# Feasibility of magnetic continuously variable transmission concept within a tidal turbine power train

Adam Harris, Ben McGilton, and Markus Mueller

***Abstract*—Tidal stream turbine installations are rapidly developing within the renewable energy industry. The power train is an integral component of the tidal turbine. Reliability is among the most important aspects of a component of a tidal turbine. Wind turbines have indicated that there are issues with mechanical gear boxes and fully rated converters. Current tidal power trains have mechanical gears and fully rated converters. This paper proposes a new power train topology where the mechanical gear and fully rated converter are replaced with magnetic gearing and a partially rated converter improving reliability. This is achieved by a magnetic continuously variable transmission (CVT).This paper sets out the state of the art magnetic CVT technology. The CVTs are compared with the requirements for tidal turbine operation. The achievable torque density is high enough for a tidal turbine power train and the values for the gear ratio range are also consistent with those required. A number of additional challenges have been put forward. It was also shown that there is an interdependence between parameters for regulation of the power train, namely the electromagnetic torque and the gear ratio of the magnetic CVT.**

***Index Terms*—Tidal turbine, power train, magnetic continuously variable transmission, CVT**

## I. Introduction

HORIZONTAL axis tidal stream turbines installations larger than 500 kW are rapidly rising on a commercial scale [1]. The power train of a tidal turbine is a key part of this continuing trend. It must be extremely reliable, as maintenance or repair adds significant cost to the venture, which is possibly the most important challenge. Besides reliability, efficiency, size and mass are influential design criteria. So far there has not been a stand out solution. The addition of a magnetic continuously variable transmission (CVT) into the power train has been mentioned in [2] and [3]. This paper takes a closer look at the concept. The state of the art magnetic CVTs are presented and evaluated for fitness. The integration of a magnetic CVT into the control system is also discussed.

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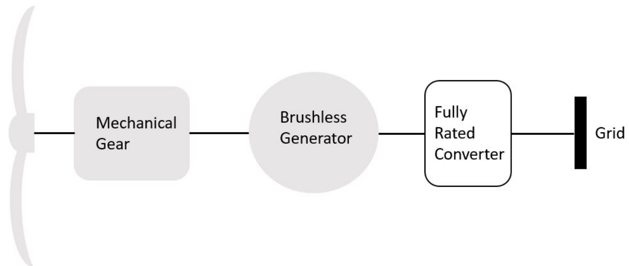


Fig. 1. A mechanically geared tidal turbine power train.

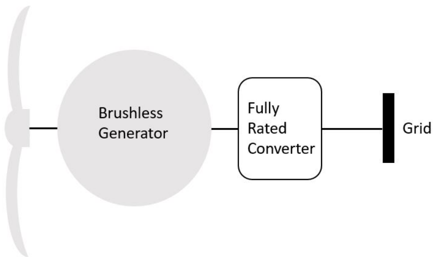


Fig. 2. A direct drive tidal turbine power train.

Though there are a number of power train options available for tidal turbines, the leading designs are predominantly mechanically geared Fig. 1, or Direct Drive (DD) Fig. 2, generator systems [1]. Using a gear box enables the use of a smaller, lighter and cheaper generator which is more easily transported and installed than large, heavy DD generators. However, there are some lessons from wind turbines that can be carried over to tidal. In off-shore wind turbines it has been shown that mechanical gear boxes have a mean time to failure of 6 years [4] in a doubly fed induction generator (DFIG). Additionally, there is significant down time associated with gear box repair as the nacelle must be opened up requiring a sea vessel with a crane and a weather window to perform the repair in. This would be even more problematic in a tidal turbine anchored to the sea bed. The reliability and availability issues associated with mechanical gear boxes have prompted some tidal turbine designers towards DD systems.

However, when looking again at wind turbines the fully rated converters (FRC) required in DD systems have higher failure rates, with a mean time to failure

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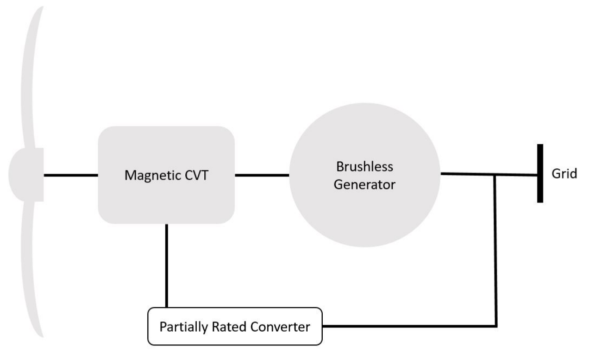


Fig. 3. A magnetic CVT in a tidal turbine power train.

of 3.2 years compared with 10 years for a partially rated converter (PRC) in the DFIG [4]. Another study by J. Carroll *et al.* [5], which included 2,222 turbines in the analysis found FRC failure rates to be 5 times higher than PRCs. It should also be noted that converter failure is easy, inexpensive and relatively quick to repair for a wind turbine. The failed converter module is simply removed and replaced with a new one. So despite the wind industry shifting to predominantly using FRCs due to the total control over the power output, especially offshore, there are drawbacks for tidal turbines. Any repair or maintenance of a tidal turbine is to be avoided due to the large cost of accessing the turbine underwater.

It is becoming evident that neither power train topology in their current form is ideal. Future power train concepts need to incorporate reliable gearing and reduce converter ratings to increase reliability.

Permanent Magnet Synchronous Generators (PMSG) are the most common generator type used in tidal systems as the brushless design has reduced maintenance issues [5]. Furthermore, PMSGs are shown to have higher efficiencies than induction generators [6]. To run a PMSG without a converter requires the input to be at constant synchronous speed to match the grid frequency. This is counter productive for a turbine as it is well established that a variable speed turbine has a much higher energy yield. A continuously variable transmission (CVT) is a gear that is able to constantly vary its gear ratio. For a variable speed input to the CVT a constant speed output can be maintained by constantly varying the gear ratio. This therefore enables a turbine to run the turbine rotor at a variable speed while operating the generator at a constant speed. Appropriate control of the electromagnetic torque allows for the elimination of the FRC interfacing between the PMSG and the grid. This is replaced with a PRC on the magnetic CVT, which is used for regulation. Fig. 3 gives the topology of this power train. Using a system with a PRC does make grid code compliance less straight forward compared with FRC, where there is total control over the power output. Grid compliance is achieved in the DFIG power train with a PRC [7], [8], however there are no studies referring to grid code compliance such as the dynamics of a voltage sag event on a magnetic CVT power train. Similar methods to those of the DFIG may be able to achieve grid code compliance for a magnetic CVT system due to the similarities of the PRC.

While mechanical CVT systems exist they are complex and prone to failure due to the many moving parts. Recently there has been a surge in the viability of magnetic gear boxes, which now can match the torque density of their mechanical counterparts [3]. Since magnetic gears have no contact between components there is no wear and no lubrication requirements. Additionally there is some inherent overload protection making magnetic gears more reliable than mechanical gears. While there are existing designs for magnetic CVTs [9]–[12] and integrated magnetic CVT generators [13]–[15], these are preliminary and a lot more research is required to determine magnetic CVTs viability within the power train. A magnetic CVT would address both gear box and converter issues for a PMSG, making for an efficient and reliable system.

## II. Continuously Variable Transmission

CVT technology has been around for some time and there are a number of designs capable of giving continuously variable transmission, the most common will be discussed here.

### *A. Mechanical CVT*

There are two mechanical designs: a variable diameter pulley (VDP) and a planetary gear. VDPs are often used in motor scooters, snow mobiles, and occasionally in automobiles and have a typical ratio range of 3.5 [16]. The example system shown in Fig. 4, has two variable diameter pulleys connected by a rubber belt, or a steel belt in higher power applications, which transmits the torque. The gear ratio can be altered by changing the diameters of the pulleys. The VDP system is simple to operate and build, hence it is commonly used and relatively cheap compared to other CVTs. A VDP has also been proposed for a wind turbine design [17] with automatically regulated control system, however it did not discuss the applicability of a VDP towards a turbine design. There are some specific areas in which problems are envisaged for tidal turbine application. The steel band connecting the two pulleys would be subject to large loads and therefore must be designed to withstand those loads while also remaining compliant, which would be a difficult challenge. It should also be noted that the steel belt has small teeth to aid in gripping the pulleys and these would create considerable wear in the system over time. This becomes even more pertinent once the turbulence factor of tidal streams is considered. The tidal transmission experiences large variations in torque over a small time period possibly causing the belt to slip and higher wear to occur. Lastly a VDP does not lend itself towards being in a flooded environment and so would require an expensive sealed system.

A planetary gear also has the ability to act as a CVT. The topology of a planetary gear is given in Fig. 5. By rotating the ring gear at a determined speed the gear ratio between the sun and the planetary gear can be

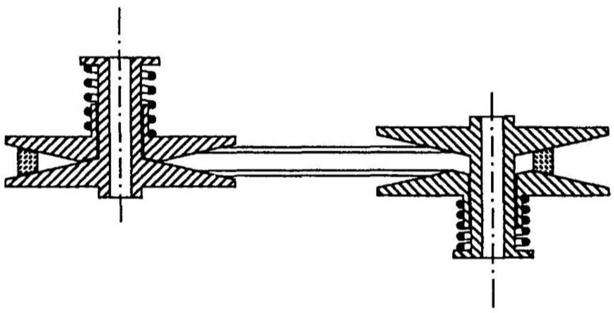

Fig. 4. A variable diameter pulley. [17]

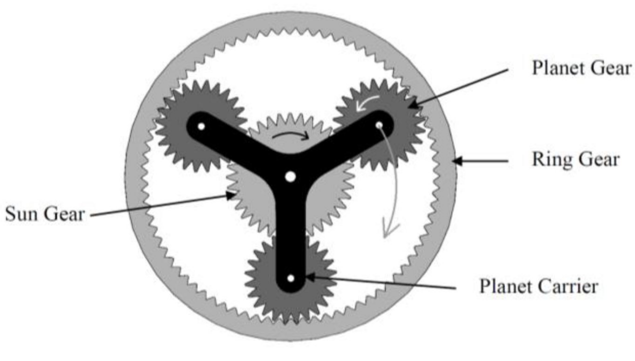


Fig. 5. A planetary gear. [21]

controlled. The design requires a machine to rotate the ring gear. Planetary CVTs have a gear ratio range of 6 [18]. It has been proposed and investigated with a simulation for a variable speed wind turbine with constant speed generator operation in [19]. This CVT also has power splitting capabilities and was used in Toyota's hybrid electrical car [20]. There are now variations from other hybrid car manufactures [18]. Planetary gears are commonly used in Megawatt power applications and so have a proven record of reliability. However they are still mechanical and so subject to wear and fatigue over time. In addition to this there are possible failures of the electrical machine used to control the planetary gear. Critically the planetary CVT cannot be flooded, requiring expensive sealing. However the efficiency of planetary CVT is higher than other mechanical CVTs including VDPs [18].

### B. Hydraulic CVT

Beyond the purely mechanical solutions, a hydraulic pump and motor system can act as a CVT. A variable speed mechanical input is converted to hydraulic pressure by a variable speed hydraulic pump, the hydraulic pressure is then used to drive a hydraulic motor, which could also be variable or fixed speed. Efficiencies of 86 - 93% are reported in [22]. However there are concerns that hydraulic CVTs have low efficiencies at low rotational speeds [23], [24]. Hydraulic CVTs are commonly used in heavy industries and so have been designed for large power applications, one example is wind turbines where a hydraulic drive train was installed in a few test turbines with the largest test being 7 MW [24]. Although the system proved to not be as efficient as expected it demonstrated the potential of the technology. Tidal turbines operate at low speed, high torque and therefore a low efficiency of the hydraulics is expected.

Hydraulics are often used in heavy industries so can be designed to be robust. The regular required servicing of the hydraulics would be an issue over the 20 year life time of a tidal turbine and potentially sharply increase the maintenance costs.

### C. Magnetic Gears

The most prominent design for magnetic gears has three rotors, Fig. 6, which is called a concentric magnetic gear. The outer and inner rotors have an arrangement of permanent magnets which make up pole pairs creating the magnetic field. The modulator rotor is made up of ferromagnetic pieces. It modulates the magnetic field in between the outer and inner rotor. This flux modulation creates the gear ratio between the rotors. For a magnetic gear with a fixed gear ratio the outer rotor is held stationary giving a gear ratio between the inner rotor and the modulator. The gear ratio is determined by the number of pole pairs on the inner rotor $p_h$, the outer rotor $p_c$ and the number of ferromagnetic pieces $n_s$ on the modulator. These are governed by the relation

$$n_s = p_c + p_h. \tag{1}$$

The gear ratio $K$ when the outer rotor is held stationary is given by

$$K = \frac{n_s}{p_h}, \tag{2}$$

This is the intrinsic gear ratio. Equation 2 shows how the high speed rotor will have a small number of pole pairs while the modulator rotor will have a greater number of ferromagnetic pieces. Equation 1 shows that the outer rotor must then also have a larger number of pole pairs compared to the high speed rotor.

Concentric magnetic gears can also act as CVTs. If now the outer rotor is no longer held stationary, but rotated at a certain speed, the flux modulation effect in magnetic gear acts to give another gear ratio from the intrinsic. By differing the speed of the outer rotor, or control rotor, the gear ratio is controlled. Gear ratios reported in the literature are from 0.3 - 3 [25], and in [11] from 2.5 - 8.5. The design, similar to the planetary CVT, requires a machine to rotate the outer rotor. Therefore the design in some cases acts as a motor and others as a generator, depending on the input speed/torque and the gear ratio demanded. Considering it was only recently that magnetic gears were able to reach a torque density of over $100$ kNm/m$^3$ [26], matching that of mechanical gears, the technology is still in its infancy. More recently torque densities of $239$ kNm/m$^3$ [27] and $286.56$ kNm/m$^3$ [28], have been reported. So far there have been no documented uses of a magnetic CVT within industry. Although the design has been proposed for uses similar to the planetary CVT in hybrid vehicles for power splitting [29], [30] and in wind turbines to enable variable speed operation [13], [15], [25], [30], [31].

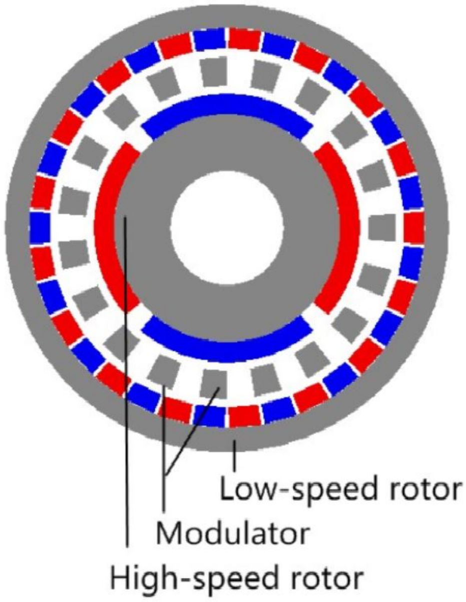


Fig. 6. A concentric magnetic gear topology. [32]

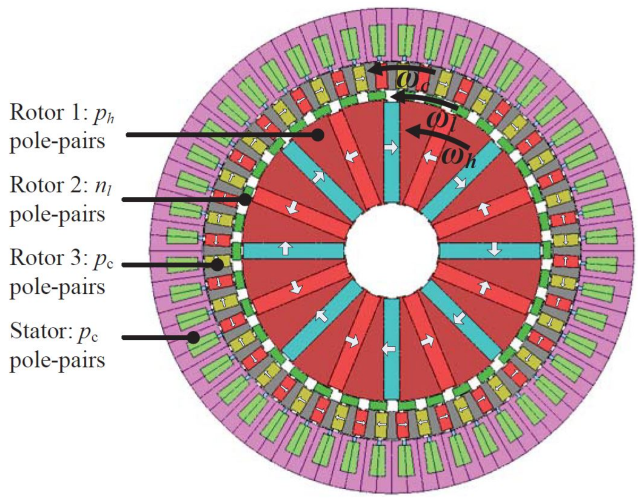


Fig. 7. This magnetic CVT is a 3 rotor plus a stator design. The topology has $n_{input} = 34$ steel pieces, $p_{output} = 8$ pole pairs and $p_{control} = 26$ pole pairs. [12]

Magnetic gearing comes with some intrinsic characteristics which make it a very reliable component. As there is no contact between the rotors no wear occurs, requiring no lubrication or lubrication system. The lack of contact reduces acoustics and there is also a form of over load protection, as the rotor will slip if the maximum, or pull-out torque, of the gear is exceeded [3]. These factors make magnetic gearing very attractive to sectors requiring high reliability. NASA and ESA are both conducting investigations towards using magnetic gears in aerospace [33]–[35]. While reliability is a particularly strong case for using magnetic gearing over traditional mechanical systems, due to the relatively recent development of the technology this has yet to be verified over full lifetime operation

Experimentally determined efficiencies of up to 97.5 % are given in [30] for a stand alone magnetic CVT unit and a rated efficiency of 76 % in [13] for the magnetic CVT component of an integrated CVT/machine design.

A magnetic CVT, due to its non contact torque transfer, can be flooded meaning that cheaper seals can be used for the tidal turbine.

Overall a magnetic CVT would have the highest reliability out of the options, which is the most important question for tidal developers. It eliminates the need for mechanical gearing and allows the replacement of FRC with a PRC and would decrease the total size of the power train compared to DD.

## III. STATE OF THE ART MAGNETIC CVTS

This section will address the up-to-date magnetic CVT topologies in the literature and discuss their merits in the power train. There are a number of magnetic CVT designs, each attempting to optimise one of the aspects of magnetic CVTs. There are two main types, either the design has three physical rotors and a stator (used to drive the control rotor) or two physical rotors and the third (control) rotor is a stator with an AC supply acting as a rotating magnetic field. Figs. 7 and 8 are of the three rotor design. These have the main advantage of having higher torque densities than the

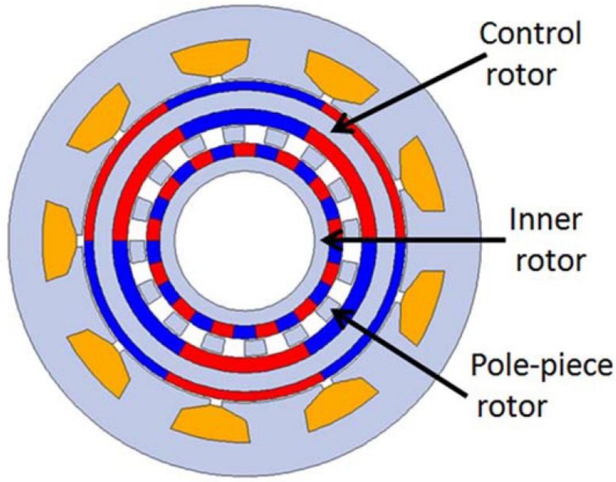


Fig. 8. This topology has three rotors plus a stator. The topology has $p_{input} = 13$ pole pairs, $n_{output} = 16$ steel pieces and $p_{control} = 3$ pole pairs. [36]

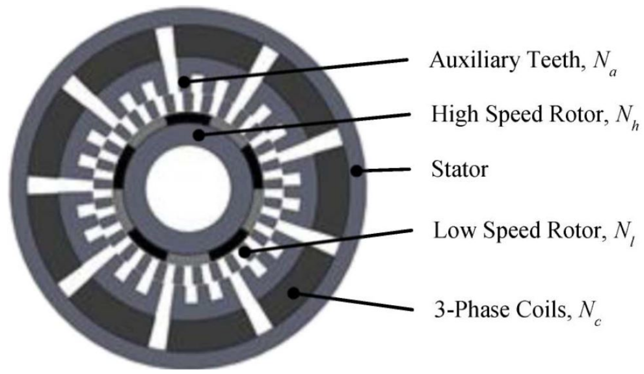


Fig. 9. This topology is a vernier magnetic CVT with two rotors plus a stator. The topology has $n_{input} = 29$ steel pieces, $p_{output} = 5$ pole pairs and effectively $p_{control} = 24$ pole pairs which is made up of 9 coil pole pairs and 27 auxiliary teeth. [10]

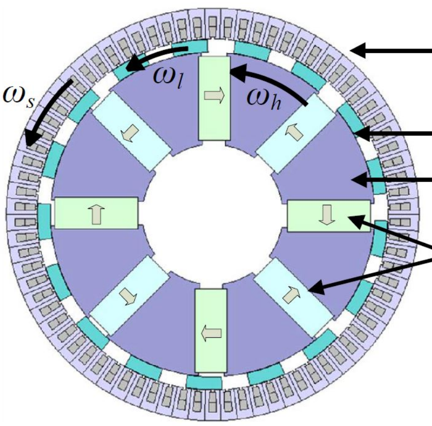


Fig. 10. This topology has two rotors plus a stator as the outer rotor. The topology has $n_{input} = 17$ steel pieces, $p_{output} = 4$ pole pairs and $p_{control} = 13$ pole pairs. [11]

TABLE I
TORQUE DENSITIES FORM MAGNETIC CVT LITERATURE

| Paper Author | Topology | Torque Density [kNm/m$^3$] |
|---|---|---|
| Pritchard figure 7 [12] | 3 rotors + stator | 136.68 |
| Atallah figure 8 [36] | 3 rotors + stator | 26.5 |
| Zaini figure 9 [10] | 2 rotors + vernier stator as control rotor | 13.24 |
| Padmanathan figure 10 [11] | 2 rotors + stator as control rotor | 10.95 |

two rotor design, however the two rotor design is simpler. The torque densities are given in Table I for each design. This difference between the two rotor and three rotor designs is almost solely due to the larger amount of rare earth permanent magnet material in the three rotor topologies. The control rotor in Figs. 10 and 9 is a wound stator, which is not able to induce a magnetic field density as strong as the permanent magnets. Since tidal stream turbines operate at low speed high torque it is important that a CVT has a high torque density.

However due to the cost of rare earth permanent magnets it is preferable to minimise their use. The two rotor design would prove more cost effective as less permanent magnet material is used. Cost and performance will need to be balanced.

Torque density is an important factor for the power train, it gives the volume that the component will occupy for a given maximum torque value. This has further effects in a tidal turbine where flow blockage can lead to reduced performance. For example, if a turbine has 3 m radius blades and the power train has a radius of 1 m then a third of the blades are redundant. In addition to this there are also then concerns of excessive weight and cost due to large volume. At present the highest torque density reported is 136.68 kNm/m$^3$ [12]. It is useful to compare a CVT to an alternative power train. In [37] the size and values for the C-GEN DD power train for a 600 kW tidal turbine are given. The DD has radius of 1.6 m and length of 0.75 m, giving a volume of 6.03 m$^3$. Using the rated torque of the turbine, 403.49 kNm, the volume of a CVT can be calculated as 2.95 m$^3$. The volume of the CVT is more than half that of the DD. This does not include the volume of the generator in the CVT power train, but clearly torque density for the design in [12] is sufficiently high.

The two rotor topologies shown in Figs. 9 [10], and 10 [11], have distinct differences. The design discussed in [10] has a slightly higher torque density than [11], see Table I, despite the use of a flux focusing high speed rotor in [11]. The design in Fig. 10 is limited by the number of pole pairs, i.e. coils, that are wound on the stator due to space constraints. While the CVT in Fig. 9 uses the vernier effect resulting in fewer coils on the stator, there is a higher effective number of pole pairs. The vernier effect is achieved by using auxiliary steel teeth on the stator creating higher order harmonics than the number of poles on the stator suggest. However the torque densities of either of these designs are not high enough for a tidal power train.

The three rotor topologies also have differences which translate into their respective torque densities. The CVT in [12] has a much higher torque density than that in [36]. This is due to design features such as a flux focusing high speed rotor and a stator which is magnetically coupled with the magnetic gear in [12]. It has been shown that flux focusing magnetic arrays can increase the peak torque of a magnetic gear by 25 % [38]. Halbach arrays have also been shown to increase the peak torque [39], [40]. Additionally [33] found that by using curved magnets that match the curve of the rotor compared to rectangular magnets, higher torque densities can be reached. This was due to flux leakage losses when using rectangular magnets.

The gear range, as reported in literature, is at first instance a question simply of the speed of the control rotor

$$K(\omega_c) = \frac{\omega_o}{\omega_i} = \frac{n_s}{p_h} - \frac{p_c}{p_h}\left(\frac{\omega_c}{\omega_i}\right), \quad (3)$$

which gives the gear ratio $K$ for a given angular speed of the control rotor $\omega_c$ [30]. $\omega_o$ and $\omega_i$ are the rotational speed of the output rotor and input rotor respectively. The speed of the control rotor can easily be varied over a large range. However the pull out torque of the rotor is the limiting factor, and something intrinsic to the design. For if the torque of the control rotor was greater than the pull out torque of the gear, then the modulation effect, which creates the gear ratio between the rotors, beaks down and they begin to slip past each other meaning no torque/speed transfer. However the efficiency of a magnetic gear is highly dependant on the load, meaning they are most efficient operating near their pull out torque. This poses a problem as the CVT will need to operate both near and away from the pull out torque in a tidal turbine.

Experimental results have been obtained in [36], which show good agreement between predicted and measured EMF waves in the stator. The results also validated the ability of a magnetic CVT to vary the gear ratio and gave the efficiency curves for a range of loads. The efficiency curves verify that, as for magnetic gears, the closer they operate to the peak or pull out torque of the gear the higher the efficiency. Efficiencies of up to 97.5 % were given. However, the experimental results did not give an indication of dynamic response of the CVT. This is an important area where results need to be obtained, as tidal turbines operate with large load variations in small time frames.

Integrated machine - magnetic CVT drives have been proposed. There are advantages to an integrated topology, for example the reduction in power train material and mass, including expensive magnetic material. Additionally some of the lost flux leakage in magentic CVTs would contribute to useful work in the generator. The most promising solution is presented in Fig. 11. It has two inner rotors and an outer stator, meaning it is a brushless generator. The stator comprises of two sets of windings, one set of windings is for the CVT/control and the other for synchronous generation.

For example in Fig. 11 the stator primary windings have the function of acting as the control rotor of the CVT and the secondary windings as the generator. The primary winds are connected to a power converter while the secondary windings are directly connect to the grid. The inner rotor in Fig. 11 is the low speed input operating at variable speed and variable torque. The outer rotor is operating at constant speed but variable torque. The CVT component regulates the torque on the outer rotor. During stable operation the sum of the torques on the outer rotor are equal to zero. Considering the outer rotor as a floating rotor, the electromagnetic torque and mechanical torque on the rotor are balanced during stable operation neglecting losses. This gives

$$T_{mechanical} = T_{stator,1} + T_{stator,2}. \tag{4}$$

$T_{mechanical}$ is the mechanical torque of the outer rotor, $T_{stator,1}$ and $T_{stator,2}$ are the electromagnetic torques from the primary and secondary stators respectively [13]. It is the job of the converter on the primary stator to regulate the electromagnetic torque $T_{stator,1}$ so that equation 4 holds true to give stable operation.

The intrinsic gear ratio between the two rotors in Fig. 11 is 1.64:1, which is very low. This has benefits and drawbacks for a power train. The low magnetic gear ratio means that higher torques can be transferred, a necessity for tidal turbines operating at low speed high torque. However it reduces the gains available from reducing the generator size, as generator size is inversely proportional to the amount of gearing in the drive train.

An important question is also how large would the converter be rated on the primary winding. Lui *et al.* [13] shows that the converter size will be proportional to the gear ratio range required for operation. This follows the argument earlier that the gear ratio range is dependant on the pull out torque of the gear since the pull out torque for [13], Fig. 11, is proportional to the magnitude of the power on the primary stator.

Additionally the torque density of the CVT in Fig. 11 is 18.68 kNm/m$^3$. Realistically the torque density must be closer to the value given in [12] of 136.68 kNm/m$^3$ for the power train.

Lui *et al.* [13] have built a prototype and the experimental results confirm the FEM analysis results for the EMF of the integrated generator. The EMF results show that the generator can be controlled to give constant peak voltage AC output, allowing direct grid connection.

However, the experimental results are limited to step changes and therefore do not represent dynamics under typical tidal stream turbine operating conditions. This is a key area where results need to be obtained in the lab before a comprehensive analysis of this type of generator's applicability to a tidal power train can be ascertained.

Other similar integrated generators have been proposed in [14], which utilizes the vernier effect to enhance the design. Niu *et al.* [15] proposes an axial version of the generator in Fig. 11.

The technology readiness level (TRL) of magnetic CVTs is a further question. On the one hand Magnomatics has a commercially available model targeted at the auto industry, however the torque density quoted on their data sheet is low (less than 10 kNm/m$^3$ [41]). Equally there have been no simulations performed for a CVT power train of a tidal turbine. There have been studies for wind turbines that have investigated control strategies for particular regions of operation [25]. Others have investigated wind turbine operation with non-magnetic types of CVTs [42] and [43]. These studies did not address the questions that have arisen from this paper.

## IV. Magnetic CVTs in a Tidal Turbine Power Train

This section outlines how a magnetic CVT fits into a tidal turbine power train. Fig. 3 shows where a magnetic CVT is positioned in the power train. The CVT enables variable speed operation of the turbine by altering the gear ratio. This follows the maximum power point for the hydrodynamics of the turbine.

Regulation of the generator electrical output is also conducted by the CVT. To maintain grid connection of the PMSG the speed of the rotor and load angle must be effectively regulated. The CVT uses the electromagnetic torque $T_{cvt,e}$ and the gear ratio to regulate these two parameters. The electromagnetic torque of the CVT similar to equation 4 must be balanced with the generator electromagnetic torque $T_{gen,e}$ and the mechanical torque of the generator rotor $T_{gen,r}$.

Consider a variable torque and constant speed input. Here the electromagnetic torque of the CVT must balance the total torque on the generator's rotor to maintain synchronous speed. Any imbalance of the total torque on the generator rotor causes an acceleration

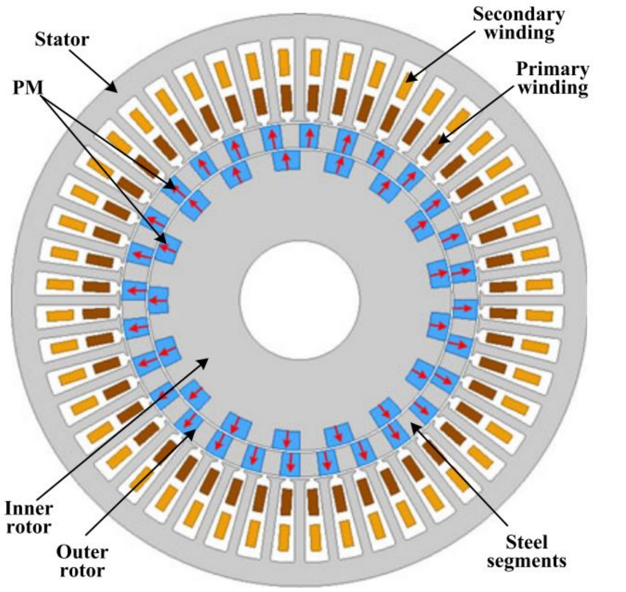


Fig. 11. An integrated magnetic CVT and generator. The topology has $p_{input} = 17$ pole pairs on the input rotor, $p_{float} = 28$ pole pairs on the outer rotor, $p_{control} = 11$ pole pairs on the primary winding and $p_{gen} = 28$ pole pairs on the secondary winding. The torque density of the machine is 18.68 kNm/m$^3$. [13]

of the rotor, and therefore synchronous speed may be lost. For the balanced system the gear ratio remains fixed in this case.

Now consider a constant torque and variable speed input. Here the gear ratio must change to maintain synchronous speed for the generator. As the gear ratio changes so does the magnitude of the torque seen by the generator. The gear ratio steps the speed up and the torque down. For example

$$T_{gen,r} = \frac{T_{turbine}}{K}, \quad (5)$$

shows how the turbine rotor torque $T_{turbine}$ is stepped down by the gear ratio. Therefore the electromagnetic torque of the CVT must also react to balance the total torque on the generator rotor.

In a variable torque and variable speed input as before the gear ratio and the total torque on the generator rotor react to maintain a balanced system. The gear ratio and the electromagnetic torque of the CVT are inter-related in the control of the generator. For system inertia $J$ the equation

$$\frac{d\omega_{gen,r}}{dt} = \left[T_{gen,e} + T_{cvt,e} - T_{gen,r}\right]\frac{1}{J} \quad (6)$$

$$\frac{d\omega_{gen,r}}{dt} = \left[T_{gen,e} + T_{cvt,e} - \frac{T_{turbine}}{K}\right]\frac{1}{J} \quad (7)$$

gives the change in the speed of the generator rotor $\omega_{gen,r}$ over change in time, neglecting losses. Therefore when designing a control strategy for this system both the gear ratio and the electromagnetic torque of the CVT will need to be used to regulate the system.

Preliminary modelling work has indicated that the gear ratio range required for a normal tidal turbine variable speed control strategy would be about 3. This is comparable to currently proposed magnetic CVT capabilities [25] and [11].

## V. Further Challenges

Magnetic gears have a nonlinear dynamic behaviour [44] and a higher degree of compliance than mechanical gears. This could cause problems associated with the natural frequencies of the power train and rotor dynamics or general control of the machine. Montague [44] gives a comprehensive overview of the problem and presents control strategies to limit oscillations.

Furthermore a key component of magnetic gear design is keeping the cogging torque low. Cogging torque produces vibrations and noise. Reducing these will improve the fatigue of the power train, especially the bearings. This is an important factor for tidal turbines where reliability needs to be high.

Floating wind turbines have been identified to have challenges to air gap deflection management, due to large accelerations [45]. Given the similarity to floating tidal stream turbines, which also experience large deflection and accelerations, the air gap management of a multi-rotor CVT integrated generator or stand alone magnetic CVT would also be an issue. It would be preferable to use them within a fixed to the sea floor design, where smaller deflections are experienced.

## VI. Conclusion

This paper has provided some discussion on the potential for magnetic CVT in solving the problems facing tidal turbine power trains. They give reliable gearing to the power train, meaning smaller generator size. A PRC is used for control of the CVT, so that the generator can be directly connected to the grid. The state of the art magnetic CVT topologies have been evaluated. Torque densities of over 100 kNm/m$^3$ have been identified, which are compatible with tidal turbines. The gear range has been identified to be large enough for variable speed regulation. The limits of the gear ratio and the control principles have been discussed. Regulation of the power train is achieved by controlling the gear ratio and electromagnetic torque of the CVT. Further work is required to develop generic design modelling tools and to investigate the dynamic behavior of magnetic CVTs.

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