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

$B. McGilton^1, A. A. Almoraya^2, M. A. H. Raihan^2, R. Crozier^1, N. J. Baker^2, M. Mueller^1$

1. Institute for Energy Systems,
University for Edinburgh, Edinburgh,
United Kingdom
Contact: ben.mcgilton@ed.ac.uk

2. School of Engineering, Newcastle University,
Newcastle upon Tyne,
United Kingdom
Contact: a.a.a.Almoraya@Newcastle.ac.uk

Overview

The aim of this work is to assess the use of linear magnetic gear in a wave energy converter Power Take-Off (PTO). The concept combines two recent developments in drive train technology, the Consequent Pole Linear Vernier Hybrid Permanent Magnet Machine (CPLVHPMM) and the Linear Magnetic Gear (LMG). The combined system was fully realised in 3D FEM and compared to a similar direct drive machine in terms of mass and efficiency in order to assess the merit of using such a system in a heaving buoy type wave energy converter.

Linear Magnetic Gear Overview

The LMG establishes a linear force-speed step change through modulation of the magnetic field interacting between translators without any physical contact occurring [1] (figures 1 & 2).

While showing high efficiencies at peak force the LMG experiences virtually no wear, minimal acoustics, reduced lubrication and reduced sealing requirements when compared to traditional mechanical gears. The LMG additionally provides added survivability as the translators can "slip" under extreme forces, such as in storm conditions, preventing mechanical damage to the PTO.

These advantages make a magnetically geared system highly suitable to marine energy converters [2].

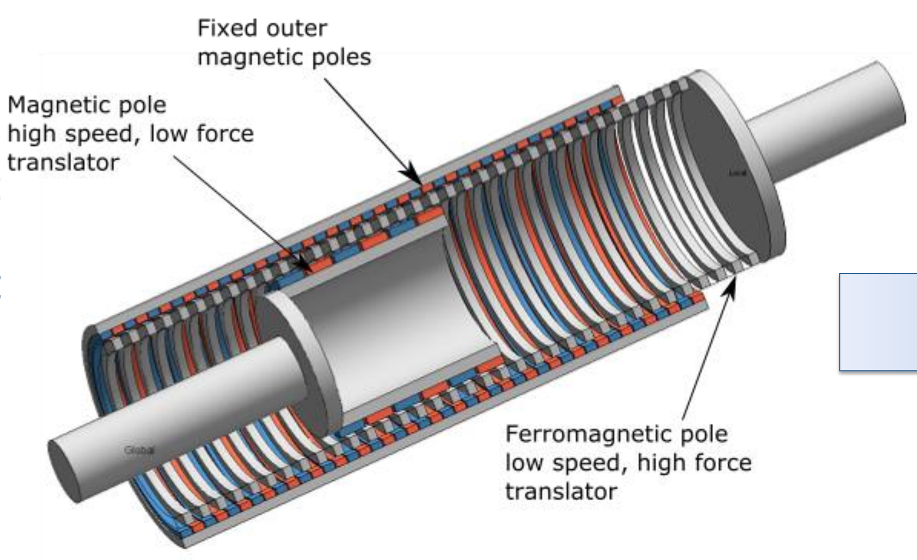

Figure 1. LMG cross section

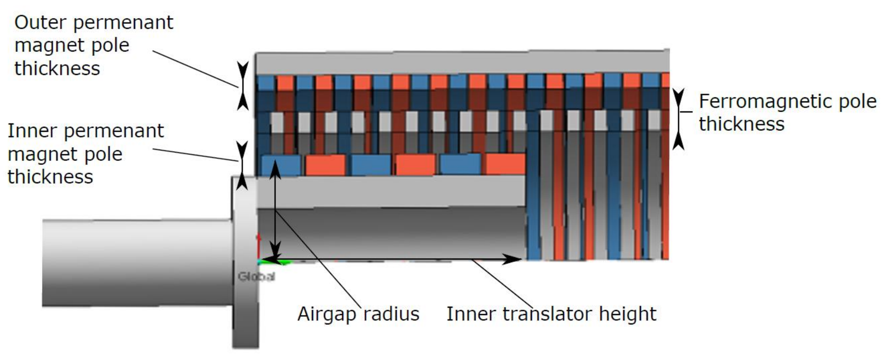

Figure 2. LMG primary force parameters

Full System Description

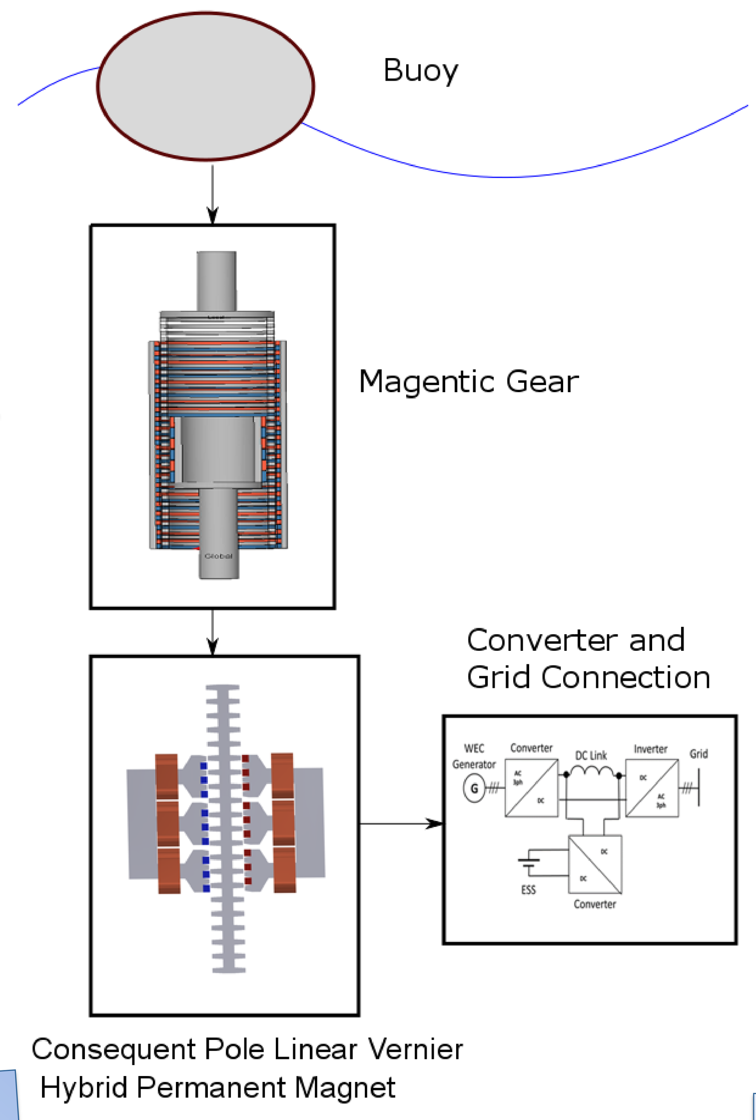

Figure 5. Proposed full system layout

The proposed system layout, shown in figure 5 has the heaving buoy attached to the magnetic gear's low speed, high force translator with the high speed translator then directly attached to the CPLVHPMM's translator.

In the case study a scaled version of a CPLVHPMM was designed for direct drive application with a max thrust of 740 N and a speed of 1.2 m/s resulting in a peak power rating of 888W. A LMG was then designed for this thrust value and a ratio of 3.3:1.

The stroke length was an important design aspect as the greater the length the more PM material is required. For this study this length was limited to 50 mm.

Consequent Pole Linear Vernier Hybrid Permanent Magnet Machines

The CPLVHPMM [2] comprises of double-sided stators with two identical E-cores facing each other in which both Permanent Magnets (PMs) and windings are located in the E-shaped stator (figure 3).

The operation principle of the CPLVHPMM is based on the magnetic gearing effect where the translator's teeth are utilised to modulate the stationary magnetic field produced by PMs to the high speed travelling magnetic field in the airgap (figure 4).

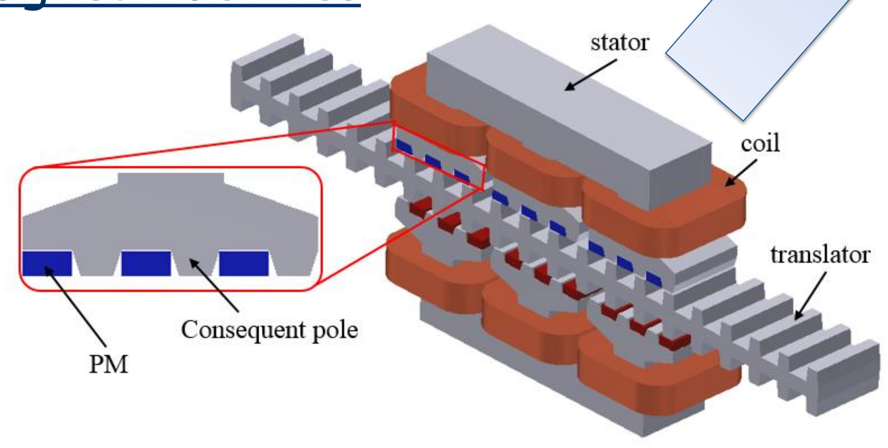

Figure 3. CPLVHPMM layout

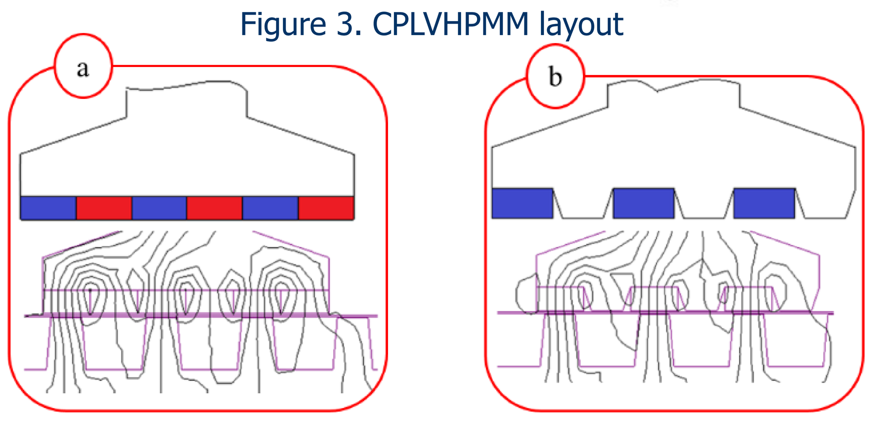

Figure 4. Effect of consequent poles on leakage flux

The translator possesses a simple pure iron rigid structure which is inherently low cost to produce a thrust force. Compared to the surface mounted version of this machine, (Figure 4a), the consequent pole version shown in Figure 4b represents a saving in magnet mass and is well suited to long stroke applications.

Case Study Results

The results of the case study are shown in the table below with the key mass comparisons shown in figure 6. The combined system resulted in an almost 30% reduction in active mass and a slight increase in efficiency. However, due primarily to the stroke length of the magnetic gear, the mass of PM material required increased by 47%, offsetting the advantage of using a consequent pole machine. Reported mass values only take into account active material and additional support systems will be required in both concepts.

Due to the increase in magnet mass, the combined system is only likely to be of use in wave energy converters characterised by low amplitude, high force oscillation.

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	%

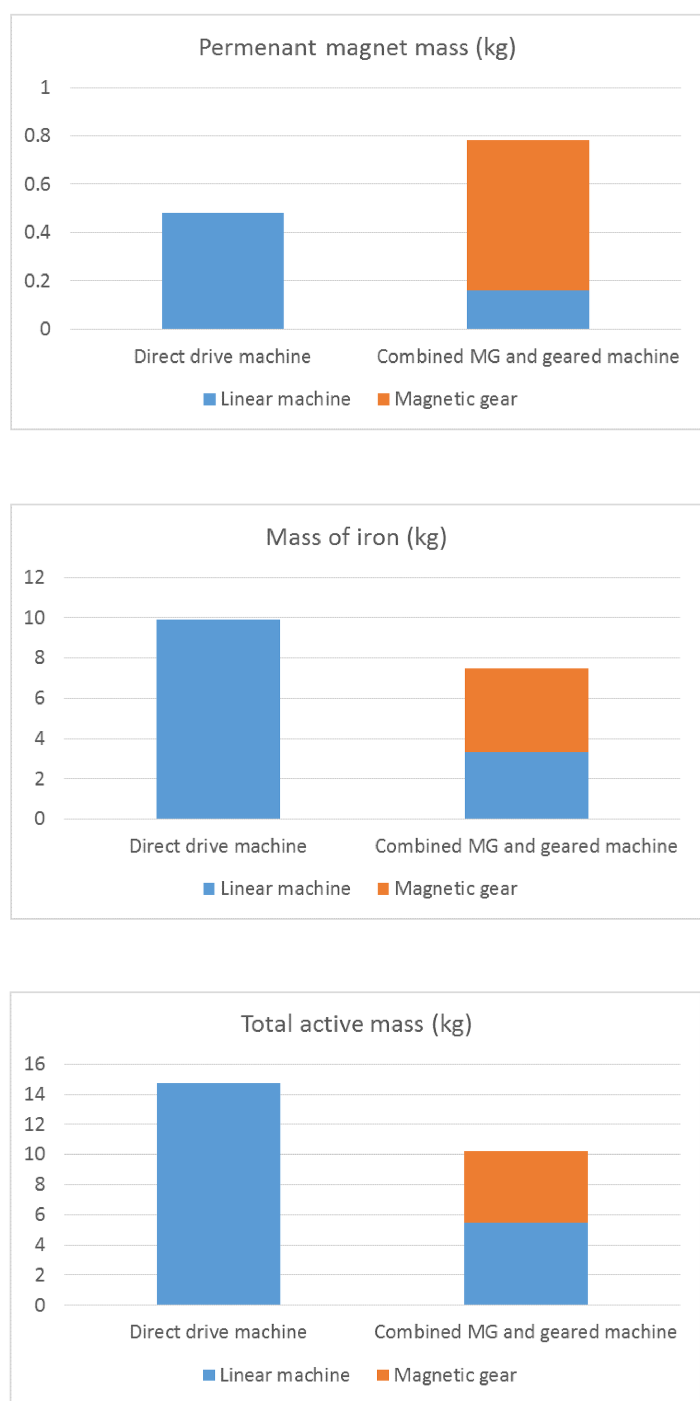

Figure 6. Key mass values of direct drive machine and combined system

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[2] B. McGilton, R. Crozier, A. McDonald, M. Mueller, "Review of magnetic gear technologies and their applications in marine energy." IET Renewable Power Generation 12.2 (2017): 174-181.

[3] 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.

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