NCL Eprint version Electric drive train design for wave energy converters

Nick. J. Baker^{1*}, A. Almoraya¹, M. A. H. Raihan¹, S. McDonald¹ V. Pickert¹

¹ School of Engineering, Newcastle University, NE1 7RU, UK

Nick.Baker@newcastle.ac.uk.

Abstract— This paper reports on the results of a project to develop the drive train for a wave energy converter – consisting of a linear generator and a power converter. Two power converters and a number of small scale linear machines have been designed, built and tested in the laboratory. A variety of simulated and laboratory results are presented and a summary of project findings described.

Keywords—wave energy, linear generator, permanent magnet

I. INTRODUCTION

Due to its large resource and high energy density, ocean wave energy is widely considered as a potential source of renewable electricity generation. Many proposed devices produce slow speed reciprocating motion, which poses a challenge to conventional electrical machines. A direct-drive power train would consist of a linear machine and power converter with no gearbox or other mechanical linkage. This paper describes a project with the aim of developing an electric power train for direct-drive wave energy converters. A number of machine and power electronic converter designs are discussed and demonstrated at scale.

II. WAVE ENERGY

Numerous wave energy devices have been proposed over the preceding decades, with varying technical and commercial success. One of the many technical challenges relates to the discrepancy between the natural motion of ocean waves (slow speed and reciprocating) compared to the conventional motion of electrical machines (high speed, uni-directional, rotary). Wave energy devices, therefore, either need some form of mechanical linkage between the moving part and the electrical machine, or developers need to move away from using conventional electrical machines. A number of groups have proposed the development of bespoke linear generators for this application, such as [1-4], offering a direct-drive power take off with all the implied mechanical simplifications. This approach poses challenges in terms of designing the electrical machine and associated power electronic converter.

Fig. 1 shows a conceptually simple direct drive wave energy device, consisting of a submerged generator coupled to a surface piercing buoy. Example devices of this type have been demonstrated by Oregon [5] and Uppsala universities [6, 7]. The design challenges associated with this device are shared by other similar concepts, of which there are many examples [8-10].

Fig. 1. A typical direct drive wave energy device coupled to a linear electrical generator.

III. MACHINE TOPOLOGIES

A. Options

A number of researchers have looked at linear machine topologies for this application, most relying on rare earth Permanent Magnets (PMs) such as transverse flux [11], flux reversal [4] or tubular permanent magnet [12]. A brief comparison of the key features of alternative topologies is given in Table 1.

TABLE I. HIGH LEVEL TOPOLOGY STUDY FOR WVE ENERGY CONVERTERS

Topology	Advantages	Disadvantages
Linear Induction Machine	simple structure low initial cost	requires excitation current low efficiency low shear stress
Linear Permanent Magnet Synchronous Machine	high power factor high efficiency	low magnet utilisation low shear stress PMs on the translator
Linear Transverse Flux Machine	very high shear stress high force and power densities	Low power factor 3D flux path PMs on the translator
Linear Tubular Permanent Magnet Machine	no end-windings can have ironless stator low attraction force high force density	PM on the translator requires a large amount of PMs low shear stress (if ironless)
Linear Flux Switching Machine	simple translator high shear stress high magnet utilisation high power factor PMs in the stator	requires a large amount of PM mass stator iron teeth are easy to saturate high cogging force high airgap closing force
Vernier Hybrid Machine	high shear stress high efficiency PMs in the stator	low power factor poor magnet utilisation high airgap closing force

As the predicted motion of wave energy converters is reciprocating with a low peak velocity and likely to have a large peak to peak amplitude, flux reversal type permanent magnet machines, where all the active components are on the stator have been the main focus of this work. The particular topology selected is known as a Vernier Hybrid Machine

(VHM) – where the term hybrid relates to its mix between a flux reversal and Vernier machine. As the magnets and conductors are both mounted on the stator, the translator can be formed of a purely iron structure – advantageous for machines with a large translator overhang. Previous studies have struggled to make more conventional flux reversal machines, which share this property, competitive [13].

A VHM design and performance analysis was presented in [14] and is shown in Fig 2. The machine is a member of the variable reluctance PM machine family and exhibits high force density due to the reluctance variation and flux reversal characteristics of the slotted translator. The VHM here is used as an initial design for investigation and for benchmarking subsequent improvements. In [14], there are two C-core stators facing each other, surrounding two sides of a toothed translator. The translator consists of equal slot and tooth with only laminated steel while multiple magnet poles and armature coils are mounted on the C-cores. Alignment and un-alignment between magnet poles and translator teeth produce maximum and zero flux linkage respectively. Moving the teeth to adjacent magnets produces a reverse flux flow around the machine. Physically displacing the translator by a short distance, the coils see a large change in magnetic flux with correspondingly high back emf and force production. This phenomena is called magnetic gearing which is a non-contact method that enables direct drive machines to reach higher force density without the use of a mechanical gearbox.

Fig. 2. The Vernier Hybrid Machine

Optimising the design of Fig.1 for peak force at a fixed current density is a sensible strategy for minimising use of the rare earth material on which this topology relies, but it was found to lead to machines with a power factor of less than 0.2. This basic machine design has been taken forward to a number of alternative topologies, driven primarily by the desire for a better power factor and a reduced mass of rare earth magnets. The current phase was assumed to be fully in the q -axis by controlling I as shown in Fig. 3, a reasonable assertion as saliency in these machines was found to be minimal.

Fig. 3. Assumed operating condition

For a fixed terminal voltage (V), power factor ($\cos \phi$) can be improved by flux concentration or reluctance minimisation

of the magnetic circuit seen by the magnets, thus, increasing the back emf . Alternatively, reducing the average inductance (X) or reducing the electric loading (I) will have the same effect. All these methods improve the per-unit magnet usage and several topologies which achieve this are described in the following section. The project also considered cylindrical versions of the Fig.1 machine in the search for a higher performance machine which would integrate well into a wave energy device.

B. Improved magnet usage.

In this section, a number of alternative flat VHM topologies are presented and compared. Results and design procedures for the individual topologies have, for the most part, been presented by the authors elsewhere [15-21]. The basic premise was to improve the effective use of the PM material. For a fixed peak force output between designs, the improved performance was used to reduce the electric loading and hence improve the operating power factor.

It has been found [15] that the stators in an “E-core” configuration generally perform better than the 3 separate “C-core” phases of the type illustrated in Fig. 1. An improvement of magnet utilisation was then achieved by switching to a consequent pole arrangement. Alternate magnets are replaced with soft magnetic poles (iron teeth) as shown in Fig. 4. In the original VHM useful flux is only contributed by two of the 6 magnets, whereas in the consequent pole machine, all three magnets are shown to contribute. Detailed design [16], such as tapering the consequent pole and reducing the magnet pitch, as shown in Fig. 5, has been used to increase the magnitude of the fundamental frequency in the back emf, e.g. Fig. 6.

Fig. 4. No load flux plots with the stator teeth fully aligned with the translator teeth for the VHM (a) and consequent pole variant (b)

Fig. 5. Variation of the magnet width by tapering the soft magnetic poles

Fig. 6. No load back emf plot at fixed velocity for the variants shown in Fig. 5.

Two further variations of the consequent pole topology were investigated and subsequently built: the flux concentrated “V-shape” version [17, 18] of Fig. 7 (a) and the Halbach arrangement [19] of Fig 7 (b). The three topologies introduced have been extensively simulated and tested in the laboratory to validate findings. A fourth topology, the non-consequent pole V-shape machine of Fig. 7(c) was shown to offer the best performance in terms of both efficiency and power factor for machines of constant magnet mass and a fixed power output [16].

Fig. 7. Alternative pole arrangements for the VHM. (a) V-shape consequent pole, (b) Halbach array consequent pole and (c) V-shape.

Efficiency and operating power factor for three machines all producing the same mechanical power are shown in Fig. 8.

Fig. 8. Simulated operating results of three topologies of fixed magnet mass and reacting the same mechanical force.

Selected figures of the laboratory prototypes are shown in Fig. 9.

Fig. 9. Laboratory prototypes of the flat VHMs showing the (a) consequent poles, (b) Halbach array consequent pole and (c) V-shape consequent pole.

C. Cylindrical VHMs

It is proposed that in this application, a cylindrical cross section will give advantages in terms of fluid sealing, reduced airgap closing forces and translator reaction to torsional forces. In general terms it has also been shown that cylindrical versions could give a mass saving compared to flat machines with a short axial length [20].

To this end, two cylindrical versions of the E-core VHM, derived from the single-sided and double sided flat variants were designed and tested. They consisted of a three tooth [20] and a six tooth [21] stator respectively. The two prototype stators are shown in Fig. 10.

Fig. 10. Laboratory prototypes of cylindrical VHMs

IV. POWER CONVERTER

A. Options

The power train of a wave energy device is essentially a variable-speed-drive, consisting of an electrical machine, an AC/DC machine side converter, a DC bus potentially including energy storage and a DC/AC grid side converter. The generator charges the DC-link capacitor via a Voltage Source Converter (VSC) or rectifier and then a Voltage Source Inverter (VSI) is used to convert the DC-link voltage and current into grid frequency AC voltages and currents. For a constant speed application this arrangement works well and the various components can be optimally selected. However, in wave energy there are a number of additional requirements which influence the drive topology. For example the generator is typically accelerating from zero to full speed and back to zero every few seconds. There is also an increased emphasis on reliability and fault-tolerance, as servicing offshore platforms is weather dependent and loss of the drive means a loss of revenue. Furthermore, if it is required to control and tune the wave energy device to maximise power output, four-quadrant operation is required. Finally, local energy storage to smooth fluctuating real power and also implement the active control associated with tuning the wave energy converter requires significant reciprocating power flows over and above the average power being fed into the grid [22].

To address these requirements, a modular approach is been proposed for the power-take-off whereby multiple electrical generators are mechanically coupled and connected to multiple power converter modules [23]. A single module of the drive is shown in Fig. 11 for both a current-source and voltage-source topology, including localized Energy Storage System (ESS).

Fig. 11. A single drive train unit including (a) voltage source and (b) current source converter.

The important elements of each module are: the generator converter, the energy storage interface and the grid inverter. The ESS, using supercapacitors, permits the dynamic exchange of mechanical energy during reactive power control of the wave energy converter and also to smooth the fluctuating real power through the grid interface.

Fig. 12. Voltage source converter schematic and hardware

In [24] a discussion of the merits of a Current Source Converter (CSC) based topology was compared with a Voltage Source Converter (VSC) based topology for a direct-drive WEC application. The basis of this comparison was to evaluate the switching and conduction losses in the main switching and passive elements when operating at two representative states of the associated WEC and generator. The study concluded that for lower switching frequencies, i.e. $< 30 - 40\text{kHz}$, the VSC topology is more efficient but at higher switching frequencies, i.e. $> 40-65\text{kHz}$ the CSC is more efficient. The motivation for a higher switching frequency is the reduction in passive component dimensions and costs for either topology. It is therefore implied that a CSC may lead to a more efficient smaller converter in this application.

For the VSC topology, a three-phase converter is employed with an AC low pass filter to mitigate the impact of high dv/dt on the generator cable and machine windings. It is assumed the DC link is maintained at a constant value based on the generator voltage specification. The system requires a bi-directional DC-DC converter to achieve the desired voltage control of the ESS. For the CSC topology, the commutation capacitors already provide a high degree of dv/dt reduction to the generator and cabling. The current to voltage DC-DC conversion for the ESS is a fundamental part of the chosen CSC topology [23].

As part of this work a VSC, Fig 12, and CSC, Fig 13 have been built for comparison. Details of the CSC design can be found in [25].

Fig. 13. Current source converter laboratory prototype.

V. SYSTEM TESTING

To demonstrate the system operation, the V-shape VHM and VSC were selected and joined to an existing scale model of a wave energy converter [9]. The buoy, machine and power converter were tested in a range of sea-states and control regimes in a wave tank [26]. At full scale, it is envisaged that the submerged heaving buoy would have the power take off situated below the buoy, similar to that shown earlier in Fig. 1. For testing purposes, the power take off unit was located above the water line and coupled to the buoy via a pulley system, as shown schematically in Fig. 14 and photographed in operation in Fig. 15.

Fig. 14. Schematic of the testing architecture used to demonstrate the system

Fig. 15. Full system scale testing setup

Fig. 16. Power output from the electrical machine when couple to a submerged bouy for a range of wave frequencies with the generator controlled to give a variable damping stiffness (K_{vel})

A plot of power output from the generator over a range of fixed amplitude varying frequency sine waves is shown in Fig 16. At each wave frequency, the generator reaction force is controlled to act as a damper, i.e. to give a force proportional to velocity. At each wave frequency, the plot shows the familiar power capture curve implying there is an optimum damping coefficient for each wave state. This demonstrates that the generator and power converter can successfully extract power from the sea, and also that the power converter can be used to implement control of the wave energy device itself.

VI. CONCLUSIONS

Many wave energy devices are anticipated to produce slow speed reciprocating motion. This paper has discussed the development of electrical drives suitable for direct drive electrical power take off. Several topologies of linear permanent magnet machine have been presented. Of these, it appears the "V-Shape" version of the Vernier Hybrid Machine can convert the power at the most favourable power factor and with the highest efficiency. Cylindrical versions of some of the machines are possible, although mass savings can only be achieved for smaller machines. The requirements and design of two power converters has been presented. Sample results of the whole system tested in a scaled wave tank show this technology is suitable for use in a controlled wave energy converter.

ACKNOWLEDGEMENT

This work has been funded by EPSRC Ref. EP/N021452/1, (EDRIVE-MEC) under SUPERGEN Marine.

REFERENCES

- [1] L. Huang, H. Yu, M. Hu, C. Liu, and B. Yuan, "Research on a tubular primary permanent-magnet linear generator for wave energy conversions," IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 1917-1920, 2013.
- [2] I. A. Ivanova, O. Agren, H. Bernhoff, and M. Leijon, "Simulation of wave-energy converter with octagonal linear generator," IEEE Journal of Oceanic Engineering, vol. 30, no. 3, pp. 619-629, 2005.
- [3] A. Wahyudie, M. Jama, T. B. Susilo, B. F. Mon, H. Shaaref, and H. Noura, "Design and testing of a laboratory scale test rig for wave energy converters using a double-sided permanent magnet linear generator," IET Renewable power generation, vol. 11, no. 7, pp. 922-930, 2017.
- [4] O. Farrok, M. R. Islam, M. R. I. Sheikh, Y. Guo, and J. G. Zhu, "Design and analysis of a novel lightweight translator permanent magnet linear generator for oceanic wave energy conversion," IEEE Transactions on Magnetics, vol. 53, no. 11, pp. 1-4, 2017.

- [5] J. Prudell, M. Stoddard, E. Amon, T. K. Brekken, and A. Von Jouanne, "A permanent-magnet tubular linear generator for ocean wave energy conversion," *IEEE Transactions on Industry Applications*, vol. 46, no. 6, pp. 2392-2400, 2010.
- [6] R. Krishna, O. Svensson, M. Rahm, S. K. Kottayil, R. Waters, and M. Leijon, "Analysis of linear wave power generator model with real sea experimental results," *IET Renewable Power Generation*, vol. 7, no. 5, pp. 574-581, 2013.
- [7] E. Lejerskog, E. Strömstedt, A. Savin, C. Boström, and M. Leijon, "Study of the operation characteristics of a point absorbing direct driven permanent magnet linear generator deployed in the Baltic Sea," *IET Renewable Power Generation*, vol. 10, no. 8, pp. 1204-1210, 2016.
- [8] H. Polinder, M. E. Damen, and F. Gardner, "Linear PM generator system for wave energy conversion in the AWS," *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 583-589, 2004.
- [9] Carnegie. (26/04/2019). Available: <https://www.carnegiece.com/wave/>
- [10] Ocean Power Technologies. Available: <https://www.oceanpowertechologies.com/> (26/04/2019).
- [11] R. Watanabe, J.-S. Shin, T. Koseki, and H.-J. Kim, "Optimal design for high output power of transverse-flux-type cylindrical linear synchronous generator," *IEEE Transactions on Magnetics*, vol. 50, no. 11, pp. 1-4, 2014.
- [12] L. Cappelli et al., "Linear tubular permanent-magnet generators for the inertial sea wave energy converter," *IEEE Transactions on Industry Applications*, vol. 50, no. 3, pp. 1817-1828, 2014.
- [13] N. J. Baker, J. Wang, and G. J. Atkinson, "Optimization and comparison of linear transverse flux and flux switching machines," in 2016 XXII International Conference on Electrical Machines (ICEM), 2016, pp. 2471-2477: IEEE.
- [14] M. Mueller and N. Baker, "Modelling the performance of the vernier hybrid machine," *IEE Proceedings-Electric Power Applications*, vol. 150, no. 6, pp. 647-654, 2003.
- [15] M. Raihan, N. Baker, K. Smith, and A. Almoraya, "An E-core linear vernier hybrid permanent magnet machine with segmented translator for direct drive wave energy converter," in 2017 IEEE International Electric Machines and Drives Conference (IEMDC), 2017, pp. 1-6: IEEE.
- [16] N. J. Baker, M. A. Raihan, A. A. Almoraya, J. W. Burchell, and M. A. Mueller, "Evaluating Alternative Linear Vernier Hybrid Machine Topologies for Integration Into Wave Energy Converters," *IEEE Trans. Energy Convers.*, vol. 33, no. 4, pp. 2007-2017, 2018.
- [17] A. A. Almoraya, N. J. Baker, K. J. Smith, and M. A. H. Raihan, "Design and Analysis of a Flux Concentrated Linear Vernier Hybrid Machine with Consequent Poles," *IEEE Transactions on Industry Applications*, vol. In press, 2019.
- [18] A. A. Almoraya, N. J. Baker, K. J. Smith, and M. A. H. Raihan, "A New Configuration of a Consequent Pole Linear Vernier Hybrid Machine with V-shape Magnets," in 2018 XIII International Conference on Electrical Machines (ICEM), 2018, pp. 2002-2008: IEEE.
- [19] M. A. H. Raihan, N. J. Baker, K. J. Smith, and A. A. Almoraya, "Development and Performance Analysis of a Double Sided Linear Hybrid Reluctance PM Machine for Low Speed Applications," presented at the International Conference on Power Electronics Machines and Drives, Liverpool, 2018, 2018.
- [20] N. J. Baker, M. A. Raihan, and A. Almoraya, "A Cylindrical Linear Permanent Magnet Vernier Hybrid Machine for Wave Energy," *IEEE Transactions on Energy Conversion*, 2018.
- [21] M. Raihan, N. Baker, K. Smith, and A. Almoraya, "Development and Testing of a Novel Cylindrical Permanent Magnet Linear Generator," in 2018 XIII International Conference on Electrical Machines (ICEM), 2018, pp. 2137-2143: IEEE.
- [22] J. K. Shek, D. E. Macpherson, M. A. Mueller, and J. Xiang, "Reaction force control of a linear electrical generator for direct drive wave energy conversion," *IET renewable power generation*, vol. 1, no. 1, pp. 17-24, 2007.
- [23] S. P. McDonald, V. Pickert, and N. J. Baker, "High-Efficiency Current-Source Converter for All-Electric Wave Energy Conversion Systems," presented at the European Wave and Tidal Energy Conference, Cork, Ireland, 2017.
- [24] S. P. McDonald, N. J. Baker, M. Espinoza, and V. Pickert, "Power-Take-Off Topology Comparison for a Wave Energy Converter," presented at the IET Renewable Power Generation, Technical University of Denmark (DTU) 2018.
- [25] S. P. McDonald, N. J. Baker, and V. Pickert, "High-frequency current source converter for a direct drive powertrain in a wave energy converter," *The Journal of Engineering: The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)*, 2019.
- [26] (30/04/2019). FloWave Ocean Energy Research Facility. Available: <https://www.flowavett.co.uk/>