An Investigation into Linear Generators with Integrated Magnetic Gear for Wave Energy Power Take Off

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Abstract

This work presents a new wave energy converter power take off system that combines two recent developments in drive train technology, the consequent pole linear Vernier hybrid permanent magnet machine and the linear magnetic gear. The combined system is fully realised in 3D FEM and compared to a similar direct drive machine. While the resulting system is lighter, reducing the active material mass by 30%, and more efficient, the system requires larger amounts of high cost permenant magnet material and increased power take off complexity. It is summarised that while such a system could be recomended in certain conditions, it is not viable for general application.

Keywords: Marine Energy, Wave Energy, Linear Generator, Magnetic Gear

1 Introduction

With an estiamted 17 PWh/yr [1] wave energy has enormous potential as both an alternative energy resource and a comercial opportunity. The technology faces some issues however which have to date limited it's development. Key among these issues are the high operation and maintenance (O&M) costs and low speed, low frequency nature of the resource itself. While a variety of devices are in development there is currently no industrial scale ready device. This can largely be attributed to the extreme environments that wave energy converters (WECs) operate in. Potential wave energy sites are usually in remote locations with fundamentally harsh conditions resulting in prohibitive O&M costs. A key issue further exacerbating the O&M costs is the naturally low frequency of the resource itself. In order to generate electrical energy efficiently at grid frequency WEC developers have turned to intermediary speed enhancement systems such as mechanical gears or hydraulics. Mechanical gears, however, are a leading cause of downtime in offshore wind [2] and hydraulic systems increase the complexity of the Power Take Off (PTO) and often have efficiency issues. Alternatively, the use of direct drive machines with fully rated converters has been suggested, removing the O&M issues of mechanical gears [3]. This requires physically large, expensive machines due to the required high pole number and studies have found that there is similar downtime resulting from the fully rated converter [4].

Electrical machines are sized on their value of torque or force. Introducing a gearbox to increase speed and reduce torque is commonly used in rotary electric drives. Previous work in linear machines has shown that that amplitude amplification can be advantageous for power take off in wave energy, where the increased translator mass required to accommodate the increased oscillation amplitude can be offset by reducing the axial length of the machine due to the reduced force requirement [5]. Introducing amplitude amplification in the form of a linear gear box is therefore a method of reducing the burden on the electrical machine, albeit at the expense of an increased oscillation amplitude. This concept is only advantageous if the combined mass and cost of the gearbox and smaller electrical machine is significantly below that of the original direct drive machine

This paper proposes an alternative solution that combines two recent developments in drive train technology, the magnetic gear (MG) [6] and the Consequent Pole Linear Vernier Hybrid Permanent Magnet (CPLVHPM) machine [7]. Both technologies will be discussed in relation to their topologies and potential benefits in wave energy applications. Then a case study is presented where the linear generator will be scaled to deliver rated power for a direct drive device. A linear magnetic gear (LMG) (Fig 2) is then designed for integration with the generator. This requires the linear machine to deliver a lower force at increased frequency, hence requiring a smaller active area (smaller stator) but over a larger displacement (longer translator). Mass and efficiency savings, calculated using an 3D finite element analysis model, are presented to assess the merit of using MGs in a linear system.

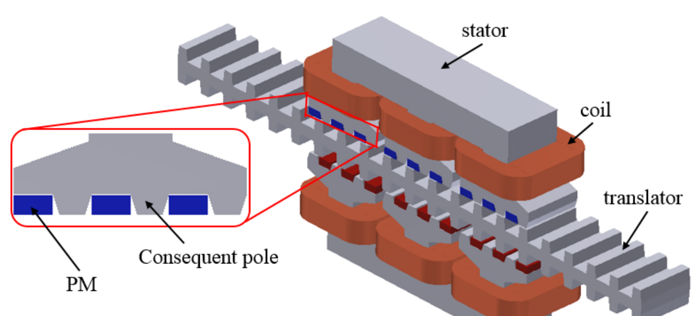

Figure 1: Configuration of CPLVHPM machine

2 Consequent Pole Linear Vernier Hybrid Permanent Magnet Machines

The Consequent Pole Linear Vernier Hybrid Permanent Magnet (CPLVHPM) machine [7] is a developed version of the Vernier hybrid machine (VHM) with an improved magnet consumption [8]. This machine comprises of double-sided stators with two identical E-cores facing each other in which both permanent magnets and windings are located in the same part of the machine, the E-shaped stator. The long iron laminated translator with salient teeth is sandwiched between the stator sides as shown in figure 1. The translator possesses a simple pure iron rigid structure which is inherently low cost to produce a thrust force.

This class of machine has the same basic structure as the baseline VHM, except the substitution of PMs with tapered ferromagnetic poles, the consequent poles. All remaining magnets have the same polarity, while the ferromagnetic poles take over the role of the missing poles. Hence, the number of pole pairs of the PM for the baseline VHM and consequent pole machine are equal. figure 2 confirms that smaller pole to pole flux leakage is produced by the consequent pole machine compared to its VHM counterpart. In other words, the flux linkage of the consequent pole machine is higher than that of the baseline machine. The effect of employing tapered consequent pole on the back EMF and cogging force characteristics has been investigated in [1]. The salient feature of using this configuration is the saving of 50% of the PM materials, especially in long stroke applications.

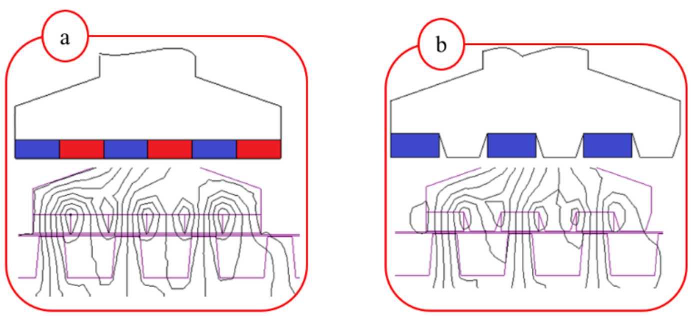

Figure 2: The effect of consequent poles on leakage flux

The operation principle of the CPLVHPM is based on the magnetic gearing effect where the translator teeth are utilised to modulate the stationary magnetic field produced by PMs to the high speed traveling magnetic field in the airgap. When the translator at its initial position and its salient teeth are fully aligned with the magnets belong to the phase A, the flux linkage in the coils reaches its maximum negative value, while the back EMF is zero. As the translator moves 90 electrical degrees the flux linkage drops steadily to zero, at which point the back EMF achieves its maximum positive value. Then the polarity is reversed in the next alignment poison, corresponding to a 1/2 translator pitch of movement. Therefore, a small translator displacement can produce a high rate change in the flux linkage, and enhancing thrust density and making the machine suitable for low speed direct drive applications.

3 Magnetic Gears Overview

MG's operate through the contactless transfer of torque between rotors in a rotary topology, or translators in a linear system, introducing a speed step change while experiencing virtually no wear and have greatly reduced lubrication requirements reducing maintenance frequency. Additionally MGs have reduced acoustics and each rotor can be hermetically sealed from the other allowing for greater options regarding marinisation. A further attribute making the technology particularly suitable to marine energy applications is the ability of the rotors to "slip" if experiencing extreme forces such as in storm conditions. This grants the MG high levels of survivabilty. The MG is highly adaptable coming in rotary [6], linear [9] and transrotary forms (which convert linear to rotary motion with a velocity increase) [10] and can be utilised with a wide variety of WECs without requiring substantial changes to the generator and without a loss in reliabilty.

The type of MG developed in this work is a ferromagnetic pole field modulated, LMG. While the concentric magnetic gear was first patented in 1968 it was Atallah et. al.'s work from 2001 which established its operating principal and high torque capabilities [6]. Initially developing the concentric rotary design, the linear model's performance was also demonstrated in [9] . The LMG has three main components: a low speed ferromagnetic pole translator, and high speed permanent magnet pole translator and fixed outer magnetic poles.

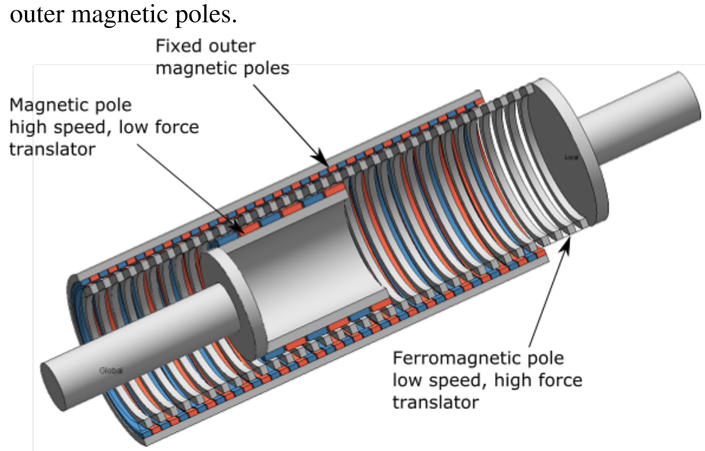

Figure 3: Magnetic gear topology

The ferromagnetic pole pieces (FMPs) forming the low speed, high force translator are placed in the airgap between the inner and outer permanent magnet pole elements as shown in figure 3. The FMPs modulate the magnetic field in the airgap such that each translator sees the corresponding pole number on the opposite translator allowing for pole alignment and the gearing effect to be established. With the outer magnetic pole element fixed the gear ratio, G_r, is calculated as:

$$G_r = p_l/p_h = (n_s - p_h)/p_h = -v_h/v_l \quad (1)$$

Where p_h and p_l are the pole pair numbers on the high and low speed translators, v_h and v_l are the velocities of the high and low speed translators and n_s is the number of FMP pieces which is determined by:

$$n_s = p_h + p_l \quad (2)$$

Beyond these fundamental design values there are numerous parameters that will effect the performance of a design, the coupling effects of which have been explored in [11] and make designing an ideal system non-trivial.

A key design constraint which should be mentioned is the torque harmonics that occur due to pole number. The harmonic variation can be quantified using (3) which defines a cogging factor f_c where:

$$f_c = (2pn_s)/(LCM(p, n_s)) \quad (3)$$

p is the pole pair number on either rotor and LCM is the least common multiple of these two values. For low harmonics this number should be as close to unity as possible [12].

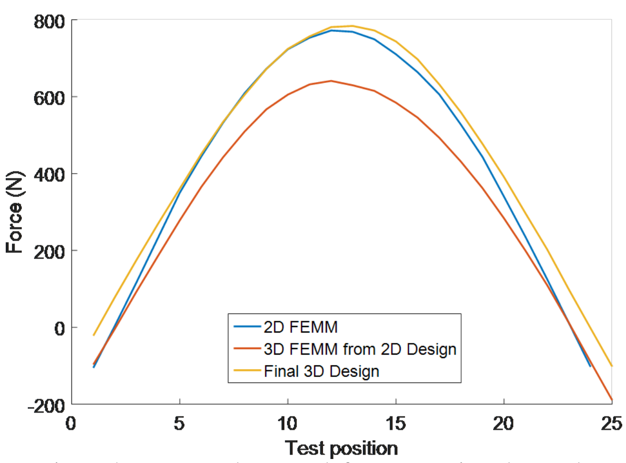

Figure 4: Forces on low speed, ferromagnetic pole translator

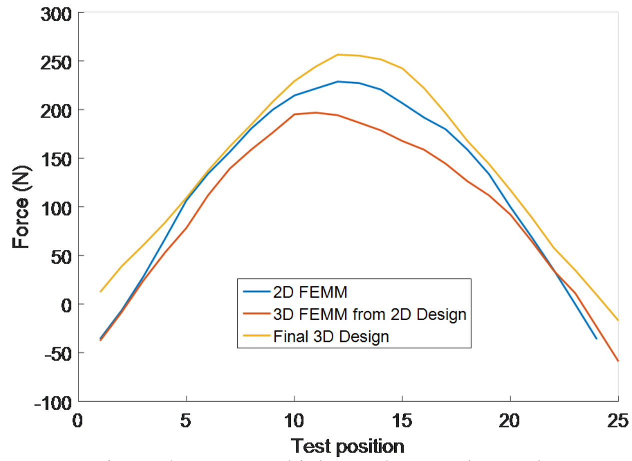

Figure 5: Forces on high speed, PM pole translator

4 Case study

This paper proposes combining a CPLCHPM machine with a LMG which would operate as a PTO for a heaving buoy type wave energy converter. The proposed system block diagram layout can be seen in figure 6. In order to see the advantages of a combined system the linear machine was first designed as a scaled direct drive PTO. The key design parameters were a max thrust force of 740 N and a speed of 1.2 m/s resulting in a peak power rating of 888 W. An LMG with a ratio of 3.3:1 was then designed with objective peak force of 740N. LMGs must be designed for a given stroke amplitude as this will greatly affect the size and cost of the device. As the high speed translator will move increased distances determined by the gear ratio, having a large ratio might result in a prohibitively large system. In this case study a stroke amplitude of 5cm was chosen for the low speed translator. The high-speed translator will then move 16.5cm at maximum amplitude and the fixed outer rotor magnetic poles will have to be at least this height in order to ensure continual magnetic field connection between translators.

Table 1: LMG parameter values

Parameter	2D Model (from FEMM)	3D Model (from 2D design)	3D Model (from MagNet)
Inner magnetic pole thickness (mm)	4	4	4
Outer magnetic pole thickness (mm)	2	2	2
Ferro-magnetic pole thickness (mm)	5	5	5
Airgap radius (mm)	25	25	25
Inner translator height (mm)	63	63	69
Inner airgap (mm)	1	1	1
Outer airgap (mm)	1	1	1
Outer backiron thickness (mm)	8	8	8
Inner backiron thickness (mm)	8	8	8
Magnetic mass (kg)	0.422	0.422	0.623
Active iron mass (kg)	3.116	3.116	4.158
Total active gear mass (kg)	3.538	3.538	4.781
Peak (high) force (N)	772	684	784

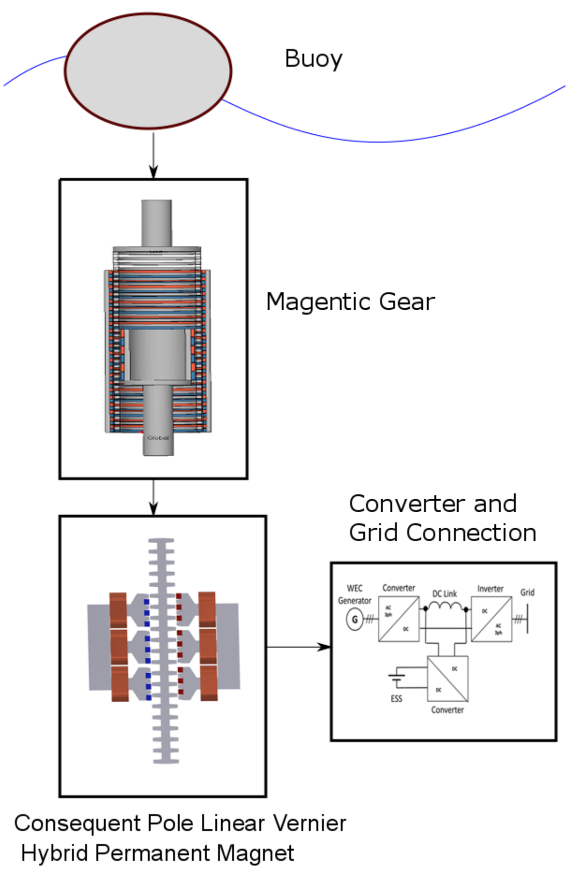

Figure 6: Combined system layout

4.1 Magnetic Gear Design

The magnetic gear was designed through a similar process to that detailed in [13] which involved initial rapid designing and optimising using 2D FEMM and then a full 3D analysis using Infolytica's MagNet to verify results. When the 3D analysis was performed with the same parameters as the 2D model, there was a reduction of approximately 11% in the peak forces. To address this difference, the 3D model was adapted such that the correct target force was achieved in order to assess the extra material required for a completed design. The key values and results are shown in table 1 with the force curves of the initial 2D model, 3D model of the same design and the 3D model of the adapted design shown in figures 3 & 4. The models were statically solved at 25 points in order to determine the full force range of each model. The primary force effecting parameters are the magnetic pole thickness, airgap radius and the height of the inner high speed translator. The airgap radius is defined as the distance from the center axis to the start of the inner airgap while the inner translators height determines the active magnetic area. These parameters are shown in figure 7.

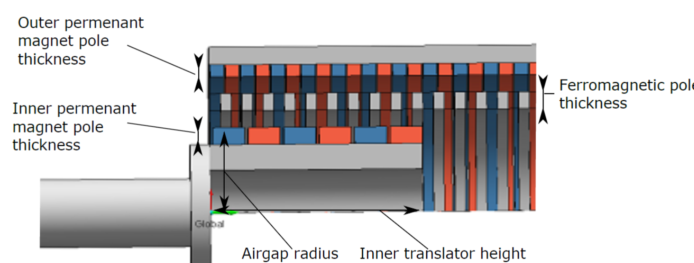

Figure 7: Main magnetic gear parameters

5 Combined System Discussion

The key results of the combined system for the CPLVHPM machine are shown in table 2 where the machines parameters are shown before and after the combination with the LMG. With the addition of the LMG the linear machine's total mass is reduced by almost 63% with the key high cost permanent magnet (PM) material reduced by 66%. Though there is an increase in iron and eddy current losses in the PMs, due to the increase in frequency, the dominant copper losses are reduced by approximately 1/3rd. The resulting machine is then more efficient while being lighter, materially cheaper and more compact. When designing a MG the differences that occur between 2D and 3D models are non-trivial and highlights the importance of full 3D analysis. Such differences have been observed in previous works [14, 15] and given the small dimensions of the gear, 3D effects can have a fairly substantial influence on the magnetic field and resulting forces. Further analysis is ongoing to determine whether the difference in results is reduced when the device is scaled for larger applications. In order to present the most realistic results the full 3D FEM model was considered to be the more accurate as it accounts for these 3D effects. The final design resulted in a total mass reduction of 30%. The key results of the direct drive and combined system using the 3D results are presented in figures 8, 9 and 10.

These values are for active material only however and auxiliary elements will be required to connect and support the system. Additionally, including the MG will increase the complexity of the drive train and increases the total high cost PM material (47%) The PM material volume, V_{pm}, also increases rapidly with regards to both stroke amplitude S_{amp} and higher ratio gr.

$$V_{pm} \propto \pi \times S_{amp} \times gr \tag{4}$$

As the CPLVHPM machine has been purposefully designed in order to decrease the high cost PM material, a combined MG system with greater PM requirements will be, in most cases, infeasible. Furthermore, as a main advantage of direct drives is the relative simplicity of the PTO, the addition of a gearing element without substantial advantages in efficiency or cost would result in no net benefit. Despite these issues the proposed system could have applications where the conditions are charaterised by low amplitude, low frequency regular waves. This could potentially increase the viability of certain sites for wave energy development.

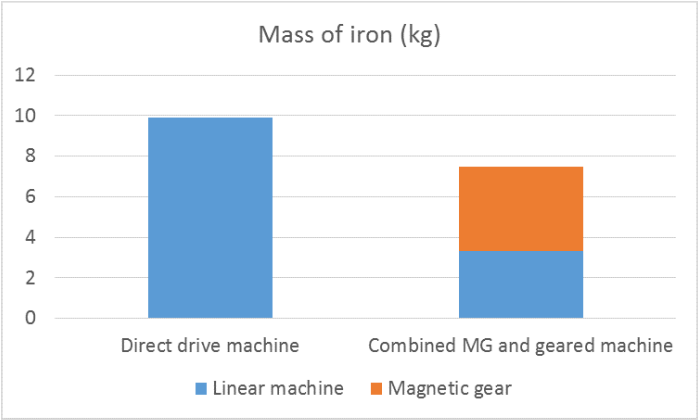

Figure 8: Mass of iron of designs

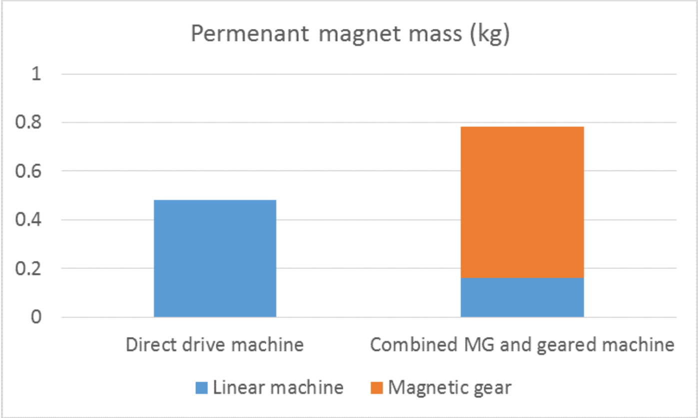

Figure 9: Permanent magnet mass of designs

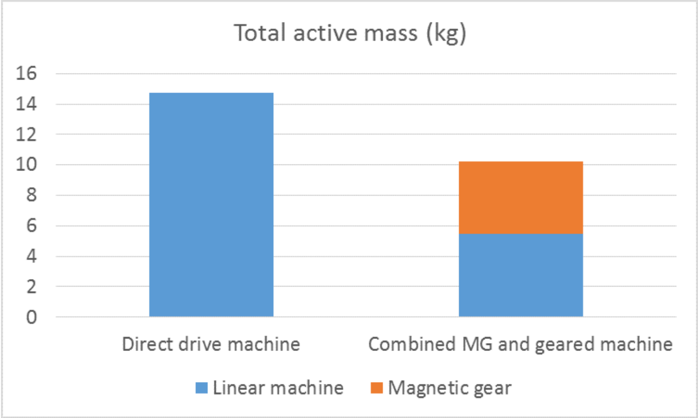

Figure 10: Total active mass of designs

6 Conclusion

The magnetically geared linear generator presented in this work has potential as a PTO in WEC technology. The resulting model, fully realised in 3D FEM, was lighter then the non-geared alternative while resulting in a more efficient generator. Despite these advantages such a system will have limited application as the addition of the gear will increase the complexity of the PTO and

Table 2: CVL values before and after MG

Description	Initial Design	Integrated design (With MG)	Unit
Velocity	1.2	3.96	m/s
Force	740	225	N
Axial length of the machine	50	15.15	mm
PM mass	0.48	0.16	kg
Copper mass	4.35	2	kg
Mass of laminations	9.9	3.3	kg
Total Machine mass	14.73	5.46	kg
Iron loss	18.3	23.7	W
Copper loss	42.4	27	W
Eddy current loss in PM	1.09	4.2	W
Total losses	61.8	54.9	W
Efficiency	93.5	94.2	%

the larger amount of required PM material reduces the advantage of using the CPLVHPM machine. Further work is planned to investigate whether it is possible to design a more integrated system rather than the basic series setup described in this work. This could potentially increase the viability of a combined system.

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References

[1] W. E. Counci, "World energy resources, marine energy 2016," 2016. [Online]. Available: http://www.google.co.uk/patents/US687292

[2] Z. Daneshi-Far, G. a. Capolino, and H. Henao, "Review of failures and condition monitoring in wind turbine generators," *The XIX International Conference on Electrical Machines - ICEM 2010*, pp. 1–6, 2010.

[3] B. McGilton, P. M. Mueller, and A. Mcdonald, "Review of Magnetic Gear Technologies and their Applications in Marine Energy," *Proccedings of the 5th IET International Conference on Renewable Power Generation*, 2016.

[4] D. McMillan and G. W. Ault, "Techno-economic comparison of operational aspects for direct drive and gearbox-driven wind turbines," *IEEE Transactions on Energy Conversion*, vol. 25, no. 1, pp. 191–198, 2010.

[5] N. J. Baker, M. A. Mueller, and M. A. H. Raihan, "All electric drive train for wave energy power take off," in *5th IET International Conference on Renewable Power Generation (RPG) 2016*, Sept 2016, pp. 1–6.

[6] K. Atallah and D. Howe, "A novel high-performance magnetic gear," *IEEE Transactions on Magnetics*, vol. 37, no. 4 I, pp. 2844–2846, 2001.

[7] A. A. Almoraya, N. J. Baker, K. J. Smith, and M. A. H. Raihan, "Development of a double-sided consequent pole linear vernier hybrid permanent-magnet machine for wave energy converters," in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, May 2017, pp. 1–7.

[8] M. A. Mueller and N. J. Baker, "Modelling the performance of the vernier hybrid machine," *IEE Proceedings - Electric Power Applications*, vol. 150, no. 6, pp. 647–654, Nov 2003.

[9] R. C. Holehouse, K. Atallah, and J. Wang, "Design and Realization of a Linear Magnetic Gear," *Magnetics, IEEE Transactions on*, vol. 47, no. 10, pp. 4171–4174, 2011.

[10] M. B. Kouhshahi and J. Z. Bird, "Analysis of A magnetically geared lead screw," *Electrical and Computer Engineering Faculty Publications and Presentations*, no. 421, pp. 1–8, 2017.

[11] D. J. Evans and Z. Q. Zhu, "Influence of design parameters on magnetic gear's torque capability," *2011 IEEE International Electric Machines and Drives Conference, IEMDC 2011*, pp. 1403–1408, 2011.

[12] K. Atallah, S. Calverley, and D. Howe, "Design, analysis and realisation of a high- performance magnetic gear," *IEE Proceedings, Electrical Power Applications*, vol. 151, 2004.

[13] B. McGilton, R. Crozier, and M. Mueller, "Magnetic Gear Design for an Oscillating Wave Surge Converte," *Proceddings of Europeant Wave and Tidal Energy Conference, 2017*, no. 421, pp. 1–7, 2017.

[14] L. Jian, K. T. Chau, Y. Gong, J. Z. Jiang, C. Yu, and W. Li, "Comparison of coaxial magnetic gears with different topologies," *IEEE Transactions on Magnetics*, vol. 45, no. 10, pp. 4526–4529, Oct 2009.

[15] S. Gerber and R. J. Wang, "Analysis of the end-effects in magnetic gears and magnetically geared machines," in *2014 International Conference on Electrical Machines (ICEM)*, Sept 2014, pp. 396–402.