Review of Magnetic Gear Technologies and their Applications in Marine Energy

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Abstract

The objective of this paper is to present a summary of the state of the art in magnetic gear (MG) technology and then investigate its particular opportunities in marine energy device applications. As an introduction, a brief reflection on the state of the marine energy industry is given and the environment in which marine energy converters (MECs) operate is discussed. A brief overview of MG development over the past century is given and then the leading technologies are discussed in greater detail with the advantages of MG systems stated. In order to demonstrate the potential of MGs in marine applications the prevailing machines, i.e mechanically geared and direct drive machines, are examined in terms of sizing, reliability and economic value using previous studies on a similar technology, namely wind. Finally MGs are conceptually applied to three types of MECs to demonstrate how existing technologies can be quite easily adapted to incorporate the technology and gain the advantages mentioned.

1 Introduction

With an estimated 95 Twh/yr of tidal energy and 69 TW/yr of wave energy in the UK alone [1], combined marine energy presents a promising economical opportunity and has led to the development of numerous devices focused on harnessing this resource. These devices vary quite substantially depending on how they interact with the marine energy be it a tidal stream or wave (heave, pitch etc) and the orientation of their power take off (PTO) systems. Though a wide range of devices exist at various stages of development, there are common issues that exist across many designs that present obstacles to their full scale deployment as viable alternative options to standard energy sources.

When compared to onshore renewable technologies, wind in particular, a key obstacle is the significantly higher operation and maintenance (O&M) costs associated with any offshore installation including specialised equipment, heightened health and safety requirements, and the need for weather windows to perform necessary maintenance and repair procedures. This is exacerbated by operating in the harsh environments usually associated with marine energy i.e high wave height, strong tidal flows and a highly saline environment. Additionally, the forces these devices can encounter during normal operation can vary greatly with storms and irregular sea conditions requiring most devices to have a high degree of survivability. These associated costs have resulted in a focus on low failure, robust systems.

The low frequency element of both wave and tidal stream energy is not conducive to convenient electrical energy production at 50-60Hz. This has often resulted in the need for mechanical gears in systems that employ a traditional electrical machine generator, such as an induction machine or field wound synchronous machine. This is problematical as studies in wind energy, which is perhaps the closest comparable technology, have shown that gear systems are a leading cause of down time with the highest associated costs to repair [2]. When added to a highly saline marine environment there is increased chance for failure of mechanical transmission elements. Alternatively, in order to eliminate this source of failure, direct drive systems have been proposed [3]. However direct drive generators are much larger requiring high pole number and robust power electronics that have been shown to result in collectively similar down times as a geared system [4].

A number of researchers, designers and developers have proposed intermediate energy conversion and conditioning steps using mechanical or hydraulic means in order to step down force/torque and step up speed and sometimes to convert linear bidirectional motion into unidirectional rotational motion which is generally the easiest input to produce electrical power. The downside of these intermediate steps is that they can have poor efficiency and reliability and O&M issues.

A possible solution to these issues is the magnetic gear (MG) concept or similar pseudo direct drive systems that offer reduced mechanical failure rates while allowing a smaller, higher frequency machine. Furthermore the MG has advantages over its mechanical counterpart, namely contactless torque transmission, greatly reduced lubrication requirements, inherent overload protection and the option for parts of the system to be hermetically sealed. This paper reviews MGs as a technology and discusses its particular advantages to marine energy.

2 Magnetic Gears

Other papers are already available which give an extensive review of MG development over the past 100+ years [5, 6]. Therefore this paper will only give a summary of the main developments of the technology and focus on the designs that the authors feel are most relevant to marine energy.

2.1 Early Magnetic Gears

Magnetic gears have been of interest since the early 20th century with the earliest designs being very similar to conventional mechanical gears with the gear teeth replaced with magnetic counterparts [7, 8]. However these designs received little attention, most likely due to the low torque densities achieved as a result of the permanent magnet (PM) materials available at the time (namely SmCo5). A renewed interest came in the 1980s with the development of neodymium iron boron (NdFeB) magnetic material though the designs still relied on direct mechanical substitution, thus resulting in poor PM utilisation and never achieved torque densities high enough to compete with traditional mechanical alternatives. [9, 10]

2.2 Modern Magnetic Gears

As of the turn of the century there are three types of MG that can be classified as modern as they have comparable torque densities to that of traditional mechanical gears (50-150kNm/m^3 for a helical gear and 100-200kNm/m^3 for a spur type gear). These are the field flux modulator gear (FMMG), the harmonic gear and the magnetic planetary gear (MPG) types as shown in Figure [1].

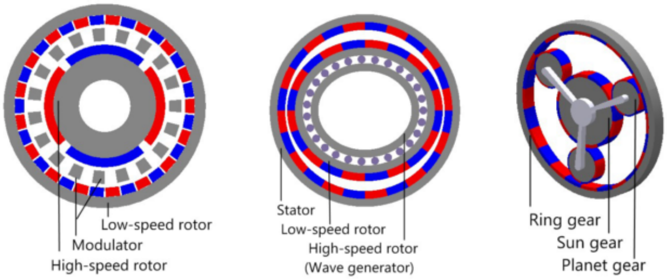

Figure 1: Concentric, harmonic and magnetic planetary gears. [5]

In 2001 Atallah and Howe proposed what is generally considered the leading design for MGs, the Concentric Magnetic Gear (CMG) [11]. Though a similar design can be seen in T. B. Martin's 1968 patent, "Magnetic transmission" [12], it was in Atallah and Howe's paper that the design's high torque capabilities were demonstrated.

The CMG falls into the category of FFMG in that they employ ferromagnetic segments in the airgap between the rotors in order to modulate the magnetic flux. This design allowed for full utilisation of all PM material and resulted in high torque density in the range of 70-150 kNm/m^3 with a relatively simple design. Additionally, after proposing the CMG Atallah *et al.* demonstrated two other forms of this MG, the linear and axial field models [13],[14] as can be seen in Figure [2]. This adaptability makes the FMMG design particularly useful in marine energy where a number of PTOs exist depending on how the device interacts with the incoming waves or tidal stream.

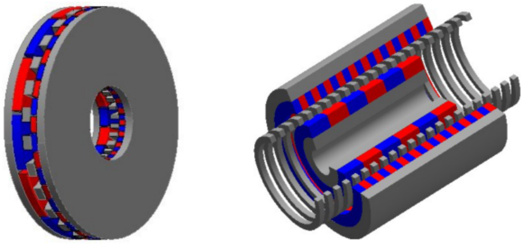

Figure 2: Disc-type and linear type concentric MG topologies. [5]

There are two modes of operation with this type of MG. Either the ferromagnetic poles are held stationary and the outer and inner magnetic rotors are allowed to rotate, or the ferromagnetic poles are allowed to rotate with one of the other rotors held stationary. The modes affect the possible gear ratio and the direction of rotation. The number of ferromagnetic segments for all three topologies are related by:

$$n_{\mathrm{s}} = p_{\mathrm{l}} + p_{\mathrm{h}} \tag{1}$$

where n_s, p_l and p_h are the ferromagnetic pole pairs, the magnetic pole pairs on the low speed side and the magnetic pole pairs on the high speed side respectively. The gear ratio G_r, with the ferromagnetic segments held stationary, is then determined by:

$$G_{\mathrm{r}} = \frac{p_{\mathrm{l}}}{p_{\mathrm{h}}} = \frac{(n_{\mathrm{s}} - p_{\mathrm{h}})}{p_{\mathrm{h}}} = \frac{-\omega_{\mathrm{h}}}{\omega_{\mathrm{l}}} \tag{2}$$

where ω_{h} and ω_{l} are the rotational speeds of the high and low speed rotors respectively. The minus sign here indicates that the rotors will rotate in opposite directions. Alternatively, with the ferromagnetic elements allowed to rotate and the outer low speed rotor held stationary the gear ratio is as follows:

$$G_{\mathrm{r}} = \frac{n_{\mathrm{s}}}{p_{\mathrm{h}}} = \frac{\omega_{\mathrm{h}}}{\omega_{\mathrm{s}}} \tag{3}$$

where ω_{s} is the rotational speed of the ferromagnetic segments. Thus the rotors will rotate in the same direction and a slightly higher gear ratio is achievable. There is a limiting factor with pole number in that it is found that with higher ratios, large harmonics become an issue. There are also physical constraints due to minimum magnetic pole size.

The harmonic gear [15] has shown very promising torque densities in the range of 150 kNm/m^3. Though attractive for its torque density, high gear ratios and smooth torque transmission, it is complicated to construct and relies on a flexible low speed rotor to produce a time-varying sinusoidal variation of the magnetic field in the airgap between the rotors. The gear ratio of a harmonic gear is given as:

$$G_{\mathrm{r}} = \frac{(-1)^{(k+1)} p_{\mathrm{w}}}{p_{\mathrm{l}}} \tag{4}$$

with p_l and p_w the number of poles on the low speed rotor and the number of sinusoidal cycles between low speed rotor and stator respectively and k represents the various asynchronous space harmonics which are associated with each harmonic of the magnetic field produced by the permanent magnets.

The MPG proposed by Cheng-Chi Huang *et al.* [16] which operates like a traditional mechanical planetary gear has reported torque densities of over 100 kNm/m^3 and offers the same advantage of 3 transmission modes along with magnetic gears contactless advantages and no lubrication requirements. Its gearing ratio is determined by:

$$G_{\mathrm{r}} = \frac{p_{\mathrm{r}}}{(p_{\mathrm{s}} + p_{\mathrm{r}})} \tag{5}$$

where p_{r} and p_{s} are the pole-pairs on the magnetic ring gear and sun gear respectively with the pole-pair relationship on the planetary gear determined by:

$$p_{\mathrm{p}} = \frac{(p_{\mathrm{r}} - p_{\mathrm{s}})}{2} \tag{6}$$

As with the harmonic gear the MPG is capable of high torque densities and gearing ratios but is more complex than the concentric design. Additionally not all magnetic material is utilised during torque transmission.

A special note is made for a recent development by Dave Rodgers *et al.* who, as of 2015, developed a variation on a conventional worm and wheel gear with helical magnetic arrangement [17]. Experimentation has shown potential gearing ratio exceeding 100:1 and airgap sheer stress in the range of 485kNm/m^2 thus far exceeding previous magnetic gear capabilities. Reportedly successful in both computer modeling and prototype demonstration, as a very new technology further verification and demonstration of operation is required. Additionally, being a worm type gear, the high shear stress will be localised in a small part of the machine and utilisation of total PM material will be low.

3 Application to Marine Energy

While MGs have been suggested for the electric automotive and aerospace industries where size, efficiency and low O&M costs are of key concern, MG technology is also highly attractive for marine energy applications.

The following section discusses its usefulness when considering machine sizing and reliability drawing from established machine sizing formula and studies conducted into the wind industry. Finally a brief discussion is included on some of the inherent advantages of MG technology.

3.1 Machine Sizing

The physical size of machines is of particular concern for offshore installations. Larger devices make transport difficult and when installing require specialised equipment like ship mounted cranes which can be very expensive to rent. The overall size of an electrical machine is governed by a few well established equations. The power ratings of the machine is directly related as follows:

$$P = T\omega \tag{7}$$

where ω is the rotational speed in radian/s and T is the torque in Nm which can be calculated as:

$$T = Fr = \sigma A r = \sigma 2\pi r^2 l \tag{8}$$

where F is the equivalent force (in Newtons), σ is the shear stress in N/m^2 in the airgap, A is the area (m^2) of the airgap, r and l are the radius of the airgap and length of the machine respectively. Thus the volume of the machine is inversely proportional to the rotational speed as follows:

$$V = \frac{P}{\omega 2\sigma} \tag{9}$$

Therefore in order to have a small, compact machine a high rotational speed is required. With the low frequencies associated with wave and tidal energy a speed enhancement system, usually a mechanical gearbox will be incorporated into the device. The alternative is a very large direct drive machine which, as well as transport issues, has additional issues that are discussed in the following section.

3.2 Mechanical Gear vs Direct Drive for Marine Energy Devices

Substantial published information on O&M is currently unavailable for marine devices. As mentioned, wind energy, in particular offshore wind, bears a high degree of similarity in terms of machine conditions and frequencies. A critical analysis of the trends will be made in order to demonstrate MGs potential as a viable third option.

Mechanical gearboxes are regarded as having a critical effect on reliability as the associated down time per failure is high compared to other turbine components [18],[19]. Furthermore, despite advancements traditional gearboxes have yet to achieve design life goals (20+ years), often requiring substantial repairs or overhauls [20]. This can be largely attributed to the physical interaction between mechanical elements under force. This is potentially exacerbated in a highly saline environment with irregular loadings.

In the paper Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines [21] Henk Pollinder *et al.* examined and compared 5 different generator concepts (namely:

namely doubly fed induction generator with 3 stage gearbox [DFIG3G], direct-drive synchronous generator with electrical excitation [DDSG], direct drive permanent magnet generator [DDPMG] , permanent-magnet generator with single stage gearbox (PMG1G) and DFIG with single stage gearbox [DFIG1G]) with the comparison focused on cost and annual energy yield for a given wind climate. The results of the comparison found that while the industry standard DFIG3G was the lightest and lowest costing it suffered from low energy yield with high losses, 70% of which are associated with the mechanical gearbox. Furthermore, it was noted that since the machine consists mostly of components consisting of copper and iron, major improvements and cost reductions cannot be expected. The DDPMG, though more expensive due to its size and power converter requirements, was shown to have the highest energy yield. Additionally a key point was that unlike the DFIG3G further improvements can be reasonably expected due to the improvement in power electronics, the expected reduction of PM material cost and further optimisation and integration of the generator system. Thus it would suggest that using direct drive systems and eliminating the gearbox associated O&M costs would result in a superior machine. However along with requiring a physically larger system there are further issues.

In [4] David McMillan *et al.* established a techno-economic comparison of operational aspects between direct drive (DD) and gearbox-driven (GD) wind turbines by providing analytical calculations regarding the availability of traditional wind turbine devices. From this a clearer understanding of the technical and economic merits of DD and GD systems can be gained. The paper supposes that the assumption that DD systems have reduced maintenance issues due to the elimination of those associated with a gearbox only holds if all other factors remain unchanged and highlights findings that indicate much higher failure rates of electrical components and generators of DD turbines when compared to GD equivalents. Though the paper excluded consideration of PM machines due to the lack of deployment, it provides some interesting results with regards to DD vs GD machines. The results state that while DD is marginally better in terms of availability, looking at revenue generated suggests GD machines have a much larger economic benefit and that from an economic analysis GD machines are still preferable unless manufacturing costs of direct drive technology can be significantly reduced. Nonetheless, it was surmised that the operational availability of DD can be significantly higher than GD as long as the majority of generator failures are minor electrical failures as opposed to severe mechanical failures (e.g bearing problems).

Tavner *et al.* [22] found that DD systems were less reliable due to increased generator, inverter and electrical system failures. However the authors recognised that overall availability would also be affected by component repair times. i.e mean time to repair for a gearbox is much more than electronics. This issue becomes much more relevant in offshore installations as extensive work can be greatly delayed due to accessibility, weather windows, equipment and vessel availability.

In [23] Echavarria *et al.* analysed a similar data set and found that DD systems have twice the generator failures as GD equivalent systems and that the power electronics had an aproxiamtely 50% higher failure rate in DD synchronous machines compared to an induction machine equivalent. It should be noted that electronics have greater opportunity for design redundancy, taking HVDC [24] as an example , which could be applied. A MG system then, could potentially result in a superior system which combines the higher frequency, smaller and lighter machines without the O&M costs associated with a mechanical gear.

3.3 Magnetic Gear Advantages

Survivability is a key concern for MECs which are often subjected to extreme conditions. The inherent overload protection of MGs has great potential in marine energy where forces can vary dramatically depending on environmental conditions. The nature of a magnetic gear allow the rotors to slip in the event of excessive force applied without damage occurring to the gear components and will naturally realign under normal operations. This contrasts with mechanical gears which in a similar event could result in significant damage. Additionally, the lack of interlocking parts greatly reduces the systems requirements for lubrication, though bearing lubrication will still be required.

Finally, as torque is transfered contactlessly, additional options are available with regards to system sealing with sections being optionally hermetically separated, which can be of great benefit when considering machine marinisation.

4 Integration of Marine Energy Converters with Magnetic Gears

This section looks at three marine energy devices that would benefit from MG integration. The chosen devices have very different power take off (PTO) systems and operating principals in order to demonstrate the wide applicability of MG's in this area.

4.1 Tidal Turbine

The horizontal axis bladed tidal turbine [25] device is perhaps the most straight forward comparison with wind turbines due to the similarities in machine orientation and power take off. For this type of MEC, a system similar to that proposed in [26] is suggested. This design uses a CMG coaxially coupled with a permanent magnet generator (PMG) demonstrated by Figure [3]. The outer rotor of the CMG is connected to the blades which capture the incoming fluid energy directly. The proposed gear ratio was 7.33 considering an average wind speed of 7m/s. This may have to be increased for a tidal rotor as tidal stream velocities are noted as being commercially viable at 2.5-3.2 m/s. To emphasize the advantages of this design a comparison was made to two similarly rated machines, a standard planetary geared machine and a direct drive machine. Through standard sizing calculations it was found that the MG machine (MGM) was the lightest and smallest. Additionally when a cost analysis of the systems was undertaken (focusing on material costs only) while the MGM was more expensive than a PMG it was still cheaper than the DD option. A prototype was built to demonstrate the functionality of the proposed system and achieved high torque values. The proposed system is directly applicable to a tidal turbine though further considerations would have to be made regarding marinisation.

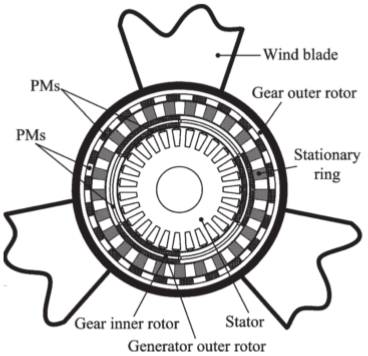

Figure 3: Proposed tidal turbine MG system option [26]

4.2 Heaving Buoy Wave Energy Converter

Point absorber, heaving buoy wave energy converters work by a simple concept of using a buoyant structure that oscillates with incoming waves. The PTO of these devices can be quite complicated however due to the linear nature of the devices primary motion. There have been some proposed models that use a linear generator [27] but due to the low frequency a large amount of poles are required and there is poor utilistation of magnetic materials. As previously mentioned, K. Atallah has proposed a linear magnetic gear device. This would allow for direct conversion of the heave motion of a buoy type system without linear to rotational mechanisms such as a rack and pinion or ball-screw systems [28].

In [29] a proposed serially integrated system saw the use of a linear magnetic gear cascaded with a linear PM generator. This allowed the high speed mover of the gear and the translator of the generator to share the same shaft. With the proposed design the low speed mover of the magnetic gear is coupled with the heaving buoy structure as shown in Figure [4]. As the buoy rises and falls with wave propagation the high speed mover connected to the linear generator's speed is amplified by a factor of the gear ratio. A similar rated machine without the MG system was calculated to have a volume 4 times that of the proposed system and with greater volumes of PMs, iron cores and copper windings (167% 214% and 271% respectively) would have a considerably higher cost. Additionally, the gearless machine was calculated to have higher copper losses. Thus while greatly reducing cost and volume the proposed machine has a greater efficiency and power density.

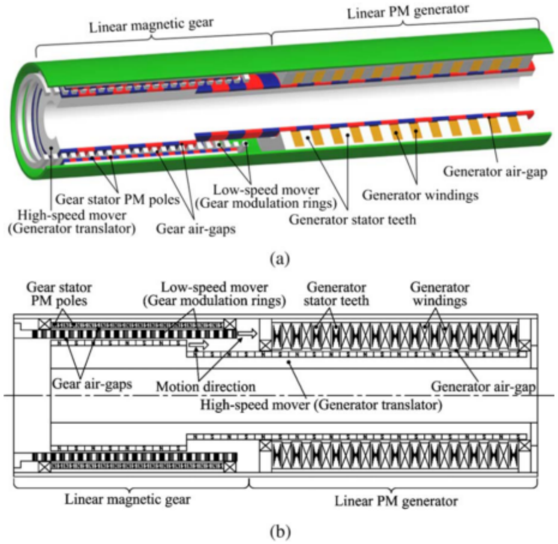

Figure 4: Proposed heaving buoy MG system option (a) Solid model. (b) Schematic[29]

4.3 Oscillating Wave Surge Converter

In their report funded by n-power juice [30], Ozan Keysan *et al.* looked at the Aquamarine Oyster oscillating wave surge converter with the aim of suggesting an optimal generator topology as opposed to the hydraulic system then employed. Of the three motion types (linear, full rotational and partial rotational) the fully rotational was found to be the most advantageous.

Secondly, the speed torque characteristics were analyzed. With an average speed of 0.45rpm and 164kW average power, the high torque requirements and very low speed meant that a direct drive solution resulted in a heavy, low efficiency generator. By using a single stage gearbox with gear ratio of either 10-15:1 the generator efficiency was increased to 90% and reduced the total mass substantially. In the proposed design, two C-GEN generators [31] with two gearboxes would be attached to each side of the Oyster flap. The gearboxes are coupled to the the devices flap shaft with the gearbox output shaft connected to the torque arm of the generator. It is proposed to substitute the mechanical gearboxes suggested in the report with axially orientated MGs [14]. Thus the same overall design can be maintained and though the MG would be potentially of a lower ratio and more expensive than a traditional mechanical gear, with its inclusion in the system similar efficiencies and mass reductions can be expected. Also, as previously discussed, the axial model theoretically allows for greater sealing options between rotors lending the machine to greater marinisation. Although the Aquamarine Oyster has been discontinued, similar devices like the Langlee Robusto [32] and the AW-Energy Ltd WaveRoller [33] are based on similar concepts that could also benefit from MG adaptation.

5 Conclusion

This paper demonstrated how MG technology is directly suited to a variety of marine energy devices. The comparison established between geared and gearless systems found that although in gearless systems O&M benefits from the elimination of a mechanical speed enhancement element, the resulting machines are large and expensive. The magnetic gear is a potentially ideal compromise having the benefits of both topologies. To further demonstrate the applicability the technology was conceptually applied to 3 existing marine energy devices with varied PTO systems using existing proposed MG designs.Though currently expensive, reductions can be expected with systems being mass produced and with similar torque values as mechanical gears, along with great reductions in O&M costs and overload protection, MGs can be an economically and functionally superior option in MECs.

Further work is suggested to compare the true cost benefit of using a MG machine over traditional systems. This would involve predicted savings in O&M costs offset against the high material and construction costs. Furthermore, the designs conceptually outlined in this paper should be investigated to develop strategies for marinisation and general MEC integration.

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