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Review

A Review of Magnetic Gear Technologies Used in Mechanical Power Transmission

Gerardo Ruiz-Ponce [1], Marco A. Arjona [1,*], Concepcion Hernandez [1] and Rafael Escarela-Perez [2]

[1] La Laguna Institute of Technology, TNM, Torreon 27000, Mexico
[2] Energy Department, Metropolitan Autonomous University Azcapotzalco, Mexico City 02128, Mexico
* Correspondence: marjona@ieee.org

Abstract: This paper presents a literature review on magnetic gears, highlighting the advantages of using these technologies for mechanical power transmission applications in wind energy conversion systems and transportation, such as in electric vehicles. Magnetic gear technologies have important advantages over their mechanical counterparts. They can perform the speed change and torque transmission between input and output shafts by a contactless mechanism with a quiet operation and overload protection without the issues associated with conventional mechanical gears. The paper describes the fundamentals and operating principle of the field-modulated magnetic gear topologies and investigates the magnetic torque transmission mechanism. However, despite all the advantages highlighted in different research and development reports, there is still no convincing evidence to show that magnetic gear technologies are an acceptable alternative for industrial applications. The aim of this paper is to summarize previous work on magnetic gears to identify the topologies most suited for mechanical power transmission systems in wind energy conversion systems and electric vehicle applications. These applications will show that research and development of magnetic gear technologies contribute significantly to solutions for sustainable systems, a subject to which our current civilization must pay a lot of attention.

Keywords: mechanical gears; mechanical power transmission; magnetic gears; wind turbine; electric vehicle

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1. Introduction

Mechanical power transmission systems are used to transfer energy from the place where it is generated to the location where it performs a particular work. The most important component of a mechanical power transmission system is the so-called gearbox, mainly because of the role it plays in the system. Typically, a gearbox comprises a gear train inside housing with an input shaft and one or more output shafts. The gear train is a multiple set of gears, meshed together to create movement. Gears use rotation to transfer torque and alter speeds, delivering power and motion from a prime mover to a driven machine or load. Mechanical gear drives exhibit important advantages such as high efficiency, accurate gear ratio, mechanical robustness, and relatively ease of manufacture. In addition, these are ideal for low-, medium-, and high-power transmission.

The gearbox can transmit mechanical power as a speed multiplier or speed reducer. Hence, two of its most studied and relevant uses, due to its impact on environmental awareness and energy saving, are in wind energy conversion systems and the automobile industry (particularly electric vehicles). In a wind energy conversion system (WECS), the gearbox is the core component of the drive powertrain. Its main function is to step up the speed transmitted by the low-speed, high-torque shaft, from the rotor blades to the high-speed, low-torque shaft that drives the electric generator to match the rotation speed required by this machine [1,2]. In a typical electric vehicle (EV) power transmission system, the gearbox is used to transfer power from the electric motor (power unit) to the drive wheels; its function is to reduce the output speed of the engine to a slower wheel speed, which will increase the torque output of the engine. The engine torque transmission to the vehicle must be smooth, quiet, efficient, and at the desired ratio a driver needs to operate it [3,4]. In both WECSs and EVs, the gearbox is one of the most critical components of the powertrain system; inside it, there is a complex combination of rotating gears that interact in different modes, resulting in a mechanical dynamic that defines its performance [5]. A criterion applied to evaluate the performance of a mechanical gear is based on the torque density, which measures how much torque can be transmitted within the unit volume of the gear. In order to achieve a higher torque density, designers and mechanical engineers have worked on multiple solutions, such as the optimization of metallic teeth geometry, the application of higher-strength materials, and gear flank surface treatments.

Mechanical gear performance has been widely discussed at various conferences, and many research results about the subject have been published in numerous technical papers and books [6–13]. However, despite the advantages of mechanical gears, the transmission often suffers from problems associated with mechanical contacts, such as gear noise and vibrations, mechanical wear, and the need for lubrication, which reduce the overall transmission system efficiency. These drawbacks have led to the development of a new class of devices based on permanent magnets, named magnetic gears (MGs). Compared with mechanical gears, MGs have advantages such as minimal acoustic noise and reduced vibration, maintenance-free operation, high transmission efficiency, and physical isolation between input and output shafts. Hence, a new concept of non-contact mechanical power transmission systems has been developed and is still being studied. One of the most important applications that can be derived from the use of this non-contact technology is in overcoming the drawbacks of working with conventional gears in mechanical power transmission systems. Therefore, MGs are expected to be applied to the powertrain in WECSs and EVs and to acquire relevance in contributing to the expected efficiency in these systems.

This paper focuses on describing MGs as a technology with particular advantages for power generation and sustainable transportation applications. The goal is to bring the reader closer to an accurate understanding of MGs, providing a comprehensive review of their topologies and an analysis of important research projects seeking to utilize them for WECSs and EVs. Following this introduction, Section 2 presents the main drawbacks of mechanical gears and underlines the importance of MGs over their mechanical counterparts, justifying the development of magnetic means as an emergent alternative in mechanical power transmission solutions. This section also introduces the theoretical fundamentals while the MGs' operation principle is presented. Section 3 presents a comprehensive state of the art on the various magnetic gear topologies with capabilities for use in mechanical power transmission systems, including information on background and current technologies. Sections 4 and 5 focus on industrially applicable MG technologies in WECSs and transportation (EVs), respectively, presenting a publication history for each application. The conclusions in Section 6 highlight that the investigations are inclined to experiment in transportation systems, mainly in EVs and HEVs. Hence, the possibility of continuing to study the MGs is opened to work on the option of applicability in wind energy systems.

2. Mechanical Gears versus Magnetic Gears

2.1. The Drawbacks of Mechanical Gears

The mechanism of gear drives is simple: the teeth of the mating gears engage, and each rolls onto the other to transmit power (actually, energy transmitted per time period). However, for two gears in contact, the power transmission capacity is limited by their resistance to two major forms of failure: one is related to surface fatigue at the teeth flank (pitting), and the other to bending fatigue at the teeth root (contribution of tooth friction) [14]. In Figure 1a, the mechanism of two meshing gears can be observed, while Figure 1b shows an illustration of how frictional forces are developed at the point of the first contact between two teeth due to kinematic movement in the gear. Tooth flanks pitting is the most significant damage that occurs with gears. It is caused by cyclically variable contact stresses from gear meshing and accentuated by any surface irregularities in the presence of a lubricant (in fact, pitting is a lubrication-related failure). Pitting causes failure because of a fatigue process when gear teeth are subjected to high contact stresses and many stress cycles. It may be a problem with the gears not fitting together properly. In this case, pitting will concentrate on highly loaded areas. The result is an area of metal removal, which is sometimes called flaking or spalling. Pitting may cause the gear teeth to deteriorate and generate dynamic forces; these forces cause the gear teeth to fail by bending fatigue. In such cases, the bending failure is secondary and not directly related to lubrication. Pitting represents approximately 14% of occurrences amongst all gear damage. Additionally, although 90% of pitting stabilizes and is not threatening to gear life, it is important to be able to detect it [15]. Figure 1c shows two common modes of tooth failure where fatigue is prevalent. Progressive pitting leads to the destruction of the gear tooth flanks. Gears begin to throb and, if the operation is not suspended, complete destruction of the gear drive can occur [16]. It can be inferred that pitting is directly dependent on load transfer; when it is destructive, we speak of a surface overload problem. In addition, there is often sliding friction between meshing gear teeth surfaces; this is one of the principal power losses in gear drives which affects the gear meshing efficiency [17]. All this means that losses are strongly influenced by the transmitted load and the friction between tooth surfaces [18].

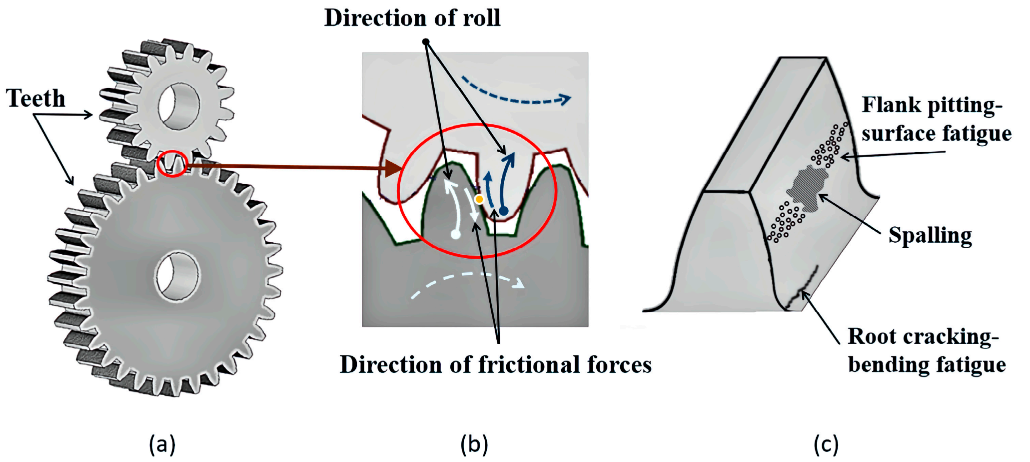


Figure 1. A typical gear drive mechanism: (**a**) Two gears in mesh; (**b**) Mechanics of gear tooth engagement (at point of first contact); (**c**) Gear tooth failures.

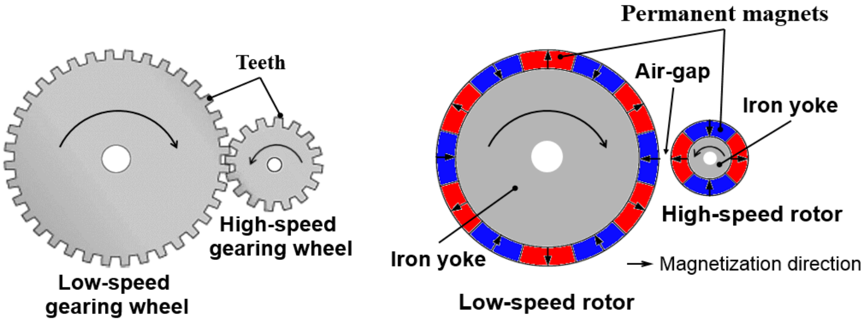
Gears drives can also be noisy due to the torque fluctuations associated with the transfer of load from tooth to tooth as the gears mesh. Having sliding between meshing gear teeth surfaces, initial tooth-to-tooth contact occurs along the whole tooth width at once, causing audible shock loads that induce noise and wear. As gear tooth faces wear, they develop groves and small pits. These gradually become larger and, as they grow, these imperfections will cause even more noise. Noise raises sharply with an increase in peripheral speed (tooth contact frequency) and to a lesser extent with an increase in tooth load. Lubrication helps mitigate these issues. However, many of the failures identified are related to the tribological conditions of the transmission system, which strongly depend on the lubricant properties that are, in turn, a function of the temperature [19]. The churning of lubrication oil is another of the principal power losses in gear drives. Hence, the need for frequent maintenance becomes a critical condition for the proper functioning of the gears.

In general, neither pitting nor severe wear in the gear drives is tolerable during a gearbox life. Such damage could lead to unacceptable vibrations. A dominant source of vibration located is at the gear mesh because of variable mesh stiffness; this is one of the most important internal excitations of gear transmission [20]. Tooth cracking causes gear mesh stiffness reductions, leading to abnormal vibration of gears [21]. Then, vibration energy is transmitted to the gearbox housing. In fact, the noise radiated to the surroundings by the gearbox is due to the vibrations of its housing [22]. Another one of the main gear vibration sources is the transmission error of the gears. This is a parameter influenced by the load on the gears, and it is defined by the difference between the actual position of the output gear and its theoretical position (the position it would occupy if the gear teeth were perfect and infinitely stiff). This difference is a consequence of teeth bending from the torque exerted upon them and the dynamic behavior of the gearbox, and it can result from manufacturing inaccuracies, assembling errors or even from a bad design [23]. Noise and vibrations are increased at high speeds; hence, the gearbox may be limited to application for large velocities. In addition, noise and vibration problems are directly related to the whole characteristics of the gear transmission system and affect its performance. Consequently, the need to reduce the noise and vibration of a gearbox has become an important concern for manufacturers.

Given the drawbacks associated with the mechanical nature of conventional gears-based transmission systems, it should be pointed out that these systems are still presented with improvement situations to achieve the required performance in the industry. Tuma concludes this way [23]: "the gearbox is a source of vibration and, consequently, noise; gears are the main sources of high-frequency vibration and noise, even in newly built units."

2.2. Conversion of Mechanical Gears into Magnetic Gears

Most mechanical gear types can be replicated as MGs, simply by replacing the metal teeth of the gear wheels with alternating magnetic poles of permanent magnets (PMs). The most basic type of MG is a design equivalent to the mechanical spur gear. This is one of the simplest gear topologies, where the slots and teeth are replaced by north poles and south poles of PMs, respectively. Figure 2 shows a sketch of this gear type.



(a) (b)

Figure 2. Equivalent gears: (**a**) Mechanical spur gear; (**b**) Magnetic spur gear.

Mechanical gears traditionally use steel teeth to transmit power. In Figure 2a, the movable gear wheels are meshed with each other through the metal teeth; hence, power is transmitted through physical contact between mating gear teeth. When two gearing wheels are rotating and touching, due to an external source of mechanical energy, the teeth of one of them push against the teeth of the other gear wheel. These contact mechanisms may give rise to the inherent issues explained in the previous section: wearing on the tooth flanges, acoustic noise, mechanical vibration, need for periodic lubrication and maintenance, and power losses due to friction.

In MGs, a set of powerful rare-earth PMs arranged in two non-contact rotors provide alternating magnetic fields to transmit power. As with all gear technology, with MGs, one rotor rotates at a different speed than the other rotor. The N and S polar PMs, usually represented in red and blue colors, respectively, as shown in Figure 2b, are mounted alternately on the iron yoke of each rotor. The space between the rotors is the air gap.

When a rotor rotates, its magnetic poles exert a force on the poles present in the other rotor transmitting a magnetic torque via the air gap, causing this rotor to rotate simultaneously. Hence, power is transmitted without physical contact through a magnetic flux in the air gap.

In mechanical gears, the change in speed from a driving gearing wheel to a driven gearing wheel is defined by the so-called gear ratio (G_R). This ratio represents the rotational speeds at which two mating gears move relative to one another. The driving gear is connected via the input shaft to a source of mechanical energy (such as a motor). The driven gear is connected via the output shaft to a load. G_R also results from the relationship between the diameters of both gears. Since the number of teeth is directly proportional to the diameter (the bigger the gear, the more teeth it has), the G_R can also be determined by the ratio of the number of teeth on each gear. Figure 2 shows that the spur gear represents a system with a transmission ratio that leads to an increase in speed. For two paired mechanical gears, as shown in Figure 2a, the G_R can be determined by the ratio of the number of teeth on the low-speed gearing wheel (the driving or input gear) to the number of teeth on the high-speed gearing wheel (the driven or output gear). For the MG shown in Figure 2b, with the slots and teeth replaced with PMs, the G_R is calculated in the same way as the relationship between the number of PM pole pairs on each of the two rotors is. Based on this, the G_R is given by the following equation:

$$G_R = -\frac{Z_L}{Z_H} = -\frac{p_L}{p_H}, \tag{1}$$

where Z_L and Z_H are the number of teeth on the low-speed and high-speed gearing wheel of the mechanical gear, respectively, and p_L and p_h are the number of pole pairs of the PMs mounted on the low-speed rotor and high-speed rotor, respectively. The minus sign denotes that the two rotors rotate in opposite directions. Concerning this ratio, there is a clear tendency to prevent G_R from having an integer value, mainly for mechanical reasons. Integer ratios would accelerate wear and tear due to an increase in the frequency at which a tooth in one gear engages with a particular tooth in another gear. This frequency is known as the hunting tooth frequency (HTF). During the normal rotation of the two gears, every once in a while, those two teeth will enter the mesh area simultaneously and contact one another. If the gear set has an integer G_R, each tooth of the driving gear always contacts exactly the same tooth or teeth in the driven gear it engages. This becomes important if a tooth is damaged; in this case, a minor defect in a tooth, in repeated contact with the same teeth in the other gear, will cause uneven wear on those teeth, usually in an oval form. Ideally, the HTF should be as low as possible to evenly distribute the wear on the two gears. Gear pairs with low HTF will wear more evenly and last longer than the ones with a relatively high HTF. In practice, HTF is typically a low frequency (less than 10 Hz). This means that some analysts studying gearboxes may miss their occurrence during vibration analysis. However, this phenomenon exists, and it can be heard as a “grunt” coming from the gear set, possibly indicating a wear situation. That is why it is desirable to avoid it as much as possible. To obtain a low HTF, it is essential to define a ratio between the number of driving teeth and driven teeth to ensure that each driving gear tooth contacts each driven gear tooth, before the driven gear tooth contacts any driving gear tooth again. This is achieved by making the number of teeth in each gear a prime number, which means that such numbers have no common factors. Hence, HTF is directly dependent on the number of teeth per gear and involves finding the gear meshing frequency and the period of coincidence between the teeth of both gears. It is calculated as follows:

$$HTF = \frac{GMF}{LCM(Z_L, Z_H)} \tag{2}$$

In the above equation, GMF is the gear meshing frequency, also known as tooth mesh frequency; this is an intrinsic frequency of each gear assembly in both healthy and faulty conditions. It defines the rate at which gear teeth mesh together in a gear set. It is calculated using the number of teeth times the shaft speed of a gear. This calculation is associated with a fundamental rule in gear ratio theory, which says, "If two gears are in mesh, then the product of the speed times the teeth must be conserved"; according to the following formula, where f is the rotating speed of the gear in s^{-1} or Hz, the GMF is given by,

$$GMF = f_L Z_L = f_H Z_H \tag{3}$$

$LCM(Z_L,Z_H)$, is the least common multiple of both the numbers of teeth of Z_L and Z_H. It represents the meshing that repeats after an $LCM(Z_L,Z_H)$ number of meshes.

Unlike their mechanical counterparts, MGs present inherent non-destructive torque overload capabilities: if the demanded output torque exceeds the maximum design value, the rotors "slip", preventing breakage of the magnetic gear. With built-in overload protection, the MGs do not suffer irreparable damage; therefore, the surrounding equipment will be protected during the operation of the transmission system. When the overload condition is solved, normal operation is completely recovered. Overload protection is probably one of the main advantages of an MG. Montage [24] establishes a clear analogy by mentioning that it is as if his behavior is that of a torque fuse, then this behavior improves system life. Because these technologies do not present friction between the gear teeth due to their contactless structure, they are not subject to mechanical fatigue or wear and tear problems; hence, the requirements of lubrication are eliminated, and maintenance is reduced. Furthermore, since there is no physical contact between any of the rotors and as they have a lower mesh stiffness (lower force induced by motion transfer errors), the MGs exhibit reduced mechanical vibrations and extremely low acoustic noise, and, therefore, a quiet operation.

2.3. Benefits of Magnetic Gear Technologies on Mechanical Power Transmission

One of the most prominent companies in the development of MGs is Magnomatics [25]. This is a high-tech engineering company formed in 2006 as a spin-off from the University of Sheffield to commercialize innovative research on magnetic transmission systems based on magnetic gears.

Early developments were led by Professor K. Atallah. Professor Atallah and his research team proposed the first highly efficient magnetic gear mechanism for use to transmit mechanical torque by magnetic means. Since then, different topologies of magnetic gears have been studied in an effort to improve their performance. Based on the advantages mentioned above, and according to Magnomatics, the benefits of MGs technology on mechanical power transmission are the following:

- high reliability,
- high efficiency (torque densities comparable to mechanical gears can be achieved with a transmission efficiency >99% at full-load and with much higher partial-load efficiencies),
- high torque capacity (in some cases exceeding the values provided by its mechanical competitors),
- higher power ratings,
- compact size (a magnetic transmission will be smaller, lighter, and have a lower cost than a mechanical transmission),
- gear ratios of 50:1 down to 1.01:1, with almost zero torque ripple,
- physical isolation between input and output shafts,
- significant reduction in harmful drivetrain pulsations.

Despite their many advantages, MGs also have some drawbacks. These can best be understood through the historical efforts to replace mechanical gears with MGs. Next, a comprehensive study of the state of the art of these devices will be presented. This will allow us to know the bases for analyzing their performance and the importance of their integration into mechanical power transmission systems.

3. The State-of-the-Art Transmission Systems Based on Magnetic Gears Technologies

3.1. Early Topologies of Magnetic Gears

Using magnetic means for gearing purposes is not a recent idea. The first efforts to apply this technology in mechanical power transmission systems with gears using only PMs date back to the early decades of the 20th century. At the early stage developments of magnetic gearing technology, MGs were very analogous to mechanical gears. Figure 2 shows a clear analogy between a mechanical gear and an MG for a spur gear. Faus initially presented this topology in 1941 with a US Patent describing an MG quite similar to a mechanical spur gear [26]. Even though the idea in the patent seemed quite effective, the gearing topology proposed by Faus was weak due to poor performance and the low energy of ferrite PMs, which made it impossible use this widely used in the industry. Later, in 1991, Ikuta et al. proposed the non-contact magnetic gear using ferrite magnets [27]. This is a simple parallel-axis MG that would later include two basic types of magnetic coupling: radial coupling, with two different topologies shown in Figure 3a,b, and axial coupling, the topology of which is illustrated in Figure 3c, [28]. The performance of this MG type has been widely studied by using different approaches and investigating various ferromagnetic materials and stronger PMs [29–42].

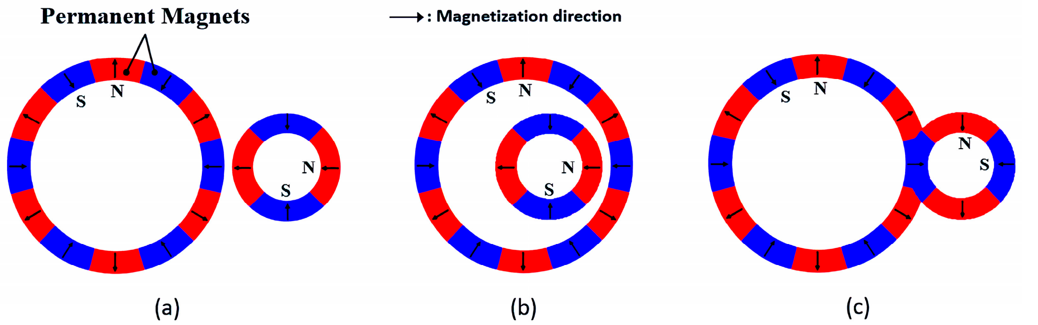


Figure 3. Parallel-axis magnetic spur gears: (**a**) External radial coupling; (**b**) Internal radial coupling; (**c**) Axial coupling.

Other MGs topologies that retain the same shape as their mechanical counterparts have also been proposed. Some of these topologies are magnetic worm gear, magnetic bevel gear, and magnetic rack-pinion gear; Figure 4 illustrates the mechanical shapes and their magnetic equivalence for each one. Baermann invented a magnetic worm drive that he presented with a U.S. patent in 1974 using barium-ferrite magnets [43]. Later, in 1993, Tsurumoto and Kikuchi described in an academic paper the basic design, principle of operation, and performance characteristics of a new magnetic worm gear prototype using samarium-cobalt PMs [44]. Tsurumoto and Kikuchi also developed magnetic analogs for bevel gears [45,46], and other researchers have continued to work on this topology [47–49]. A magnetic bevel gear operates in the same way as a spur gear by exchanging the intersecting angle; hence, this topology has also been studied as a perpendicular-axis magnetic spur gear. Although the topology of parallel-axis or perpendicular-axis MGs is very simple, the results of research work show that their torque density is still very low, typically less than 12 kNm/m^3; hence, their use in industrial applications is limited. The magnetic rack-pinion gear is used to convert rotational motion to linear motion. However, few studies have been published on this topology [50].

The aforementioned MGs types have mechanical and dynamic performance characteristics, useful for industrial tasks. According to Tsurumoto [51], the magnetic spur gear can have an internal and an external gear. By exchanging the distance between their centers, the spur gear is capable of transmitting motion between parallel axes. In the magnetic worm gear, the meshing is based on internal contact to enlarge the meshing and reduce the size of the gear and, despite its intricate structure, it has been shown that a magnetic worm gear with internal meshing can be manufactured [44]. In fact, its geometry is less complicated, unlike its mechanical counterpart, which has noticeably advanced geometry, but it makes this type of gear difficult to manufacture [52]. Magnetic worm gear transmits motion between non-parallel and non-intersecting shafts. As for the magnetic bevel gear, this type of transmission possesses the merits of a simple operation principle and ease of manufacture. It is used to transmit torque across perpendicular shafts; this type of gear operates in the same way as a spur gear, i.e., by exchanging the intersecting axle. It can change the intersection angle of the axis between the driving gear and the driven gear during operation. Some studies have shown that a magnetic bevel gear has a significantly improved volume, weight, and full load torque compared to the commercial mechanical bevel gear [48]. Finally, the magnetic rack-pinion gear, containing linear and rotary gears, can also be used to connect non-parallel and non-intersecting axes. This type of gear can perform all the operations of its mechanical equivalent, being very similar to it, both in construction and applications, without the drawbacks of the mechanical gear.

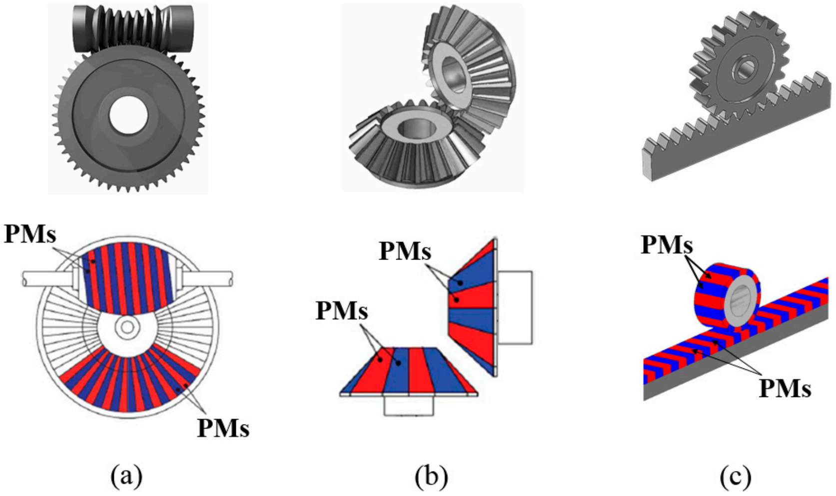


Figure 4. Mechanical gears and their equivalents MGs: (**a**) Worm; (**b**) Bevel; (**c**) Rack-Pinion.

Another topology of significant relevance in industrial applications, including the wind industry, is the planetary gear. Similar to its mechanical analog, the planetary magnetic gear has a higher torque density and power transmission capacity than previous topologies.

Initially, the planetary magnetic gear was designed based on geometry as it would be transformed directly from the topology of its mechanical analog, as shown in Figure 5. Gear designs based on this topology have been published by Tsurumoto [53–56]. However, perhaps the most outstanding work was the one published by Huang in 2008 [57]. Although it is another adaptation of the traditional planetary mechanical gear, which operates under its same principles, Huang's proposal exposes notable advances in the development of magnetic gears. He presents the design, simulation, and construction of the prototype of a planetary magnetic gearbox for applications in torque transmission systems where strong rare-earth (neodymium-iron-boron) permanent magnets were used in his prototype. The gear topology combines the structure of a mechanical planetary gear (Figure 5a) with the transmission principle of the spur magnetic gear (Figure 2). The number of planetary magnetic gears is the key to improving the torque transmission. Figure 5b shows the configuration of this gear with three planetary gears. For the magnetic version, Huang's paper proposes that increasing this number to six makes it possible to obtain almost twice the level of transmission torque. The prototype simulation showed that the topology with three planetary gears can achieve a torque density of 48.3 kNm/m^3, but that with six planetary gears, the torque density is almost 100 kNm/m^3. This torque density is comparable to that of a mechanical spur gear (100–200 kNm/m^3). However, the experimental results resulted in considerably lower values (approximately 16 kNm/m^3); the reason for this substantial decrease in the expected torque density was not explained. However, Huang's work set a precedent for more investigations, with increasing interest in using planetary magnetic gears for various applications such as wind power generation and transportation.

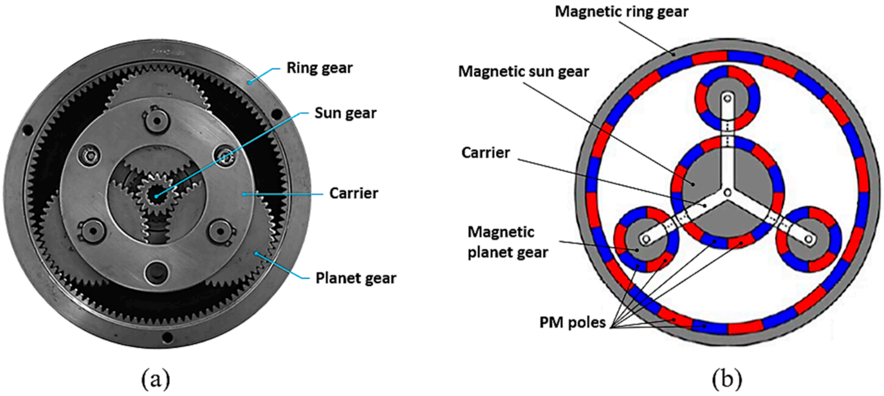


Figure 5. Planetary gear: (**a**) Mechanical; (**b**) Magnetic.

In general, all these magnetic gear topologies present quite acceptable mechanical characteristics and dynamic performances. Moreover, it has been demonstrated that it is possible to build power transmission mechanisms without any contact between their moving parts, avoiding the drawbacks of mechanical gears. By replacing the mechanical teeth with pairs of alternating permanent magnet poles, a magnetic gear that is a functional duplicate of its mechanical counterpart is obtained. Hence, these can be considered traditional conversion gears. However, in these topologies, only some permanent magnets participate simultaneously in power transmission, resulting in a low torque density when compared to mechanical gears, making them unattractive for large-scale industrial power applications. The exception may be in the planetary magnetic gear, which exhibits high torque densities. In this topology, the higher the number of planetary gears, the higher the torque density as more permanent magnets are involved in coupling the magnetic field compared to the previous topologies. However, including more planets requires a more complex mechanical configuration. Despite this complexity, interest in planetary magnetic gear has prevailed among researchers and academia.

3.2. The Energy Sources in Magnetic Gears

Early MG topologies, as shown in Figures 2–5, were first developed using non-rare-earth ferrite magnets, a low-price material, and high coercivity, but with a low remnant flux density. Subsequently, aluminum-nickel-cobalt (AlNiCo) PMs were used to develop MGs. AlNiCo is also a non-rare-earth material which offers high remnant flux density and very low cost, although it suffers from low coercivity. This was the first widely used commercial PM, whose development began in 1931 when it was discovered in Japan, with substantial improvements made through the 1960s. However, the maximum energy product $(BH)_{max}$, which is proportional to the energy stored in the magnet, is not high in these materials. Hence, early MGs yielded very low torque densities, and they did not receive much attention from research institutions and industry at the time; instead, they were considered inferior designs compared to their mechanical competitors. The discovery of high-energy density magnetic materials stimulated a significant increase in research to achieve magnets with higher values of both the maximum energy product (the most common factor of merit for a permanent magnet) and coercivity (resistance to demagnetization), which, in turn, led to the development of powerful rare-earth PMs, namely samarium-cobalt (SmCo) and neodymium-iron-boron (NdFeB). SmCo magnets were discovered in the United States in the early 1960s and commercialized since 1969, while NdFeB magnets, developed in Japan and the United States, first appeared on the market in 1984 [57]. Because of their magnetic properties, including high remanence, high intrinsic coercivity, and high-energy products, rare-earth PMs such as SmCo and NdFeB were widely adopted for the manufacture of magnetic gears. From both, NdFeB is more frequently used than SmCo because of its economic advantages, increased affordability, and stronger magnetic field strength; in fact, NdFeB has the highest (BH) max of any permanent magnet available today [58–60].

With these breakthroughs in magnet technology, the use of powerful rare-earth PMs for MGs applications is commonplace. The concept of contactless torque transmission through the interaction of magnetic fields began to attract attention again from engineers, research institutions, and industry. Nowadays, rare-earth PMs have become essential for a wide range of applications in modern technology requiring powerful magnets. Currently, rare-earth PMs, mainly NdFeB, have already been implemented in the EV and WECS industries, but their commercial use for mechanical power transmission is still under development.

3.3. Magnetic Gears with Higher Torque Density

The early designs which were developed to achieve contactless mechanical power transmission using magnetic fields demonstrated that simple MGs are possible. However, the MG topologies presented above have one disadvantage: they exhibit low torque density compared with their mechanical equivalent. When high-energy rare-earth PMs were employed, these early designs were improved, achieving higher torque density in MGs. Nevertheless, these simple MGs still have poor transmitted torque density capacity, which makes them ineffective. This is because only a fraction of PMs engages actively, contributing to torque transmission at a specific time. In addition, these topologies have lower transmission ratios and just one transmission mode. As previously mentioned, the main criterion that evaluates the performance of a mechanical gear during power transmission is based on the torque density or torque/volume ratio referred to as the capacity to transmit torque within a unit of volume size. An equally important criterion is efficiency, considered to be the output power/input power ratio and expressed as a percentage or decimal fraction. Therefore, it becomes clear that these criteria are important factors that must also be considered for magnetic gears.

The first magnetic gear designs, proposed as a traditional conversion of their mechanical equivalent, exhibited a common drawback: their torque density and gear ratio were very low, mainly because only a fraction of the permanent magnets was actively involved in the torque transmission at a specific time. Regarding the illustration in Figure 6, it can be seen that mechanical gears typically make surface contact with one to three teeth at a time. Therefore, after the first magnetic gear designs appeared, they were found to have poor magnet utilization and, consequently, a low capacity for mechanical power transmission, reporting torque densities of less than 12 kNm/m^3 [28]. For a particular case like the spur gear topology, the contact area between the gears is very small. Studies on magnetic coupling [57] confirmed that higher torque transmission can only be achieved when a large number of magnets are coupled simultaneously; the key point is to cover most of the perimeter of the gear with magnets.

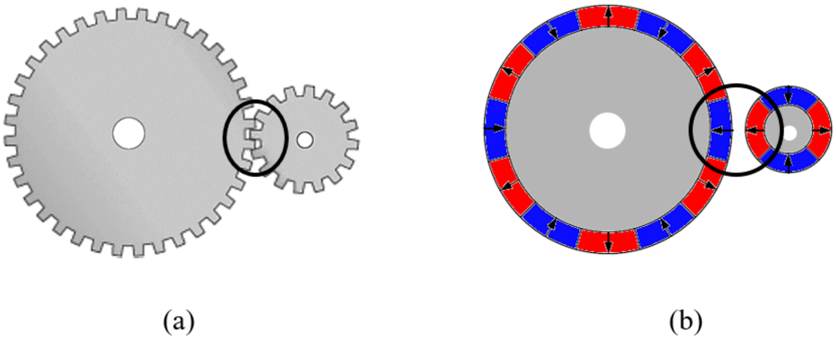

(a) (b)

Figure 6. Analog gears: (**a**) Mechanical spur gear; (**b**) Magnetic spur gear.

With the availability of materials to obtain powerful rare-earth permanent magnets with high energy density, research on magnetic topologies based directly on mechanical structures has increased. Among all these topologies, the planetary-type gear received considerable attention; it was observed in its configuration that a large number of permanent magnets are involved in its magnetic field coupling compared to the other topologies derived from their mechanical analogues. Conventional 3-, 4-, 5-, 6-, and 9-planet magnetic planetary gear designs were presented [61–66] with outstanding analytical and experimental results, making it one of the best-studied topologies in the effort to obtain a magnetic gear that could replace its mechanical analog. Simulations with a 6-planet magnetic planetary gear reached torque densities of 97.3 $\mathrm{kNm/m^3}$ [65]. However, despite showing superior advantages for torque transmission, their designs are still considered to have excessive moving parts; this drawback represents a disadvantage for its usage in applications such as those that require their integration into electrical machines with permanent magnets [67].

While the work on the planetary magnetic gear, based on the conversion of its mechanical analog, continued to be developed even beyond the first decade of this century, a new topology was consolidated as an innovative magnetic gear that can simultaneously couple all the permanent magnets for torque transmission. This disruptive topology, presented by Atallah and Howe in 2001 [68], consists of a completely different configuration from that which a direct conversion of a mechanical gear might have. The application of the magnetic flux modulation principle, an idea proposed by Neuland in 1916 [69], stands out in this topology. Its configuration adopts the concept of Reese's (1967) [70] and Martin's (1967) [71] patents, which were contributions made to improve Neuland's approach. The Atallah design uses three concentric structures: a high-speed internal rotor, a low-speed external rotor, and a modulator ring. Each rotor, with an iron core, has radially magnetized permanent magnets mounted on its surface. Between the two rotors, there is a stationary ring of ferromagnetic pole pieces, separated from each other, forming the modulator. Its function is to reorganize and modulate the distribution of the magnetic field produced by the permanent magnets so that a magnetic coupling can be established between the two rotors to transmit the electromagnetic torque. Since the gearing effect is governed by the principle of magnetic field modulation for mechanical power transmission to occur, this new topology is known as flux-modulated magnetic gear or simply field-modulated magnetic gear [72]; its basic configuration is illustrated in Figure 7.

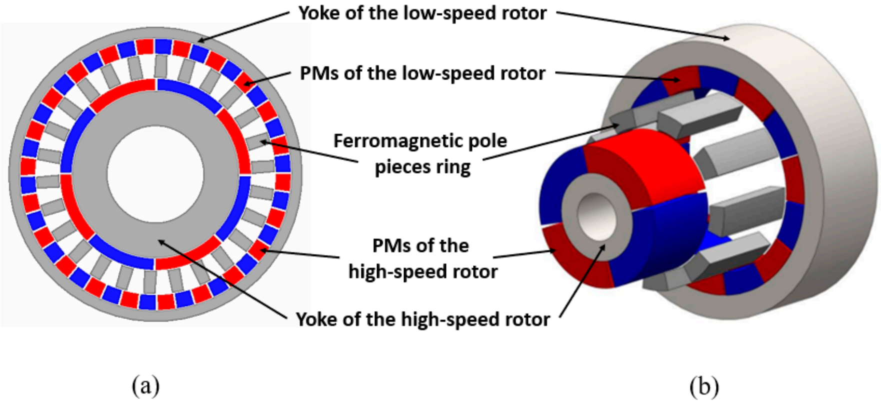


Figure 7. Field modulating magnetic gear. Main elements of its active components: (**a**) Front view; (**b**) Isometric view.

The field-modulated magnetic gear is closely related to the planetary magnetic gear converted from its mechanical equivalent. Figure 8, an analogous operation between the two can be clearly seen, with the external rotor acting as the ring gear, the internal rotor as the Sun gear, and the stationary steel pole pieces (modulator) acting as planetary gears (due to their rotating magnetic field, not precisely due to the pole pieces themselves). Note that, in contrast to the planetary magnetic gear version converted directly from its mechanical analog (Figure 8a), the field-modulated magnetic gear topology (Figure 8b) evidently has fewer moving parts [67].

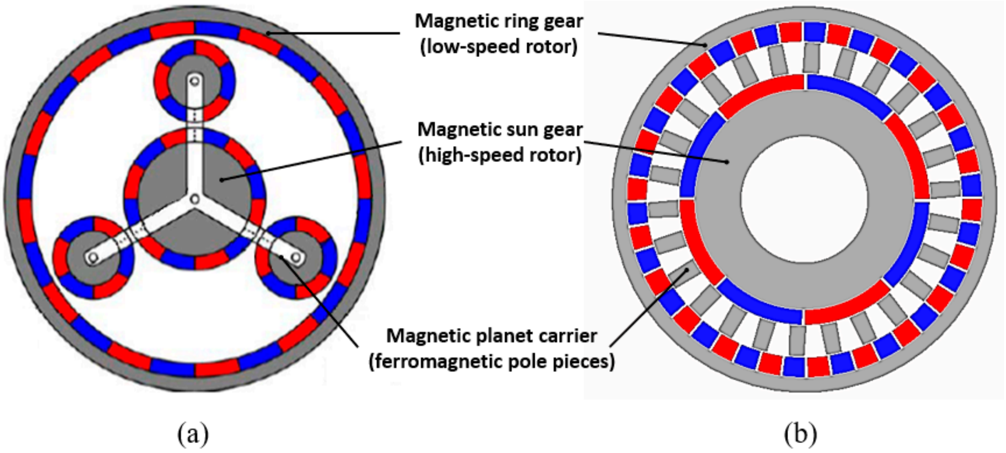


Figure 8. Magnetic gear: (**a**) Planetary type; (**b**) With field modulation.

Due to its operating characteristics, it is common to identify the Atallah design as a concentric planetary magnetic gear [73] or a coaxial planetary magnetic gear [74]. However, it is clear that such a design corresponds to a radially magnetized coaxial magnetic gear. This terminology may not be appropriate since other designs have continued to evolve, preserving the concept of field-modulated gear but with changes in the topology and arrangement of its components.

From the design point of view, magnetic gears can be organized into two main types: on the one hand, there are traditional conversion magnetic gears, which are derived from replacing steel teeth with magnetic pole pairs from permanent magnets; in these, the mechanical toothed gear is replaced by a magnetic field coupling. Although this type of direct conversion magnetic gear can avoid the drawbacks caused by physical contact transmission, its performance has no comparative advantage compared to its mechanical equivalents. On the other hand, there are field-modulated magnetic gears, which are not derived from an analogous mechanical gear. In this type of magnetic gear, the gear effect is carried out by modulating the magnetic fields of the permanent magnets with the ferromagnetic segments located between the two rotors. In addition to having a non-physical contact operation, these gears provide a high torque density comparable to that of mechanical gears.

Field-modulated magnetic gear topology was presented in 2001 [68]. Then, with simulation studies, the torque density was investigated, showing results greater than 100 kNm/m^3. The details of its design, the principle of operation, and the analysis of its performance were explained in 2004 by the same Atallah's team [75] using an experimental prototype with a transmission ratio of 5.75:1, which reached a torque density of 72 kNm/m^3 and an efficiency higher than 97%. Perhaps its main merit is the concentric arrangement of its three structures, which allows all the permanent magnets to contribute simultaneously to the transmission of torque. Eighteen years after its introduction, new studies with an optimized coaxial concentric magnetic gear design, with surface-mounted permanent magnets and radial magnetization, achieved torque densities of 274 kNm/m^3 with 2D-based finite element analysis (FEA) simulations and 210 kNm/m^3 with 3D FEA simulations [76].

The concentric, coaxial, field-modulated magnetic gear with surface-mounted rare-earth permanent magnets in both rotors and radial magnetization has become a benchmark for the basic topology of high-performance magnetic gears because its configuration has proven to have a capacity to achieve high torque density and high efficiency. As a result, many of the advances in the field of magnetic gears have been reported around this design. In fact, the term magnetic gear is currently used as a synonym for this topology [72].

A considerable amount of research work, some with designs and prototypes, has continued to be developed to improve the performance of the flux-modulated magnetic gear of concentric and coaxial structures. Based on this approach, numerous configurations have been presented that ultimately seek to optimize the design parameters to obtain a higher torque density and better efficiency in the mechanical power transmission process, objectives aimed at strengthening its application in the industrial environment. Although this topology has proven to be quite efficient and have a high performance, it was presumed from the beginning that surface-mounted permanent magnets in rotors would present mechanical integrity problems. These arguments were verified when the first version of the efficient magnetic gear matured and was studied in detail [76–78].

One way in which the effort of researchers, academics, and developers in the evolution of magnetic gears can be measured is to consider how the permanent magnets have been used to carry out magnetic coupling, with a focus on the direction of its magnetization. In this context, two basic topologies stand out: the topology with a linear design and the topology with axial flux. Their original standard designs are shown in Figure 9.

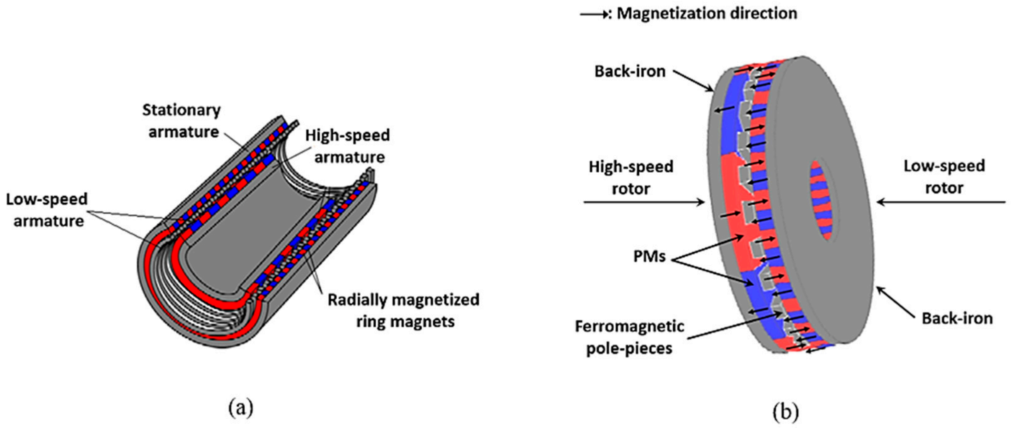


Figure 9. Magnetic gear: (**a**) Topology with linear design; (**b**) Axial flux topology.

The linear magnetic gear has a tubular topology, as shown in Figure 9a [79]. Its operating principle is similar to that of the coaxial magnetic gear with radial flux described in [75]. Simulation studies have shown that this topology can achieve a transmitted force density greater than 1.7 MN/m^3. Furthermore, an investigation which used a prototype built for an aerospace application concluded that the linear design is sensitive to the axial separation between the rings of ferromagnetic parts [80]. In this reference, it was argued that, when combined with a permanent magnet linear machine, the linear magnetic gear can offer significant advantages, such as its application in the energy generation from the sea waves. This fact that was studied, analyzed, and confirmed in subsequent publications [81–84].

The axial flux magnetic gear consists of two disk-shaped rotors, each with surface-mounted permanent magnets that alternate their north and south poles, from which flux is obtained in an axial rather than a radial direction. A modulating ring of ferromagnetic pole pieces is located between both rotors, thus forming a sandwich-type structure. The design is shown in Figure 9b [85]. In the same way, as for the linear design, the axial type is described with the same principle of operation given for the coaxial magnetic gear with radial flux. In its original publication, the axial topology reported a torque density exceeding 70 kNm/m^3 in simulation studies, pointing out that the axial forces exerted on high- and low-speed rotors are relatively low. Furthermore, the publication mentioned that this topology is suitable for applications that require hermetic insulation between the input and output shafts, mainly in pumps for the chemical and pharmaceutical sectors, which are also valuable for the food and aerospace industries [85]. However, its simple design would soon attract attention to investigate its potential applications in other industries, such as wind power, details that are mentioned in the next section.

The study of the first topologies developed by Professor Atallah's team triggered the modern development of high-efficiency magnetic gears. The first works focused on the study of the excitation sources of magnetic gear. These sources are represented by radially magnetized rare-earth permanent magnets. It was discovered that the flux density in the air gaps (air spaces separating the rotors from the modulator ring) varies significantly with the design of each rotor, primarily with the way the permanent magnets mounted on the cores are used. Then, different arrangements were proposed in the permanent magnets, guiding the work towards the direction of their magnetization and the exploration of new geometric configurations to reduce their volume, which gave rise to the topologies shown in Figure 10.

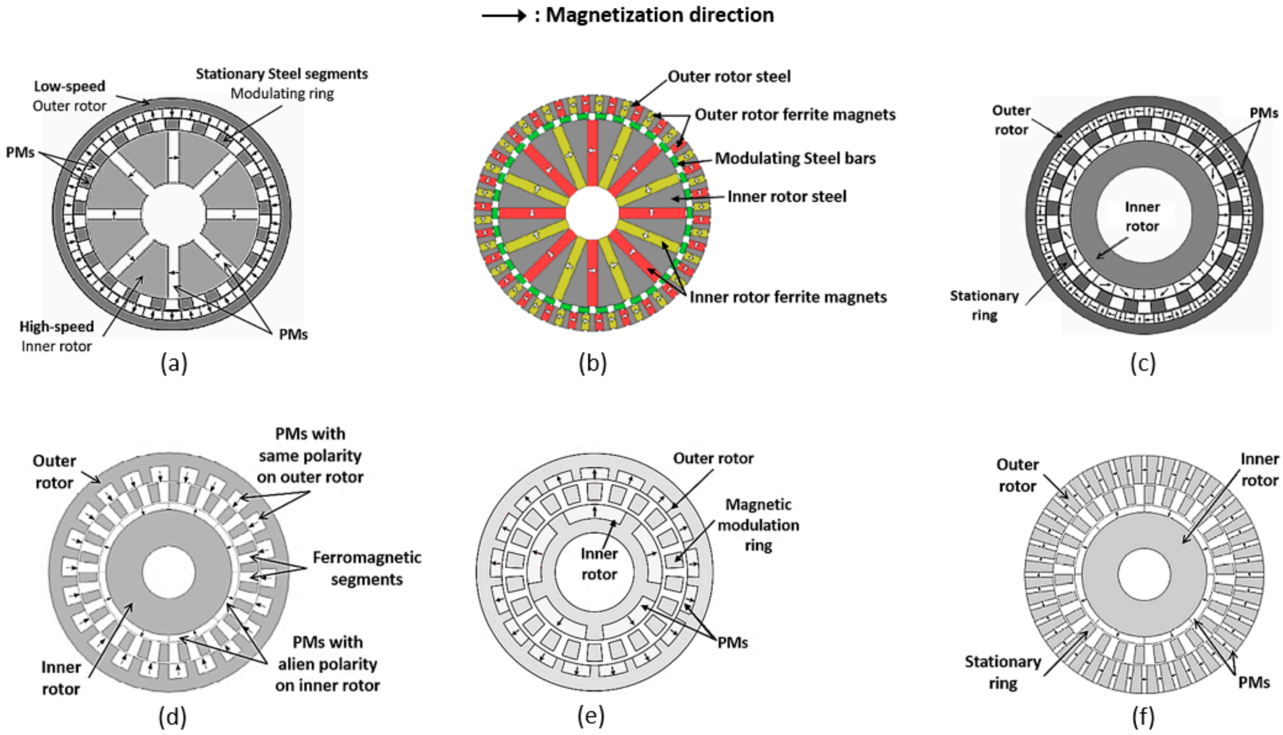


Figure 10. Field-modulated coaxial magnetic gear topologies: (**a**) Spoke-Type Coaxial MG Tangentially Magnetized—Inner Rotor; (**b**) Spoke Ferrite MG; (**c**) Surface-Mounted Coaxial MG Halbach Magnetized; (**d**) Coaxial MG Same-Polarity Magnetized—Outer Rotor; (**e**) Coaxial MG Radially Magnetized, Same-Polarity—Both Rotors; (**f**) Surface-Mounted Coaxial MG Tangentially Magnetized—Outer Rotor.

Rasmussen [86] proposed a topology to strengthen the mechanical structure of the conventional magnetic gear, configuring the high-speed inner rotor with rectangular permanent magnets magnetized in the tangential direction, arranged like a spoke wheel instead of surface-mounting, as shown in Figure 10a. Finite element simulation and prototype testing showed a torque density of 92 kNm/m^3. The theoretical efficiency was 96%, but only 81% was achieved, and this reduction could be attributed to constructive details in the prototype. It was proposed to explore other designs that included complete optimization in their construction. With this same scheme, Uppalapati [87], in a later work, proposed a low-cost system using ferrite magnets in a topology with a flux approach in both internal and external rotors. The design is shown in Figure 10b. Experimental results reported a torque density of 239 Nm/L. However, due to the usage of solid steel in its components, the eddy current losses were high, reducing the efficiency of the design.

A Halbach permanent magnet array can increase the magnetic field on one side of the array, canceling it on the opposite side. Halbach [88] and Choi [89] showed that this arrangement allows a strong field intensity and flux density in the air gap to be quite acceptable. Jian [77,90] incorporated the Halbach arrangement into the coaxial magnetic gear in a surface-mounted permanent magnet design. This topology is shown in Figure 10c. The results in the simulation studies verified a torque density 13% higher than that calculated in the conventional topology. However, when considering centrifugal forces and mechanical stresses, the surface-mounting of the magnets does not make this design appropriate for transmissions where high speed or high torque are required. In addition, the Halbach topology experiences difficulties in achieving a good mechanical assembly. Fujita [91] observed that all the stationary pole pieces of the modulator contribute to the transmission of torque when the permanent magnets are surface-mounted. Such an observation led him to propose a coaxial magnetic gear with an optimized shape of its stationary pole pieces and a Halbach arrangement on the high-speed rotor magnets (inner rotor). With an analytical model, it was concluded that, with the proposed poles, the torque transmission could be increased by more than 15% compared to conventional poles. Som [92] carried out studies and experiments with a coaxial magnetic gear with Halbach magnetization, concluding that although this topology can generate a high torque compared to the conventional topology, it still has difficulties achieving a suitable practical implementation.

Liu [93] proposed and implemented a topology for the concentric magnetic gear like the one shown in Figure 10d. An important feature of this design is that, while in the inner rotor there are permanent magnets in a conventional arrangement, i.e., mounted on the surface with alternating polarities, in the outer rotor permanent magnets which are magnetized with the same polarity are inserted along the circumference in the iron core. This is in an attempt to improve the mechanical integrity of the gear and reduce the material of the permanent magnet in an effort to maintain the torque transmission capacity. As a result, the volume of permanent magnets was significantly reduced to 16.5%, but the low number of these materials in the prototype's external rotor decreased torque density, reaching 53.3 kNm/m^3. Shen [94] made an exhaustive study of this topology, proposing a magnetic gear in which all the magnets in each rotor, external and internal, are magnetized in the same radial direction. Figure 10e shows the proposed topology. In addition, he built a prototype using ferrite magnets to reduce costs. With minor modifications in its geometry, this topology managed to reduce the volume of the number of permanent magnets to 75% in the external rotor and 80% in the internal rotor, with an improvement in torque density of 24%, all compared to the values obtained in another prototype with the surface-mounted topology.

Li [78] modified the topology proposed by Rasmussen [86]. Li's design consisted of placing the permanent magnets on the surface of the internal rotor with radial magnetization, while the magnets in the external rotor, with a radial-type rectangular shape, had tangential magnetization, as shown in Figure 10f. In 2D finite element simulation studies, a torque density very close to that obtained by Rasmussen at 98.1 kNm/m^3, approximately 25% higher than the value of conventional topology, but with small additional ripples in the torque. In a later investigation, Jing [95] worked with Li's topology, obtaining a torque density of 162.31 kNm/m^3 with 2D FEA simulation studies. Jing explained that this increase in torque density was due to changes the research team made to the geometry of the inner rotor permanent magnets and tangential magnetization of the outer rotor permanent magnets.

Other topologies preserve the coaxial design with field modulation and present different configurations in the geometry and arrangement of its components. Although these topologies do not exhibit high torque densities, they are interesting proposals that seek to achieve the qualities of high-performance magnetic gear in their designs. Figure 11a shows a configuration proposed by Frank [96,97], consisting of a concentric magnetic gear with a reinforced stationary modulating ring and rectangular permanent magnets with parallel magnetization in the inner rotor. The design in Figure 11b was proposed by

Abdel-Khalik [98] and constitutes concentric magnetic gear without bearings, with levitation windings embedded in the pole pieces acting as a magnetic suspension. Figure 11c illustrates the topology presented by Liu [99] following the coaxial magnetic gear concept but with curved magnetic flux modulators, resulting in a design for applications where the axes do not intersect. The topology in Figure 11d was presented by Aiso [100] and relied on salient poles in the high-speed (inner) rotor to develop a simple and robust structure, thus achieving a reluctance magnetic gear for transmission at high speeds. Figure 11e is the design of a magnetic gear with transversal-flux topology, introduced and analyzed by Yong [101] with the intention of increasing mechanical resistance in the weakest parts of the concentric topology while maintaining a high torque density. Bomela [102], with a slight variation in the design of this transversal topology, improved the torque density, albeit with a result well below that which can be obtained by concentric magnetic gear with radial flux. Subsequently, Desvaux [103], in an experimental study, concluded that the transversal topology presents limitations for many applications. However, it is interesting to note that the concept of transversal flux, whose design has similarities with the axial topology, appears to be one of the designs that, after the concentric topology with radial flux, has presented promising application proposals in machines with permanent magnets which are used in power generation systems utilizing wind energy [104–107].

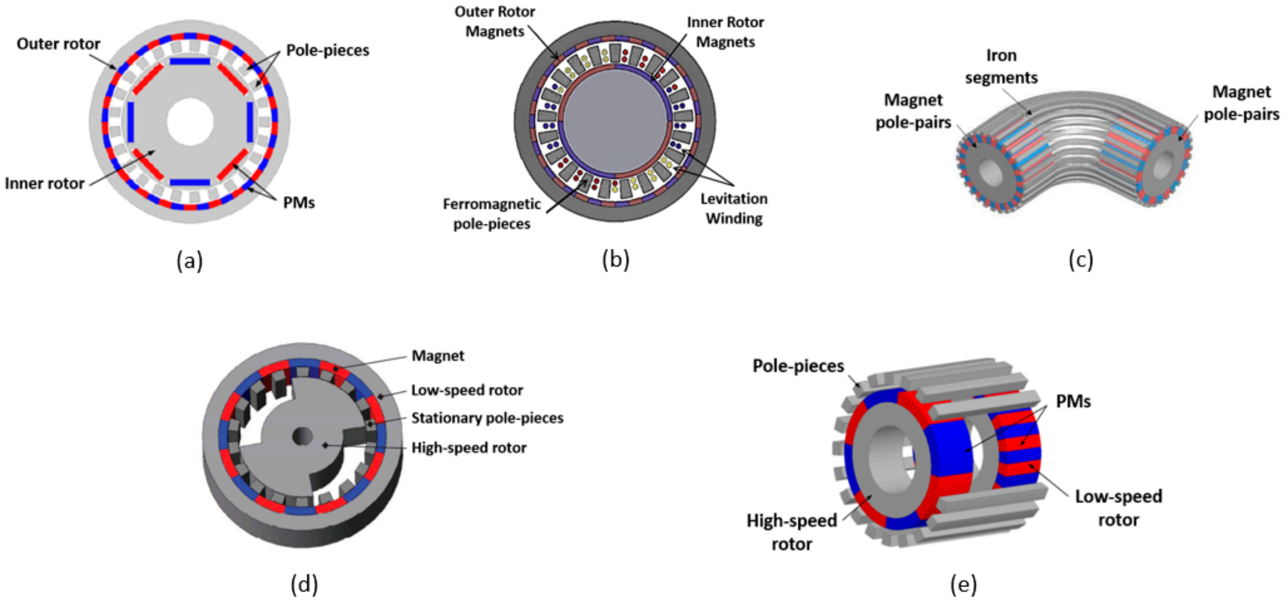


Figure 11. Variations of flux modulated coaxial magnetic gear topologies: (**a**) Surface-Mounted Coaxial MG with interior PM rotor; (**b**) Bearingless Coaxial MG: magnetic planetary gear with magnetic suspension; (**c**) Intersecting-axes MG; (**d**) Reluctance MG; (**e**) Transverse flux MG.

Many topologies, based on coaxial magnetic gear with flux modulation, have been proposed to reach a model that obtains a high torque density to allow for optimal mechanical power transmission. Most of these topologies depend on the selection and configuration of some design parameters and on how the permanent magnets have been used to provide the magnetic flux, focusing on their magnetization direction. The dynamic evolution with which magnetic gear technology has developed makes it possible to understand why many publications present the results of their research arguing by for high-performance topologies when they first reach solutions that had not been shown before. However, if the main objective is to have topologies with high performance, without limiting any of its parameters, geometries and structures that are different from the configuration of the coaxial arrangement are necessarily considered. Some of these retain their essence, but others inevitably give rise to new approaches. These topologies would not only be evaluated in terms of torque density and efficiency but also consider appropriate gear ratios and a balance between cost, weight, and volume. Some concepts proposed to satisfy these characteristics, with acceptable results, are shown in the designs of Figure 12, and they are traditional conversion structures that adopt eccentric rotation in some of their components.

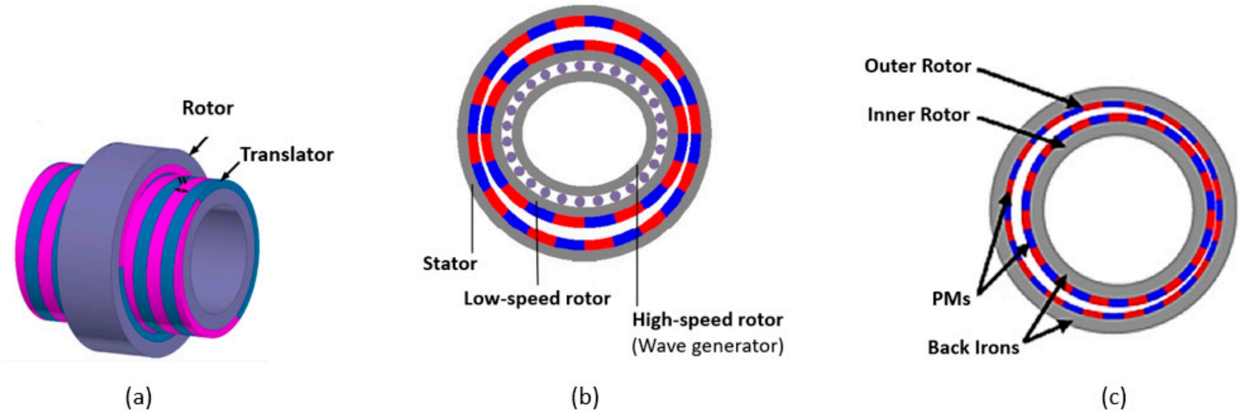


Figure 12. Magnetic gear designs with modulated flux and different from the coaxial concept: (**a**) Trans-Rotatory MG; (**b**) Magnetic Harmonic Gear; (**c**) Cycloidal MG.

The trans-rotary magnetic gear, shown in Figure 12a, was designed to convert linear to rotary motion. It was presented and experimentally analyzed by Pakdelian [108–111]; his proposals include applications for wave power generation [112,113]. Figure 12b corresponds to the topology of a harmonic magnetic gear studied by Rens [114,115]; it is suitable for applications that require high gear ratios (greater than 20:1). However, its implementation is complicated since it requires a flexible low-speed rotor.

A topology that considerably attracts the attention of researchers and developers, mainly due to the degree of efficiency it presents, is that of the radial flux cycloidal magnetic gear, shown in Figure 12c. This topology was presented by Jorgensen [116], indicating that it is potentially capable of achieving high torque densities and high gear ratios with high levels of efficiency. In Mexico, the cycloidal design was extensively studied analytically and experimentally by Chicurel Uziel [117], leaving an invaluable legacy of dissemination on the subject of magnetic gear transmissions [118]. However, even with all the virtues that the magnetic gear with cycloidal topology has for potential applications in magnetic transmissions, its construction is still more complicated than that of the coaxial concentric type. This might explain why most research and development work has turned to concentric magnetic gearing with field modulation. However, a more reasoned judgment on this possible conclusion can be made based on the results of Gardner's work [119]. In his article he argues that, for low gear ratios, the optimal coaxial topology generally achieves higher torque densities than the optimized cycloidal topology and, conversely, at medium and high gear ratios, the cycloidal gear can outperform the coaxial gear, with certain limitations on magnet thickness since the cycloidal topology varies with some design parameters, such as its outer radius. Gardner concludes that the cycloidal structure faces significant manufacturing challenges, primarily because the axis of one rotor must orbit the axis of the other.

Based on the magnetic gear topologies discussed above, those with high torque density, high gear ratio, and high efficiency can be summarized into three categories according to their design: concentric, harmonic, and cycloidal, considering their potential application to replace the gearbox in a power transmission system. Table 1 presents a summary of the main MGs technologies discussed in this section; the advantages, disadvantages and characteristic torque density are detailed.

Table 1. Summary on Magnetic Gears Topologies.

Magnetic Gear Topology	Advantages	Disadvantages	Performance	Figure	Reference Number
Linear MG	To convert linear motion to electrical power.	Only a portion of the magnetic material is in use during its operation. Sensitive to the axial separation between the rings of ferromagnetic pole pieces.	Transmitted force density >1.7 MN/m^3 (calculated).	Figure 9a	[79]
Axial MG	Compact design. Suitable for applications that require hermetic insulation between the input and output shafts.	Lower torque density compared to coaxial topology due to the impact of axial forces.	Torque density: 70–289.8 kNm/m^3 (calculated).	Figure 9b	[85]
Spoke-Type Coaxial MG Tangentially Magnetized-Inner Rotor	Flux-concentrating effect and high mechanical reliability.	Large end-effects. Significant reduction of torque capability when compared with the surface-mounted PM configuration.	Torque density: 92 kNm/m^3 (calculated). 54.5 kNm/m^3 (measured). Torque ripple: 0.79%	Figure 10a	[86]
Spoke Ferrite MG	Low-cost (using ferrite magnets). Relatively high torque.	High eddy current losses due to the usage of solid steel in its components.	Torque density: 84.4 kNm/m^3 (calculated).	Figure 10b	[87]
Surface-Mounted Coaxial MG Halbach Magnetized	15% higher torque density, 67% reduction in cogging torque and 28% reduction in the total iron losses over a conventional one.	It is difficult to assemble mechanically. Not suitable for practical implementation.	Torque density: 110.7 kNm/m^3 (calculated). 108.3 kNm/m^3 (measured).	Figure 10c	[77,88–92]
Coaxial MG Same-Polarity Magnetized—Outer Rotor	High mechanical integrity and reduced PM material while maintaining torque transmission capability.	Torque density is decreased because of the lower PM consumption at the outer PM rotor.	Torque density: 55.8 kNm/m^3 (calculated). 53.3 kNm/m^3 (measured).	Figure 10d	[93]
Coaxial MG Radially Magnetized, Same-Polarity—Both Rotors	Exhibits superior attributes of lower PM volume but higher transmission capacity. Higher cost effectiveness of ferrite MGs, and slightly larger losses and end-effect.	The actual pull-out torque is slightly lower than the calculated one because the MG end caps are made of steel, a quality which may cause more flux leakage in the axial direction and thus weaken the effective field.	Torque density: 35.4 kNm/m^3 (calculated). 23.2 kNm/m^3 (measured).	Figure 10e	[94]
Surface-mounted Coaxial MG Tangentially Magnetized—Outer Rotor	Better torque density than Spoke-Type Coaxial MG. Flux-focusing effect.	An increase in ripple torque compared to Spoke-Type Coaxial MG.	Torque density: 98.1 kNm/m^3 (calculated). 54.5 kNm/m^3 (measured). Torque ripple: 1.12%	Figure 10f	[78]
Surface-Mounted Coaxial MG—Interior PM Rotor	Inner rotor designs with both interior and spoke-type PM configurations are considered. Both configurations significantly reduce torque capability when compared with the surface-mounted PM configuration.	The PMs on the inner rotor are subjected to large centrifugal forces during high-speed operation,	Torque density: 64 kNm/m^3 (calculated). 42 kNm/m^3 (measured).	Figure 11a	[96,97]
Reluctance MG	It can operate in high-speed regions because the structure of a high-speed rotor is very simple and robust.	Torque density and efficiency should be improved with optimization design if it is to be used for high-speed motors.	Torque density: 29.4 kNm/m^3 (calculated).	Figure 11d	[100]
Transverse Flux MG	Significantly easy manufacturing.	Low torque density.	Torque density: 80.6 kNm/m^3 (calculated).	Figure 11e	[102]
Trans-Rotatory MG	It can convert high-torque, low-speed linear motion to high-speed, low-torque rotation. Hence, it is highly applicable to wave energy.	Only a portion of the magnetic material is in use during its operation.	Force density: 10 MN/m^3 (calculated).	Figure 12a	[108–113]
Magnetic Harmonic Gear	Suitable for applications that require high gear ratios (greater than 20:1). It exhibits high torque density.	Complicated structure. Its practical implementation is complicated by the need for a flexible PM low-speed rotor.	Torque density: ≈110 kNm/m^3 (measured).	Figure 12b	[114,115]
Cycloidal MG	It presents extreme torque density and a very high gear ratio.	Complicated construction.	Torque density: 141.9 kNm/m^3 (calculated). 106.8 kNm/m^3 (measured).	Figure 12c	[116,119]

In addition to torque density, a key criterion applied to evaluate the performance of an MG is efficiency. MGs have a similarity to electrical machines that have permanent magnets and windings which are characterized by high efficiencies, such as permanent magnet synchronous machines with efficiencies greater than 95%. One way to determine the efficiency of an MG is to consider the power losses that occur in each component during its operation.

Figure 13a shows an elementary schematic of a mechanical power transmission system based on a coaxial MG with radial magnetization topology. Its operation is based on the principle of modulation of the magnetic flux.

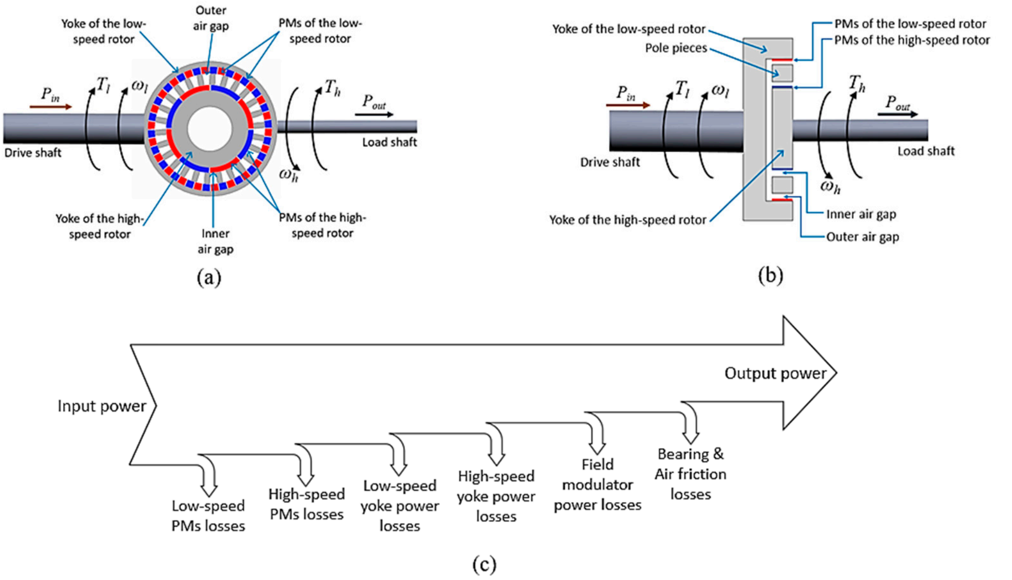


Figure 13. Essential elements of an MG for the transmission of mechanical torque: (**a**) Elementary schematic of a transmission system based on a Coaxial MG; (**b**) Basic components of the Coaxial MG; (**c**) Power losses in a Coaxial MG.

The modulation effect consists of the fact that the magnetic fields produced by the rotors of the magnetic gear, when passing through the pole pieces, become modulated fields, thereby creating spatial harmonics in the air gaps. The modulated field of one rotor interacts with the magnetic field in the air gap of the other rotor to transmit torque between both rotors, like what is done in a mechanical transmission, only now without physical contact.

Figure 13b shows how the main components of the MG interact. Since the gearing effect in the MG is carried out without mechanical contact, power losses during transmission are reduced to losses in ferromagnetic materials (rotor yokes and pole pieces of modulator), bearings and air friction. However, when using PMs as excitation sources to achieve high magnetic torque, eddy currents inevitably occur in ferromagnetic materials, causing the highest losses in mechanical power transmission.

Figure 13c presents a diagram showing the flow of power losses in an MG. All these losses are the cause of a reduced torque in the transmission. Amongst of the key goals of engineers, developers and researchers is the reduction of these losses to obtain high performance magnetic gears. In principle, everything indicates that selecting powerful permanent magnets, preferably rare-earth magnets, and using low conductivity ferromagnetic materials could lead to MGs with high torque density and high efficiency for practical applications.

4. Magnetic Gears in WECSs

Horizontal-axis wind turbines conventionally use mechanical gears in the drive train to transmit mechanical power from the rotor to the electrical generator. The basic configuration of this transmission system is schematized in Figure 14a. It consists of a gearbox that allows matching the low-speed, high-torque output of the blade shaft from the rotor to the high-speed, low-torque shaft at the input of the generator, which is usually a permanent magnet machine characterized by its high torque density. However, due to the inherent problems of the mechanical gear mechanism, an important segment of the wind turbine industry chooses to avoid using the gearbox by adopting a direct drive system to move the generator directly from the rotor blades, as shown in Figure 14b.

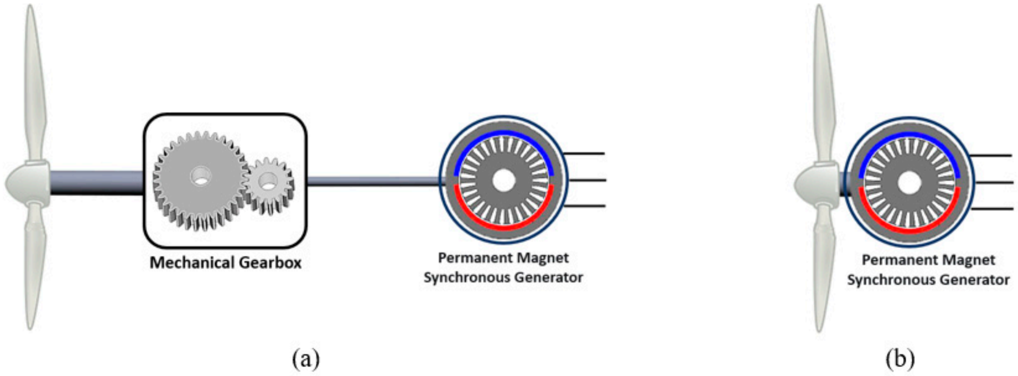


Figure 14. Powertrain of a wind turbine: (**a**) Conventional scheme: mechanical indirect drive; (**b**) Traditional direct drive.

Although the direct drive is a real solution to avoid the problems associated with the gearbox, the generator required is of large dimensions, causing weight and size problems in the wind generation system. Therefore, faced with these drawbacks, an alternative is using magnetic gears.

Magnetic gears have shown themselves to possess excellent operation and torque transmission capabilities, competitive with those of mechanical gears [75], and electrical machines with permanent magnets have important advantages compared to electromagnetically excited machines [120]. These qualities have led to the study of different ways of combining magnetic gears with electrical machines with the purpose of achieving a scheme to provide a transmission with high performance. For this, the magnetic gear with concentric modulated flux topology has been considered the most suitable, mainly because it presents an optimal use of the permanent magnets in its internal and external rotors and a high torque density. Moreover, due to its geometry, this device acquires the capacity to integrate with a permanent magnet machine for applications in wind systems. However, to achieve maximum powertrain performance in practical applications, it is essential to consider factors related to system volume, weight, and cost. This gives rise to the fact that research, in addition to focusing on achieving a transmission with high torque density and high efficiency, also focuses on finding simple and more compact mechanical structures with better use of permanent magnets and lower manufacturing costs [121]. The interest in optimizing the power train in a wind turbine, to the point of eliminating the problematic mechanical transmission elements, has prompted researchers to adopt the approach of schemes in which practically the electric generator can be driven directly by the wind turbine's blades. The result is the magnetic gear-integrated permanent magnet machine, illustrated in Figure 15a [122].

The permanent magnet machine, integrated with magnetic gear, is a topology formed by a coaxial magnetic gear mechanically coupled to a permanent magnet generator to share a common high-speed rotor. This configuration is intended to maximize the benefits of both elements found in a single arrangement with high torque density and high efficiency.

The design, in addition to presenting a more compact and lighter system compared to the traditional direct drive, offers to overcome the failures in transmission with mechanical gears. In wind turbines, this topology would for allow direct wind capture with the blades mounted on the external rotor structure of the magnetic gear, with torque and speed parameters that make it extremely attractive for wind power systems. Currently, studies on this topology continue at an experimental level with different configurations, guiding research to improve the performance of this machine. Some works have presented prototypes for application in wind turbines [121–124].

Other topologies use the above concept to optimize the wind energy conversion system [125]. If a set of coils is also added to the low-speed external rotor to produce an additional magnetic field, by which the speed and direction of rotation of the internal rotor can be controlled, the machine becomes a scheme identified as pseudo-direct drive [126]. In this topology, a flux-modulated coaxial magnetic gear and a permanent magnet generator are mechanically and magnetically coupled. The structure of this design is shown in Figure 15b [127]. In wind system applications, the low-speed external rotor of the magnetic gear is driven directly by the shaft of the wind turbine blades, while the high-speed internal rotor is coupled with the rotor shaft of the electric generator in a single structure. This topology was developed by the British company Magnomatics® and is already available on the market, being promoted for several applications [128], pointing out that pseudo-direct drive systems for wind turbines include the largest magnetic gear ever manufactured so far [129]. The pseudo-direct drive was used to build the prototype of a wind energy conversion system, using an asynchronous machine to represent the dynamics of the wind turbine rotor [130]. Computer simulation and experimental tests demonstrated that the proposed system offers lower volume and weight characteristics and higher energy efficiency than a traditional direct drive system. Other published works have investigated the concept of pseudo-direct drive in prototype wind turbine powertrains [131–135]. A variant of the conceptual structure with mechanical and magnetic coupling is the doubly fed brushless generator for electricity generation with wind power [136–138]. It consists of a configuration identical to the coaxial magnetic gear, in which the permanent magnets of the rotors have been replaced by two stationary windings fed by an alternating current (AC) excitation; the only rotating element is the modulator, which is driven by the mechanical power source (wind turbine rotor) in a coaxial arrangement between the internal and external windings. In this topology, the voltage of the outer winding, connected to the electrical network, is adjusted according to the speed of the ferromagnetic pole pieces of the modulator, which depends on the wind speed, in order to operate the machine at its maximum power. The low-speed operation of this design represented an attractive direct-drive scheme for small wind generation systems, with reduced cost due to the elimination of permanent magnets and reduced transmitted torque.

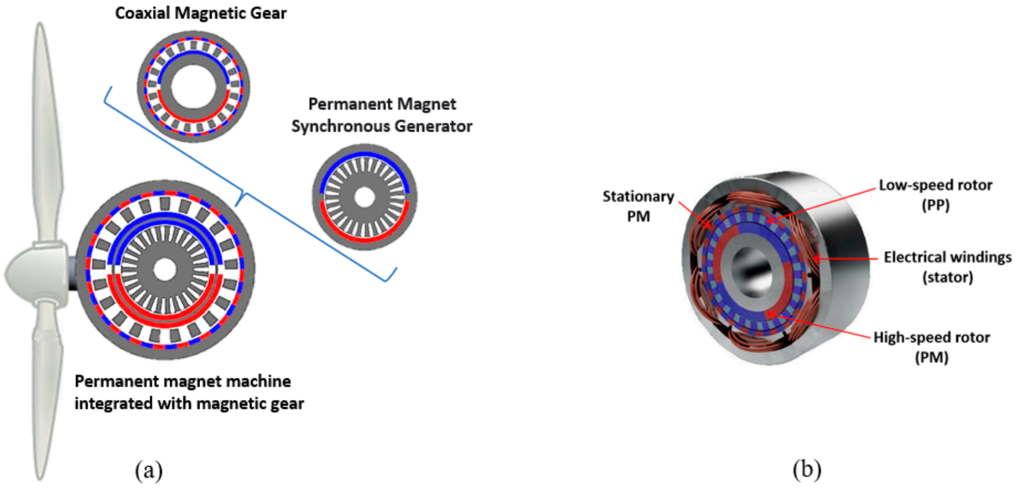


Figure 15. Powertrain configurations in a wind turbine using magnetic gear technology: (**a**) Permanent magnet machine integrated with magnetic gear [122]; (**b**) Pseudo-direct drive [127].

A study of the topologies described in [125] details that the integrated machine and the pseudo-direct drive are characterized by a direct integration scheme of a coaxial magnetic gear, a permanent magnet generator, and, therefore, a higher torque density compared to hybrid schemes that have at least one permanent magnet rotor of the magnetic gear replaced by an armature winding. However, they have the drawback of a mechanically complex structure and a tendency to cause reliability problems in the mechanical power conversion system. On the other hand, the topology of the doubly fed generator, which is a conceptual structure of a magnetic gear in which the permanent magnets have been replaced by windings, is exposed as the simplest when operating with a single rotating element; however, these devices have a much lower torque capacity, this being one of the weaknesses of the topologies that combine permanent magnets and armature windings. These are identified in some works as modulated flux machines [139–141].

It is clear to understand that, for a practical application in wind turbines, the integration of a magnetic gear with an electric generator is a desired alternative because it offers the advantages of a direct drive scheme for low-speed and high-torque operations. Another alternative is an electromagnetic gear which would further reduce the space occupied in the system. However, it is already known that, even presenting high efficiency and competitive torque densities for wind power generation, the integrated machine has drawbacks related to its manufacture. In addition, the electromagnetic gear, with a simpler structure and the possibility of wider ranges of speed, may exhibit less torque capacity.

Additionally, it is known that the coaxial magnetic gear with radial magnetization has a simple structure in which the efficient use of permanent magnets allows it to offer a high torque density for application in wind power systems. Although a magnetic gear can carry out a mechanical power transmission, using it as the only element of the drive train, it is still a passive transmission since it does not have electrical input or output ports like the electromagnetic gear.

To avoid the complex structure of an integrated machine, the simplest method is to replace the gearbox in the conventional scheme with a magnetic gear. This is then mechanically coupled with a high-speed permanent magnet synchronous generator, as shown in Figure 16. This scheme is identified as an indirect magnetic drive [142] or magnetic gear semi-direct drive [143]. It has been proposed as an intermediate solution between the conventional mechanical indirect drive scheme and the traditional direct drive, highlighting the merits of the coaxial magnetic gear with radial magnetization in overcoming the disadvantages of a mechanical transmission and pointing out the competitiveness of this topology for applications in wind power generation systems.

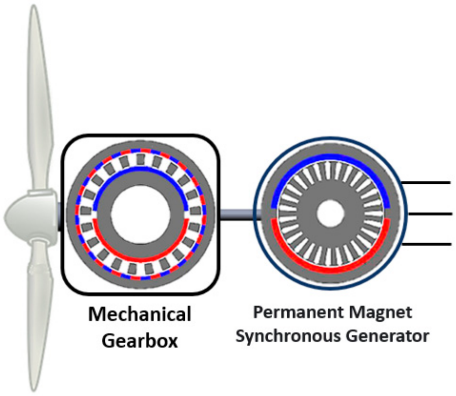


Figure 16. Illustration of the powertrain in a wind turbine. Conventional scheme: magnetic indirect drive.

In this comprehensive review of gear-based mechanisms, it can be seen that magnetic gears represent an important emerging technology that is being investigated for optimal mechanical power transmission. It has been seen that, in the two decades of development, many topologies have been presented depending on the selection of design parameters and how rare-earth permanent magnets have been used. Furthermore, different structural concepts have been highlighted in which magnetic gear technology is incorporated into electrical machines to achieve an optimal performance scheme in the wind turbine powertrain.

During the second decade of this century, the research works that study the different magnetic gear designs for applications in wind turbines have multiplied, addressing questions to improve their torque density and optimize their topological structure. The scheme that has received the most attention is the concentric one with radial magnetization [144–164], but proposals have also been presented considering other topologies. Such is the case of the linear magnetic gear which, as mentioned, when studied led to applications for wave energy [81–84,165,166]. Other topologies, no less important, correspond to the trans-rotary magnetic gear, with applications in wave power generation [112,113], and to the transversal flux magnetic gear for applications in wind turbines [104–107]. The permanent magnet Vernier generator, which can be categorized as an integrated machine with magnetic gear, is added to these topologies [167,168]. This type of machine is proposed as a quite reasonable alternative for a direct drive scheme in wind turbines, mainly because it offers a high torque density due to the magnetic gear effect in its architecture [160,169–176].

Although various structural concepts have been presented around using magnetic gears for wind turbine applications, this topic is still in full swing. The current results indicate that the coaxial concentric topology continues to be the most studied. However, there remains a structure with a concentric architecture whose research still needs to concluded, this being the magnetic gear with axial flux. Apart from having a simpler design for manufacturing than the radial flux design, the axial topology also offers potential applications to operate as part of the drive train in wind turbines. Even though the axial flux magnetic gear has also been studied as part of the structure of integrated machines [177–184], there are few publications that directly include this topology in studies with applications in mechanical power transmission [170,185–187]. Therefore, this topic is a subject that opens the possibility of continuing with its study to obtain a closer look at its architecture and probe the possibility of an application in wind power systems. Figure 17 shows the number of publications that have reported research on the potential applications of MGs in WECSs has evolved during the two decades that have elapsed in this century.

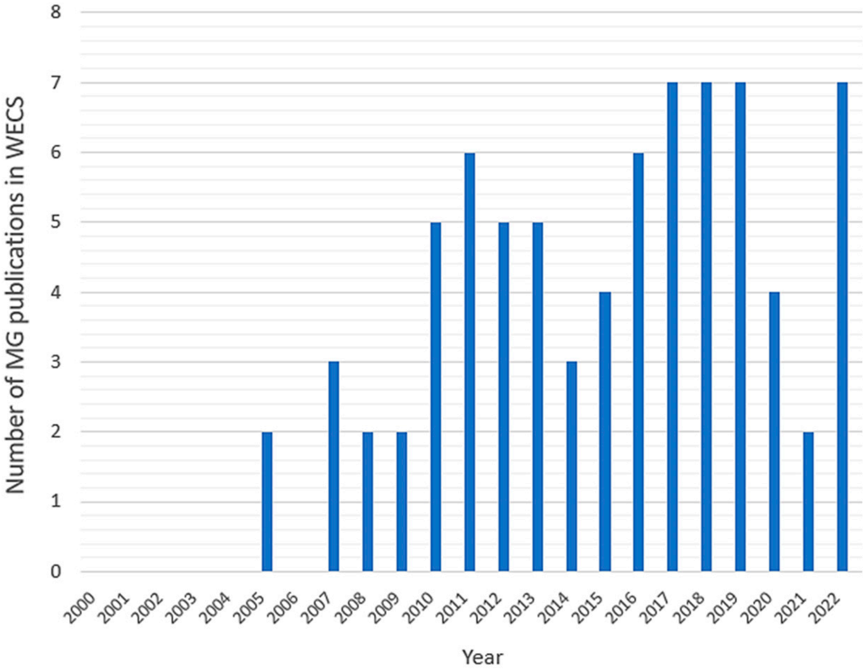


Figure 17. Publications of MGs applications in WECSs.

5. Magnetic Gears in Transportation (EVs)

Nowadays, one of the most pursued goals in a conscious society is to reduce environmental pollution to care for the environment; the automotive industry has begun to play an important role in achieving this purpose. In addition to reducing harmful emissions to our planet's atmosphere, automobile manufacturers also seek to improve the performance of the systems involved in the transmission of mechanical power, where noise and vibration reduction, minimization of dimensions, and maintenance simplification are of key concern. This fact has considerably increased interest in magnetic gears as an emerging technology whose potential uses in industrial applications can provide benefits in caring for the environments where the activities of living beings occur. Typically, in an EV, the mechanical power from the electric motor is transferred to the drive wheels via a single ratio transmission performed with a mechanical gearbox. Unlike the gearbox in a wind turbine, the gearbox in an EV has only one driving gear operating as a step-down transmission to provide an appropriate speed and torque to the traction wheels of the car. The application of MGs in EVs, and in general, in transportation systems, is similar to its use in WECSs because the application is specifically focused on the mechanical power transmission system. Many researchers have made excellent contributions to the application of MGs to various transportation systems, mainly EVs and HEVs.

Most of the published works use the scheme of the PM electrical machine integrated with magnetic gear, as presented in Figure 14. The works of the researchers team led by K. T. Chau stand out [188–193]. Other works investigate the use of cycloid magnetic gear in the power transmission system for hybrid vehicles (HEVs). [194]. In [195], a magnetic-planetary-geared permanent magnet brushless machine for HEVs is presented. In [66], a new type of in-wheel motor for EVs, namely a magnetic planetary geared outer-rotor permanent-magnet brushless (PMBL) motor, is proposed. An excellent investigation, related to the development of magnetic gears for transportation applications, is presented in [196]. Recent research on this topic focuses on optimizing designs that employ MGs in EV applications [197].

Since the first developments with high-efficiency MGs were presented at the beginning of this century, interest in their application in transportation, mainly in EVs and HEVs, has increased significantly, as shown in the histogram of Figure 18.

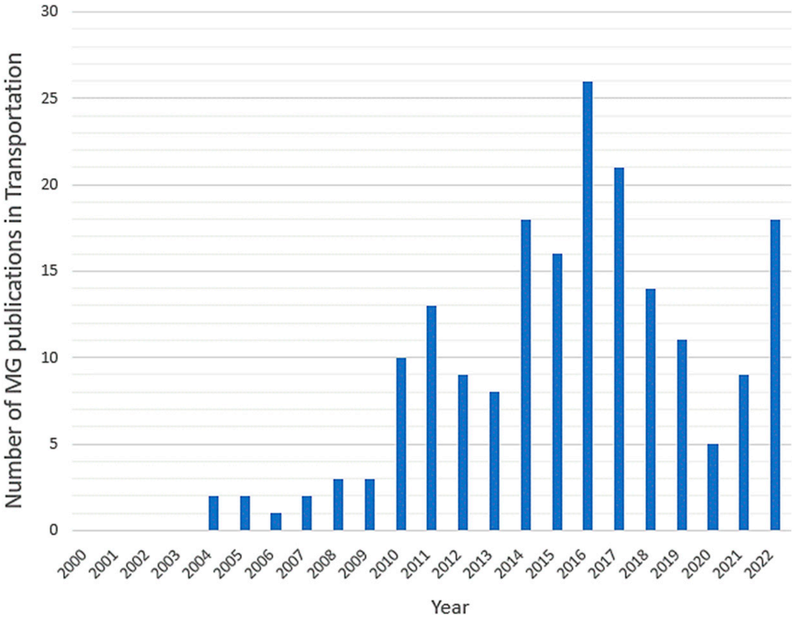


Figure 18. Publications of MGs applications in Transportation.

6. Conclusions

This paper has presented a comprehensive review of magnetic gear technologies for mechanical power transmission, focusing on wind turbine and transportation applications. This survey has attempted to gather and discuss all the investigations that have given impetus to using MGs in practical applications. In the histograms presented, it can be clearly seen that, on the subject of mechanical power transmission, the investigations are inclined to experiment in transportation systems, mainly in EVs and HEVs. Therefore, this topic is a subject that opens the possibility of continuing to studying MGs in order to understand this technology better and work on the possible applications in wind power systems. From the authors' point of view, the content of this paper can help readers get a clear and comprehensive overview of the importance of MG technologies in the industry.

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