed applications, as shown in Fig. 14. The rated speeds of the low-speed element in all the papers are lower than 1600 rpm, and there are basically two study regions. For wind power generation, the wind turbine speed is always below 200rpm, so as to extract the maximum mechanical power under different wind speeds [34]. For EV/HEVs, a wide speed range is required when considering the different operation conditions. The machines should be capable of operating at the maximum speed around 1600rpm by assuming the maximum vehicle speed of 200km/h [37].

It is well known that the torque of the machine is largely determined by its active volume and cooling condition, while the power of the machine also depends on the rotor speed. At present, since most MGd machines are studied based on small prototypes, only few cases can be found with the power rating matching the practical applications, as shown in Fig. 14. In [42], two mechanically coupled MGd machines are designed and



(a) (b)

Fig. 17. Hybrid power train in HEVs. (a) With conventional machines. (b) With MGd machines.

Fig. 14. Statistic summary of output power and speed of the MGd machines.

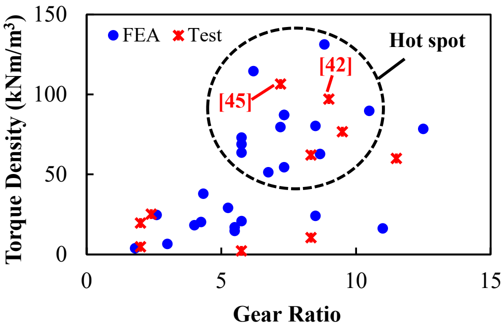


Fig. 15. Statistic summary of torque density of the MGd machines.

successfully implemented in an EV, and the whole operation condition of the EV is simulated and tested. Results show that the machine can output a maximum power of 60kW, and has high efficiency within the whole speed range.

### *C. Torque Density*

Fig. 15 shows the torque density of the MGd machines. As can be seen, when $G_r$ ranges from 5 to 10, the machine is more likely to have high torque density, and the maximum torque density has reached over 130kNm/m$^3$ [35]. Even for machines with experimental validation, the maximum torque density around 100kNm/m$^3$ has been reported [42, 45], which is much larger than that of the conventional PM machine (always below 30kNm/m$^3$). Therefore, the advanced torque performance of MGd machine can be verified.

## V. PERFORMANCE COMPARISON OF MGD MACHINES

### *A. Performance Comparison*

The basic concepts and evolution methods of four types of MGd machines have been presented in Section III, Figs. 6-9. TABLE I lists the basic structure of each machine type, from which both mechanical and electromagnetic performance can be qualitatively compared, as shown in Fig. 16.

*1) Torque density:* both Type 1 (mechanically coupled machines) and Type 2 (Pseudo machines) can be regarded as the direct integration of a PM machine and a MG. Therefore, they all have higher torque density than Type 3 (mechanically and magnetically coupled machines) and Type 4 (partitioned stator machines), of which one PM rotor of the MG is replaced by armature winding. In addition, Type 1 has the highest torque density since the equivalent air-gap length of the subordinate PM machine in Type 2 is large.

*2) PM volume:* among various MGd machines, Type 1 has the maximum PM usage and is more likely to have the highest cost since it has 3 PM layers. In contrast, Type 3 and Type 4 have the minimum PM usage since they only have 1 PM layer.

TABLE I
MECHANICAL STRUCTURE OF DIFFERENT TYPES OF MGD MACHINES

| | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Min. number of air-gap | 3 | 2 | 2 | 2 |
| Min. number of rotor | 2 | 2 | 1 | 1 |
| Max. number of rotor | 3 | 2 | 2 | 1 |
| Number of PM layer | 3 | 2 | 1 | 1 |

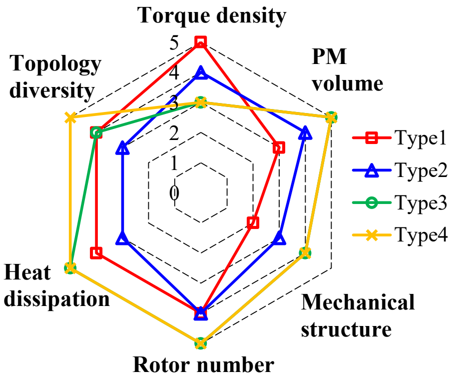


Fig. 16. Characteristics of four types of MGd machines.

*3) Mechanical structure:* compared with the conventional electrical machines, the main drawback of MGd machines is the complex mechanical structure, since they all have at least 2 air-gaps. For Type 1, it has minimum 3 air-gaps and 2 rotors, making its structure most complicated and bringing issues of system reliability. In comparison with Type 2, the machine structures of Type 3 and Type 4 are simpler since they can operate with only one rotor rotating.

*4) Rotor number:* for most low-speed applications, only one rotor is required as effective mechanical port. For Type 1 and Type 2, they all have an additional high-speed rotor, resulting in strict requirements of bearings and mechanical clearance.

*5) Heat dissipation:* for Type 2, it has 2 PM layers and one of them is close to the hot copper windings, thus suffering high temperature rise and risk of demagnetization. In contrast, the temperature rise of PMs in Type 3 and Type 4 can be efficiently managed by forced cooling since the PMs are static and remote from the hot copper windings.

*6) Topology diversity:* in comparison with other three types, Type 4 has more topology possibilities since all the stator-PM machines together with their hybrid-excited, wound-field variants can be converted [80-82].

### *B. E-CVT and Power Split*

In addition to Type 4, the other three types of MGd machines can have more than two mechanical ports and at least one electrical port, TABLE I, making them possible to realize electric continuously variable transmission (E-CVT) and power split, which are suitable for wind power generation and HEVs [29, 63-68, 83].

Taking HEVs as an example, for typical series-parallel HEVs, the hybrid power train is shown in Fig. 17 (a), which consists of two conventional PM machines and a planetary gear [63]. Each machine can work in motor or generator mode, and by controlling the speeds of them, the speeds of the internal combustion engine (ICE) and the final drive are decoupled, making the ICE work within high efficiency region. In addition, the power flow can be adjusted according to the different load conditions of the vehicle. However, the vibration, noise and maintenance caused by the planetary gear become the main issues. For this reason, a new type of hybrid power train with MGd machines is proposed and shown in Fig. 17(b), which eliminates the planetary gear [63, 83]. As can be seen, one rotor of the MGd machine is connected to the ICE while another rotor can be directly connected to the final drive. By controlling the MGd machine through the power electronics module, the torque and speed differences between the ICE and the final drive can be matched. Normally, another traction motor is connected to the final drive through the same shaft of the MGd machine, aiming to provide additional torque supplement. Detailed analysis regarding machine design and motion control can be found in [66], and the experimental validation based on a practical hybrid power train system is also described [67].

## VI. CONCLUSION

Recent developments and research status of MGd machines have been overviewed in this paper. Based on a MG, four evolutions of MGd machines have been classified and qualitatively compared. Results show that each type of MGd machine has its own merits. In addition, the design parameters and performance of MGd machines in the published papers have been extracted and summarized, from which the research hotspots have been identified and superior torque performance have been verified. The multi-power port characteristic of MGd machines has also been presented.

Based on the overview, the research trends and key issues of MGd machines may be predicted and recognized from the following aspects:

1. New and novel topologies of MGd machines are still emerging. Various concepts from the conventional electrical machine and MG can be adopted to further develop the MGd machines, such as axial-field [84-87], transverse-flux [88], hybrid-excited [82], memory [89], triple-excited [90, 91] etc.

2. In addition to multi-mechanical port, MGd machines can be also designed with multi-electrical port, e.g. adopting two sets of windings on the stator [92, 93], which brings more degrees of freedom and are more flexible utilizing in wind power generation and HEVs.

3. For mass commercial applications of MGd machines, there still many challenges need to be dealt with. Most importantly, due to the complex mechanical structure of MGd machines, system simplification and integration should be well considered so as to improve the system reliability and guarantee the torque benefit [35]. In addition, many practical issues, such as PM loss reduction, end-effect mitigation and heat management of MGd machines deserve great attention [36-42, 46, 68].

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