

MARINE HYDROKINETIC POWER TAKE-OFF USING MAGNETIC GEARING

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ABSTRACT

This paper reviews different power take-off approaches for rotary based marine hydrokinetic power generation. The technology for wind power generation is used as a guide. A discussion on the potential benefits of utilizing magnetic gearing is presented.

INTRODUCTION

In order for marine hydrokinetic (MHK) power generation to have a chance at being competitive with conventional power generation technology the power take-off (PTO) system needs to be low-cost while at the same time it must be exceptionally reliable, efficient, robust and environmentally benign [1-4]. Due to limited weather windows and associated logistical challenges regular servicing of the PTO system is highly cost prohibitive in most marine locations and therefore improvements in durability and reliability will significantly impact the leveled cost of energy. This paper will review and compare current rotary based ocean PTO technology options and evaluate the potential benefits of using a magnetically geared PTO approach.

ROTARY BASED OCEAN POWER TAKE-OFF SYSTEMS

Rotary based ocean power generation systems are in some ways analogous to the generation technology that has been developed for wind power conversion. However the MHK generators must contend with operating at lower input speeds and with significantly higher mass flow rates [5-7]. Various PTO technologies have been proposed and the main approaches are summarized in Figures 1 to 5. Figure 1 shows the fixed speed PTO approach in which a squirrel cage induction generator (SCIG) is directly connect to

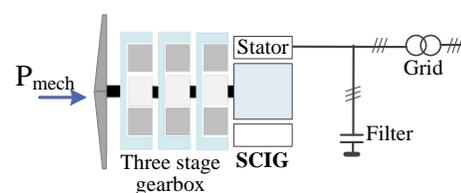


FIGURE 1. SQUIRREL CAGE INDUCTION GENERATOR (SCIG)

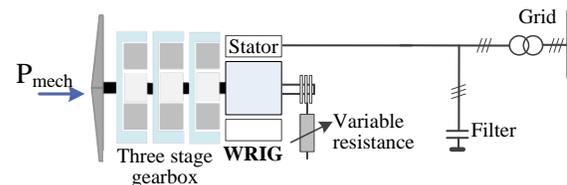


FIGURE 2. VARIABLE SPEED OPERATION WITH WOUND ROTOR INDUCTION GENERATOR (WRIG) USING RESISTANCE CHANGE

the grid via a transformer. In a fixed speed turbine the MHK torque fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. This approach does not enable any type of electrical speed control it also requires a stiff grid in order to handle power fluctuations. The mechanical construction must also be sufficiently robust to handle the high mechanical stresses caused by the fixed speed operation. This approach is often called the “Danish concept” [8]. Verdant Power is an example of a MHK company that is currently using this approach [9]

A second approach, as shown in Figure 2, involves using a wound rotor induction generator (WRIG) in which the rotor winding resistance is variable. This approach enables the speed to be changed by up to 10% above synchronous speed [10]. The amount of speed variation is limited by the size of the winding resistance. This

amount of speed change improves performance but at the cost of increased losses within the rotor winding. The technique was extensively used by wind turbine maker Vestas in the 1990's [11]. The need for brushes and slip rings were eliminated by using an optically controlled converter.

The third approach, as shown in Figure 3, also involves using a winding on the rotor however the electrical slip frequency on the rotor is actively controlled by a power electronic converter and this enables the electrical frequency to be always synchronized with the grid. This approach is often called the doubly fed induction generator (DFIG) technique [8, 12-15]. As only the slip power is applied to the wound rotor (via brushes) the power electronic converter only needs to be rated to around 30% of the total generating power [8, 12, 13]. With this design input speeds within the range of $\pm 30\%$ of the synchronous speed can be handled. Although the DFIG has been used in a number of near-shore oscillating water column generators [16] it has not been utilized extensively for offshore MHK generation [17]. This is likely due to the need for replacing the rotor brushes as well as concerns for gearbox reliability.

The fourth option is to use a direct-drive (DD) approach in which either a wound rotor synchronous generator (WRSG) or permanent magnet synchronous generator (PMSG) is directly connected to the input shaft of the MHK device. Such a PTO approach is shown in Figure 4. In this case the rotary speed is completely variable and the full power flows through the stator and converter to the grid. The converter then has to be rated for the total generating capability and therefore this increases the power electronic conversion costs. In addition, as a gearbox is not used the torque capability of the DD generator must be very high. The torque density of traditional electrical generators are much lower than for a mechanical gearbox and therefore the generator becomes massive in size [18-21]. The advantage of this approach is that the power can be generated over the full speed range and the gearbox is eliminated. Columbia Power Technologies [22], Ocean Renewable Power Company [23], Free Flow Power [24] and Alstom [24] are examples of companies that have used a DD-PMSG approach. For cost and reactive power control reasons the majority of wind turbines were using the WRSG approach however this trend is starting to change.

A fifth option is to use a gearbox in series with the PMSG or SG, this approach is shown in Figure 5. The gearbox could have a lower gear ratio than that used by the DFIG. This approach results in a more compact design and still enables the speed

to be controlled over the full speed range. This fifth approach is being looked at for use in very high power wind generators because otherwise the size of the DD generator becomes prohibitively large [25].

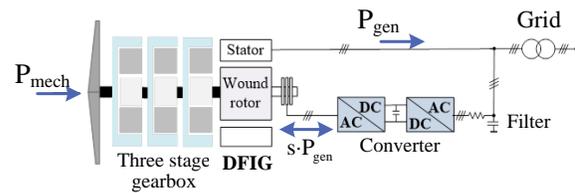


FIGURE 3. DOUBLY-FED INDUCTION GENERATOR (DFIG)

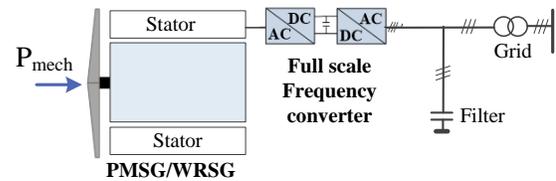


FIGURE 4. WOUND ROTOR SYNCHRONOUS GENERATOR (WRSG) OR PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

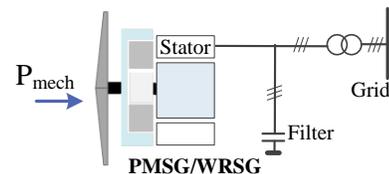


FIGURE 5. PERMANENT MAGNET SYNCHRONOUS GENERATOR OR WOUND-ROTOR SYNCHRONOUS GENERATOR WITH GEAR-BOX

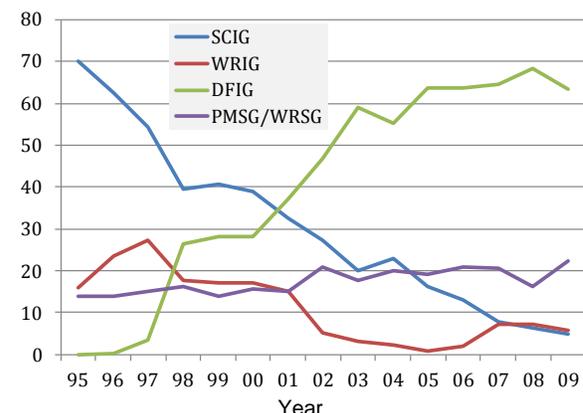


FIGURE 6. WORLD SHARE OF YEARLY INSTALLED WIND POWER FOR DIFFERENT WIND TURBINE POWER TAKE-OFF APPROACHES [10]

The use of these different PTO techniques by the wind industry between 1995 and 2009 is illustrated in Figure 6 [10]. It can be seen that early on the fixed speed SCIG was very popular due to its simplicity. However as the wind turbine industry matured and performance was more important the DFIG and to a lesser extent the WRSG/PMSG approach gained in popularity. The

DFIG is now the leading approach; this can be more clearly seen from Figure 7 in which the cumulative installation of wind turbines is shown. According to [10] as of 2009 the DFIG is used in almost 60% of all installed wind turbines. It should be noted however that this value is not universally agreed upon, for instance in [25], it is reported that in 2008 around 85% of wind turbines worldwide used the DFIG approach.

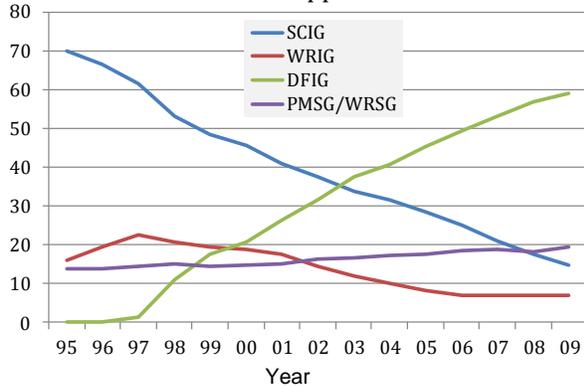


FIGURE 7. PERCENTAGE WORLD SHARE OF CUMULATIVE INSTALLED WIND POWER FOR DIFFERENT POWER TAKE-OFF APPROACHES [10]

DIRECT-DRIVE AND GEARED PERFORMANCE COMPARISON

From the discussion given in the previous section it can be noted that either a DD or mechanically geared approach is utilized. Studies conducted for the wind turbine industry can again help to make comparisons in performance and cost with respect to these two techniques. Polinder was one of the first to publish a performance analysis between geared and a DD generator system for a 3MW 15RPM wind turbine. Salient analysis results are summarized in Figure 8 and Figure 9. The use of a 3-stage or 1-stage gearbox is denoted by 3G and 1G in the comparison. It can be immediately noted that the DD-WRSG and DD-PMSG both have the highest mass and highest cost associated with them while the DFIG (with 3 and 1 stage gearbox) have the lowest cost. The amount of energy yield when using either the geared or DD approach is similar. As the DD approach does not require a gearbox the reliability should improve. Despite DD's size disadvantage this has been one of the driving forces behind utilizing DD technology.

Although the wind turbine gearbox has not been the component with the greatest failure rate [26], the mean-time-to-repair (MTTR) for the gearbox is very high [26] and the gearbox's 20 year design life has been far lower than expected [3, 27]. Some reports suggest that the wind turbine gearboxes achieve an operational life of between 7-11 years [28]. The problems associated with wind turbine gearboxes have led to a multi-year gearbox research reliability collaborative [3].

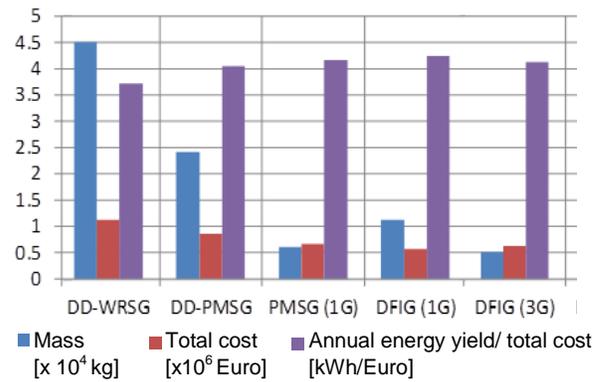


FIGURE 8. PERFORMANCE ANALYSIS OF DIFFERENT POWER GENERATION APPROACHES [29]

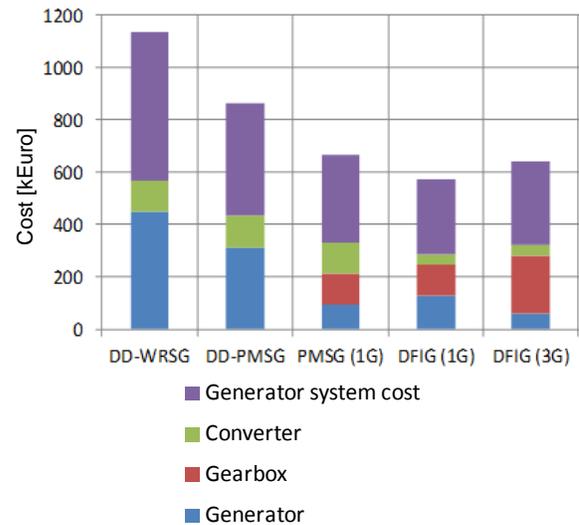


FIGURE 9. ESTIMATED COST BREAK DOWN FOR DIFFERENT POWER TAKE-OFF SYSTEMS (1996) [29]

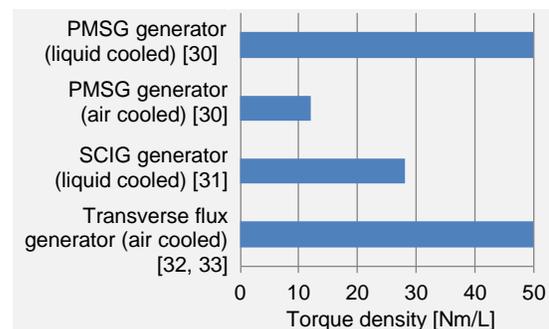


FIGURE 10. ILLUSTRATION OF MAXIMUM CONTINUOUS TORQUE DENSITY VALUES

The costs associated with the DD approach is related to the size of the generator and the size is related to the torque density. The maximum continuous torque density achievable using a DD generator is typically less than 50Nm/L [30-33]. A higher peak torque can be maintained for very short periods but not continuously due to the heat created by the windings [30]. A torque density comparison with a number of different motor designs is shown in Figure 10.

A MAGNETIC GEARBOX

A magnetic gearbox (MG) creates speed change without any physical contact. Early MG designs tried to mimic their mechanical counterpart. For instance, Armstrong [34] and Faus [35] proposed the radial magnetic spur gear such as shown in Figure 11 [35] and Tsurumoto studied an axial type magnetic spur gear as shown in Figure 12 [36]. Kikuchi proposed a magnetic worm gear as illustrated in Figure 13 [37]. These early MGs achieved very low torque density values because only a small fraction of the magnetic field on one rotor ever interacted with the opposing rotor.

A number of patents on topologies that moved away from mimicking mechanical gearboxes have also been proposed. For instance, in 1916 Neuland patented a MG that utilized field harmonic modulation to create speed change, this topology is shown in Figure 14 [38]. While in 1968 Martin patented the field modulated MG as shown in Figure 15 that used permanent magnets [39]. However, both of these designs would not create high torque density. In Neuland's case this is because only current excitation on one rotor was used while Martin's design did not utilize the magnet field in an efficient way.

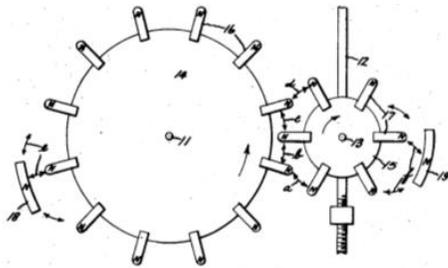


FIGURE 11. RADIAL MAGNETIC SPUR GEAR PROPOSED BY FAUS [35]

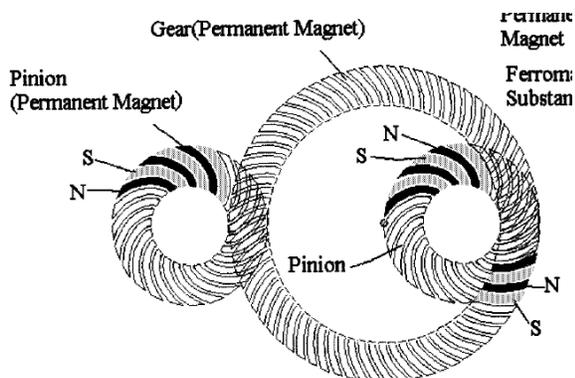


FIGURE 12. AXIAL SPUR MAGNETIC GEAR PROPOSED BY TSURUMOTO [36]

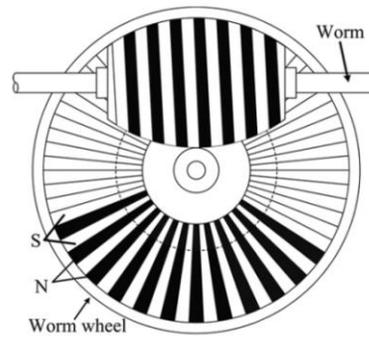


FIGURE 13. MAGNETIC WORM GEAR PROPOSED BY KIKUCHI [37]

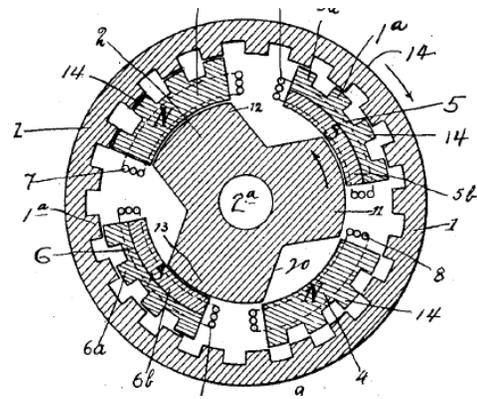


FIGURE 14. COAXIAL FIELD MODULATION MAGNETIC GEAR TOPOLOGY USING CURRENT EXCITATION PROPOSED BY NEULAND [38]

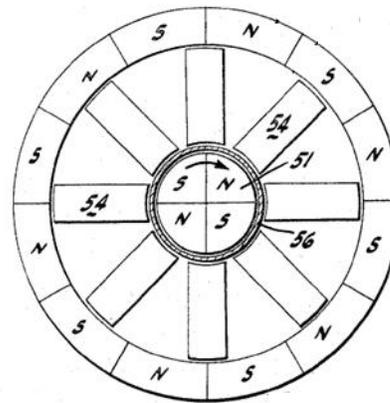


FIGURE 15. COAXIAL FIELD MODULATION MAGNETIC GEAR TOPOLOGY USING PERMANENT MAGNETS PROPOSED BY MARTIN [39]

In 2001 Atallah demonstrated that a MG was capable of creating a significantly higher torque density than a current excited electrical machine [40]. Atallah studied the coaxial MG as shown in Figure 16 and calculated that a torque density of up to 100Nm/L was achievable. The topology is essentially the same as Martin's. However, back-iron was used along with NdFeB magnets. In this design there is an inner rotor, consisting of p_1 pole-pair permanent magnets

rotating at ω_1 , a middle rotor with n_2 individual ferromagnetic steel poles that can rotate at ω_2 and an outer rotor with p_3 pole-pairs rotating at ω_3 . The inner and outer rotors that contain permanent magnets interact with the middle steel poles to create space harmonics [39-41]. If the relationship between the steel poles is chosen to be $p_1=|p_3-n_2|$ then the rotors will interact via a common space harmonic [39-41] and the angular velocities for each rotor is

$$\omega_1 = \frac{n_2}{n_2 - p_3} \omega_2 - \frac{p_3}{n_2 - p_3} \omega_3 \quad (1)$$

For the example shown in Figure 16 $p_1=4$ pole-pairs, $n_2=17$ and $p_3=13$ pole-pairs. This gives

$$\omega_1 = 4.25\omega_2 - 3.25\omega_3 \quad (2)$$

If the outer rotor is fixed ($\omega_3=0$) the gear ratio will be 1:4.25.

Other types of MG have more recently been shown to exhibit high torque density such as a harmonic MG [42] and a planetary MG [43]. However, these designs require (even more) unusual mechanical construction techniques and therefore most researches have focused on the coaxial type MG. In [44] Gouda conducted a scaling analysis of a coaxial MG and determined that a torque density of up to 140Nm/L could be achieved when the MG was scaled up to 0.6m. However, recently Uppalapati experimentally verified that an active region torque density of 150Nm/L [45] is achievable when using a 0.11m diameter rotor. Uppalapati utilized the flux focusing MG topology as shown in Figure 17. This indicates that more analysis needs to be conducted in order to understanding the fundamental scaling capabilities of the coaxial MG. In addition, multi-stage MGs have to-date only been minimally investigated.

The use of a MG in MHK offers the ability to create speed change without gear lubrication and they have the potential for operating with high conversion efficiency [45-47]. In addition, MGs have unique capabilities such as the physical isolation between input and output shafts and inherent overload protection. If excessive torque is applied due to large ocean disturbances a MG would simply slip magnetic poles, in contrast, a mechanical gearbox would catastrophically fail. Therefore, the sizing of a MG can be based more closely around the rated torque rather than extreme torque conditions.

A CONTINUOUSLY VARIABLE MAGNETIC GEAR

If the outer rotor of the MG is controlled with a stator winding then the variable input speed, ω_2 , can be converted into a constant output speed, ω_1 , by actively controlling the rotor mechanical

frequency, ω_3 . An example of a continuously variable magnetic gear (CVMG) is shown in Figure 18 [48, 49]. As the electrical frequency, ω_e , and mechanical frequency are related by:

$$\omega_e = \omega_3 p_3 \quad [\text{rad/s}] \quad (3)$$

equation (1) will become

$$\omega_1 = 4.25\omega_2 - 0.25\omega_e \quad (4)$$

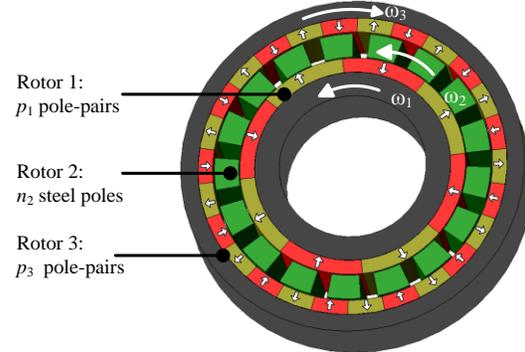


FIGURE 16. A COAXIAL MAGNETIC GEAR USING SURFACE PERMANENT MAGNETS WITH $p_1=4$ POLE-PAIRS, $n_2=17$ STEEL POLES AND $p_3=13$ POLE-PAIRS ON THE OUTER ROTOR [40]

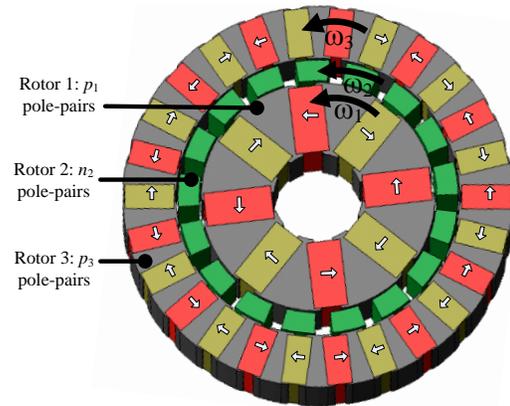


FIGURE 17. A FLUX FOCUSING COAXIAL MAGNETIC GEAR WITH $p_1=4$ POLE-PAIRS, $n_2=17$ STEEL POLES AND $p_3=13$ [47, 50].

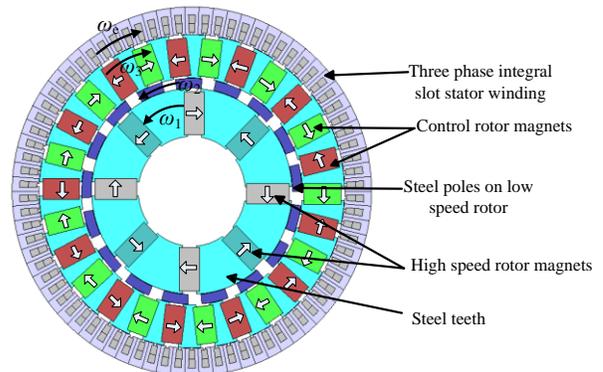


FIGURE 18. A CONTINUOUSLY VARIABLE MAGNETIC GEAR WITH AN OUTER FLUX FOCUSING CONTROL ROTOR AND INTEGRAL SLOT WINDING. (WITH $p_1=4$ POLE-PAIRS, $n_2=17$ STEEL POLES AND $p_3=13$ ON CONTROL ROTOR AND STATOR WINDING). [48]

A number of authors have studied CVMG topologies however currently experimentally verified designs have not exhibited high torque densities [51-54]. Nevertheless if higher torque densities can be demonstrated this type of topology holds promise.

MAGNETICALLY GEAR GENERATOR

A further possibility is to integrate a stator winding into the high-speed side of the MG [55-57]. An example of this approach is illustrated in Figure 19. Frandsen recently experimentally demonstrated that a torque densities of over 100Nm/L can be achieved with a magnetically geared traction motor [55]. While a recent analysis by Gerber indicated that a magnetically geared PMSG can create three times higher torque density with less magnet mass than a traditional fractional slot wound electrical machine [58]. Therefore, the additional mechanical complexity created by introducing magnetic gearing may be shown to be worthwhile. However, further research into the mechanical construction and testing of such machines is needed.

MAGNETICALLY GEARED POWER TAKE-OFF

There are a number of potential ways in which a MG could be integrated into a MHK PTO. Three possibilities are shown in Figure 20 to Figure 22. One option would be to connect the MG in series with a DD generator, such as illustrated in Figure 20. As the MG has a much higher torque density than the DD generator the overall system size, and therefore cost should be lower [41]. However, in this topology the power converter has to be sized to handle the full power and this adds to the conversion cost. A second approach would be to integrate the MG within the electrical generator itself [55-57]. As the MG and generator both create torque via magnetic fields the integration of the MG within the generator has the capability of being quite a very compact design.

A third approach would be to mate a CVMG in series with a higher speed (and therefore smaller) PMSG such as shown in Figure 22. In this approach the variable speed input coming in from the MHK device would be both magnified and converted into a constant output speed by the CVMG and then a smaller high-speed PMSG could be used to interface with the grid. Utilizing such a technique the magnetically geared configuration would have the same electrical capabilities as the DFIG approach (as shown in Figure 3) but without the need for brushes or the reliability issues surrounding the mechanical gearbox. Which MG PTO approach would be the most cost effective

would in many respects rest in the overall achievable torque density of each approach.

There are a number of challenges with regard to the use of magnetic gearing. There is concern raised with regard to the increased mechanical

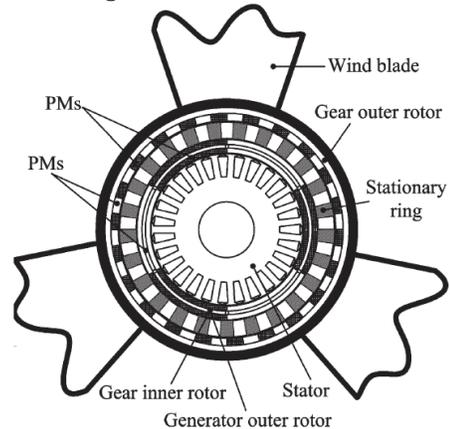


FIGURE 19. AN EXAMPLE OF AN INTEGRATED MAGNETIC GEARBOX WITH A PERMANENT MAGNETIC SYNCHRONOUS GENERATOR [57]

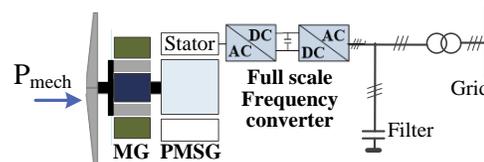


FIGURE 20. MAGNETIC GEARBOX IN SERIES WITH A DIRECT DRIVE PERMANENT MAGNET OR SYNCHRONOUS GENERATOR

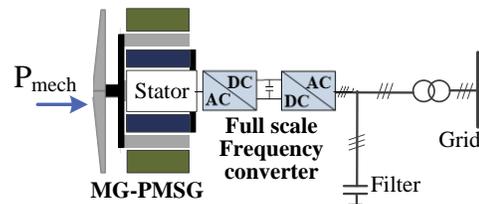


FIGURE 21. INTEGRATED MAGNETICALLY GEARED PERMANENT MAGNET SYNCHRONOUS GENERATOR

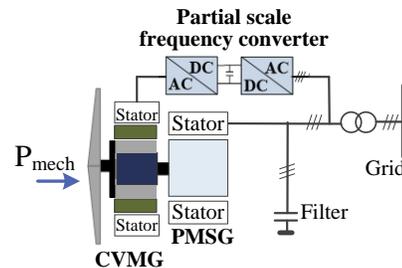


FIGURE 22. A CONTINUOUSLY VARIABLE MAGNETIC GEAR IN SERIES WITH A PERMANENT MAGNET SYNCHRONOUS GENERATOR

complexity due to the need for additional rotating parts. There is concern with the difficulty with mechanical fabrication, particularly the thin central steel modulation poles are complex to

fabricate. Additionally there is concern raised with regard to the amount of stiffness and damping that is magnetically created and of course there is concern with regard to the use of NdFeB magnets and the associated costs and supply issues surrounding this material. Despite these concerns the recent developments in magnetic gearing have shown that much higher torque densities than hitherto thought possible are achievable and therefore there could be tangible cost savings that could be achieved particularly if it can be clearly demonstrated that the torque/kg of magnet material is lower than more traditional PMSGs.

CONCLUSIONS

This paper has reviewed different PTO techniques for rotary based MHK generation. The PTO techniques for wind turbines have been used as a guide. However, unlike in wind power generation it was noted that few MHK generators use the DFIG approach.

The use of a mechanical gearbox enables the PTO to be compact in size but decreases the reliability of the PTO. While the use of DD generator offers the potential for high reliability but at the expense of a much larger machine and consequently higher initial capital cost. The use of a magnetically geared generator offers the possibility of achieving a PTO system that is both compact in size while also being highly reliable. If the torque-per-kg of magnet can be shown to be sufficiently high, the use of magnetic gearing also offers the tantalizing possibility of being a relatively low cost solution.

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