Electric Machine Design for Wave Energy Converters

N.J.Baker, M.A.H.Raihan, A.A. Almoraya, J. Wang,

School of Electrical and Electronic Engineering, Newcastle University

Merz Court, Newcastle upon Tyne, NE1 7RU, UK.

nick.baker@ncl.ac.uk, m.a.h.raihan1@ncl.ac.uk

***Abstract*— Direct Drive Wave Energy has a unique set of requirements for an ideal power take off. The slow speed reciprocating nature of many primary movers leads designers to use either intermediate mechanical systems or force dense machine types. There is a play off between electrical machine capital cost, mass, efficiency, force ripple and power factor. This paper presents the development of a case study wave energy device and uses it as the basis to assess a number of machine topologies for use as the direct drive power take off. The aim is that it can be used to aid future electrical machine design studies for other devices.**

***Keywords*—Direct drive, linear generator, consequent pole, Vernier hybrid, flux switching machine**

I. Introduction to Direct Drive

This Paper relates to the development of an all-electric Power Take-Off (PTO) for a Wave Energy Converter (WEC). The natural motion of many wave energy converters presents two key challenges for the electrical machine designer: it is slow speed and reciprocating. This leads to the use and development of high force density and possibly linear machines.

High force density is often achieved by the use of rare earth permanent magnets (PMs), where the designer has the choice of topologies which minimise magnet use, such as the transverse flux machine at the expense of a poor power factor, or using a naturally higher power factor machine with a higher PM content. There is hence a play off between cost of machine, driven by magnet mass, and cost of converter, driven by VA rating.

In the case of a linear machine, a further unique set of problems results from the need for an overhang of either the translator or stator in order to have a constant active area throughout the stroke. This tends to favour designs where the coil and PMs are mounted to the same component, which precludes the use of the most torque dense designs.

This paper uses a nominal 25kW reciprocating wave energy device to asses four new designs of linear electrical machine in terms of performance, material cost and converter rating. The Vernier Hybrid Machine [1] is used as a baseline to compare performance. The paper discusses the development of the specification as well as the optimisation results of the four machines.

II. Specification

A. Target power and power

In order to evaluate alternative electrical machine topologies, a specification for a 25kW heaving buoy is devised. In wave energy, there are uncertainties in terms of resource, device architecture and rated verses average values of power in addition to control algorithms and non-linear effects of mixed seas, making a general design study challenging. To aid with this and allow general machine designs to be investigated, the following assumptions are made.

- Deep sinusoidal waves with a significant wave height of Hs = 2.75m, simplified to a wave 2.75m peak to peak, (1.375 m amplitude) and period 7.25 seconds.
- Device restricted to heave following profile of the wave
- Maximum energy extracted when average power is 50% of available power
- 25kW is average real electrical power output
- Electrical power converter efficiency = 95%
- Rms into electrical power converter = 26.5kW
- Peak power into electrical power converter =53kW
- Generator consists of 10 equal 2.5kW modules

These parameters are used to create a design specification and investigate alternative electrical machine topologies and machine design techniques.

B. Controller and assumed power take off behaviour

This is a relatively low power wave energy device, and we assume it is well enough controlled such that wave amplitude equals device amplitude (1.375m). I.e. peak to peak displacement (H_s) of 2.75 m and Peak speed ($\hat{\dot{x}}$) of 1.19m/s.

Electrical machine design is typically governed by the required force. Hence the design of the machine is inherently linked to the required generator force profile. The generator can be assumed to act like a damper, or to give a constant force.

Since Power = Force x velocity, if the generator is assumed to behave like a damper, then force from the generator is proportional to velocity, the power is proportional to velocity squared ($P=kV^2$). If the motion is a sine wave, the power is a $\sin^2$ function and the average power is 0.5 of the peak.

Alternatively, if the generator is connected to an active power converter, the force from the generator could be controlled. If rms current is fixed throughout a cycle, so too is generator force and hence power follows velocity and the profile would be a rectified sine wave, with the usual rms of peak/sqrt(2).

TABLE I: THE EFFECT OF POWER TAKE OFF CONTROL ON POWER AND FORCE

Parameter	**Velocity^2 (damping)**	**Constant force**
Average power	Peak/2	Peak /$2^{0.5}$
Average real power output (kW)	25	25
Peak power (kW)	53	37.5
Peak force(kN)	44	29.4

The relationship between peak and average values for the two force profiles is given in Table 1. Power and force profile for these scenarios are shown in Fig 1 for a single wave length /mechanical cycle.

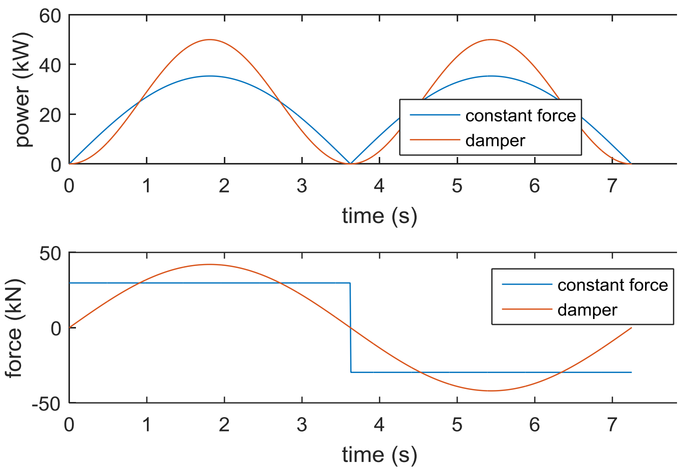

Fig. 1 Comparison of force and power for different power take off control for a 25kW average output.

For the same average power, therefore, the damper scenario requires a higher peak force.

Regardless of current control, within each electrical cycle, back emf will vary approximately sinusoidally, and there will also be some variation of electrical force (force ripple).

For a peak back emf of 339V (rms 240V), and a pole size of *pitch*, the flux linkage will vary approximately like

$$\Psi = \hat{\Psi}\sin\left(\frac{x}{pitch}2\pi\right) \quad (1)$$

The emf will vary as the derivative of this

$$emf = \hat{\Psi}\left(\frac{x}{pitch}2\pi\right)\dot{x}\cos\left(\frac{x}{pitch}2\pi\right) \quad (2)$$

This is a variable frequency variable amplitude signal.

For the damper scenario, current is assumed to follow the emf profile. The rms is therefore the rms of 2 sine waves

$$I_{damper\,rms} = \frac{\hat{I}}{\sqrt{2}\sqrt{2}} = \frac{\hat{I}}{2} \quad (3)$$

For the constant force profile, the current profile has a fixed amplitude and variable frequency, so

$$I_{constant\,rms} = \frac{\hat{I}}{\sqrt{2}} \quad (4)$$

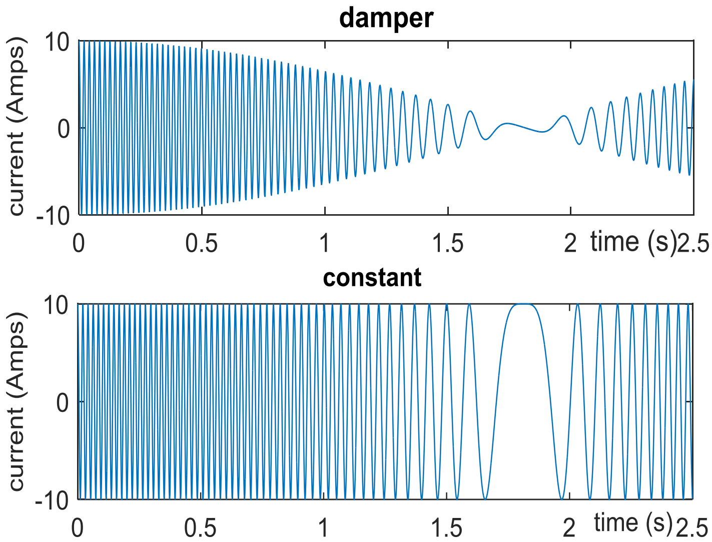

Fig. 2 Comparison of current profile for different power take off control. Peak current I the same, but for the damper Irms is greater

Both current profiles are shown in Fig 2, i.e. for the damper, I peak is sqrt(2) bigger than for the constant force scenario.

To allow for some control, we should allow an overload condition. Here, the average power should be allowed to be double the rated for 30 seconds without overheating

$$\overline{P_{overload}} = 2\overline{P_{rated}} = 53kW \quad (5)$$

The peak force required from the generator = peak power / peak velocity = 53/ 1.19 = 44kN

During normal operation we will assume a damper type system – in line with most assumptions to date. When control is being implemented, we will assume a constant force approach.

Common practise is for rms current in un cooled machines to be in the range of 3-8A/mm^2. Taking J_{rms}=3.5 A/mm^2 for ‘normal operation’ and assuming the ‘damper’ profile, the current will abide by equation (3).

For the 30 second overload condition, we assume J_{rms}=12 A/mm^2. As this is when the device is being controlled, it is more likely to follow the constant force profile and equation (4) is used to define rms current.

C. Specification and machine design

Table II shows the overall specification used for this electrical machine design study based on the arguments in the preceding section. Values of current density include a nominal fill factor and are chosen to remove the need for an external cooling circuit. Identical material characteristics assuming standard grade electrical steel (M270 -35A) and Neodymium Iron Boron magnets are used in all cases.

TABLE II: SPECIFICATION FOR ELECTRICAL MACHINE

Parameter	**value**	**unit**
Number of modules	10	
Average real power output	25	kW
Rated force	44	kN
Overload force	81	kN
Amplitude of oscillation	1.375	M
V_{phase} output	240	V_{rms}
Current Density (rated)	3.5 7	A/mm^2 rms A/mm^2peak
Current Density (overload)	12 17	A/mm^2 rms A/mm^2peak
airgap	1	mm

Fundamentally, electrical machines are sized on their rated torque (for example the machine in section III). For a permanent magnet machine, the design can be altered depending on whether machine size, cost, efficiency, power factor or force ripple is prioritised. In reality, it is a compromise between all these conflicting requirements and geometry is varied until a happy compromise is reached. This process can be done manually, as demonstrated in sections IV and V below, or it can be done via numerical optimisation with a weighted objective function, as presented in section VI below.

III. BASELINE MACHINE (VHM)

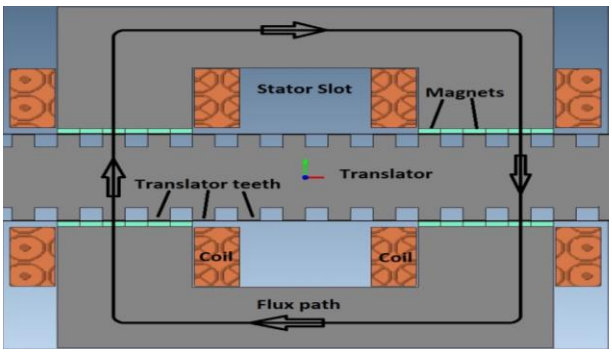

Fig. 3 The baseline single phase C-core design – the VHM

A Vernier Hybrid Machine (VHM) design and performance analysis was presented in [1] and is shown in Fig 3. The machine is a member of the variable reluctance PM machine family and exhibits high force density due to the perfect reluctance variation and flux reversal characteristics of the slotted translator. The VHM is here used as a baseline machine as it is known for high power and force density with simple and rigid structural construction In the base-line design [1], 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 mover 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, and a corresponding high back emf and force production - this phenomena is called magnetic gearing. This magnetic gearing is a non-contact method that enables direct drive machines to reach higher force density without the use of a gearbox.

The baseline machine has been taken forward to two alternative improved topologies, as discussed in the below sections.

IV. E CORE VHM

A. Topology Development

The three C-core units of the VHM can be integrated together to make two 3-phase E-core units that reduce the active volume of the machine, increase the robustness and mechanical stability [2]. Each generator module consists of two E-cores that are electrically and magnetically decoupled and can form independent 3-phase units. The advantage of two neighbouring E-cores is that, by 180 electrical degree phase shift between them, it is possible to reduce the cogging and force ripple and thus improve the performance of the machine [2]. Each E-core consists of three stator faces 120 electrical degrees apart to make a complete 3-phase machine unit.

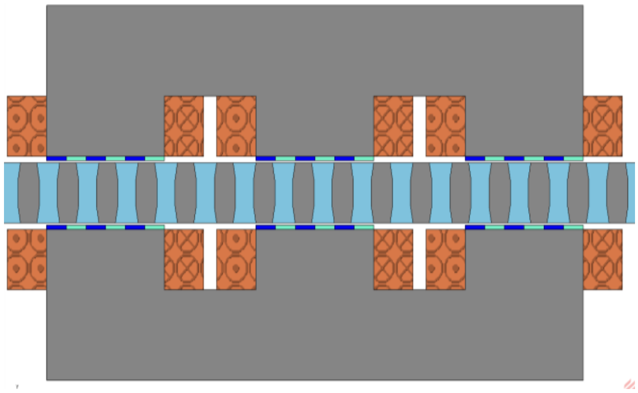

Fig. 4. One E-core unit of the two E core VHM design module

As the flux circulates between top and bottom E-cores through the translator, it is possible to redesign the translator without the core. The coreless segmented translator minimises the active translator mass substantially and is shown in Fig 4.

Laminated teeth are separated by non-magnetic spacer teeth. The entire translator structure may be encapsulated in a non-magnetic sleeve, or perhaps potted. The non-magnetic spacer teeth could be a very low mass material, making the entire translator neutrally buoyant.

The translator teeth are chamfered to distribute the flux inside the fringed teeth, allowing more space for the flux in the middle of the tooth and avoiding saturation in the tooth root. Segmenting and chamfering the translator improves the back EMF and the average force, as shown in Fig.5.

After all the design improvements were applied to the magnet, stator tooth, coils, translator tooth and slots and ultimately combining 3 phases within the new E-core model, the segmented translator model can produce 25% more back EMF and 16% higher force then the initial C-core model of VHM Fig. 6.

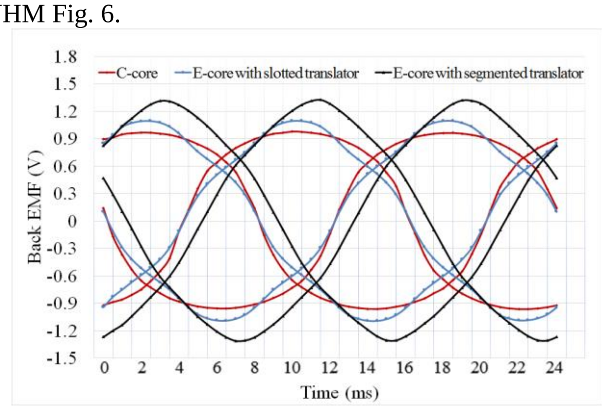

Fig. 5. Back EMF per turns comparison between the baseline VHM and the E- core VHM models.

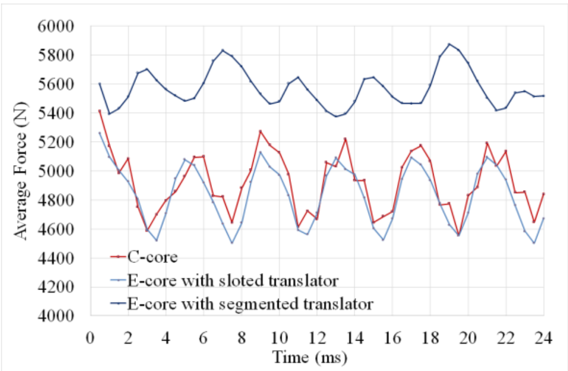

Fig. 6. Rated force comparison between baseline and E-core models.

B. *25kW Design (minimum magnet mass)*

Magnet height has been manually investigated and it's been found that 2.1mm height of magnets gave best results in terms of cogging, back EMF and active forces [2]. Normally force and back EMF should increase linearly with magnet height while in the VHM the leakage is prevalent due to the adjacent polarity magnets and in fact force reduces with the increase of magnet height. By performing magnet optimisation, it is possible for the E-core model to save 48% magnet mass, while providing higher force and back EMF.

In the 25kW generator model, 10 identical modules of two E-core units have been used in the direction of motion. Each of the modules produces 2.5kW of power with an efficiency of close to 94%. The complete machine is able to generate 44kN force with a ripple of less than 8%. Power Factor (PF) of the machine is 0.37, which is relatively high in this type of machine [3,4], albeit low for 'normal' machines.

C. *25kW Design (improved power factor)*

Variable reluctance machines including the VHM have the reputation of very poor power factors in the range of 0.25~0.4 [2, 3]. By increasing magnet mass, it is possible to increase inductance and hence improve power factor. Magnet height was fixed in the previous section and so increasing magnet mass is here achieved by extending the machine axially. Back EMF per turn increases linearly and thus the rated MMF for a constant force is reduced. This procedure improves the PF almost linearly – Table III.

TABLE III: INFLUENCE OF AXIAL LENGTH ON THE PF AND BACK EMF (E CORE)

Axial Length (mm)	**75**	**110**	**150**	**225**	**300**
PM thickness (mm)	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
PF	0.23	0.31	0.38	0.53	0.63
Back EMF (Peak)	20.2	29.6	40.4	60.6	80.8
PM mass (kg)	10.2	15	20.4	30.6	40.8

D. *Lab scale prototype dimensions*

Design and analysis has so far been considered as 2 dimensional, with a constant cross section into the plane of the paper, with a double sided configuration. In fact, linear machines can be constructed single sided or with a cylindrical cross section. For use in wave energy converters, the cylindrical design *may* have advantages in terms of sealing and being able to twist, whereas a square cross-section must rigidly react against lateral torque. A cylindrical version of the E-core machine is being investigated, Fig. 7. The shown dimensions are capable of producing the design power and force, although no electro-mechanical advantages or mass savings have yet been found with this design.

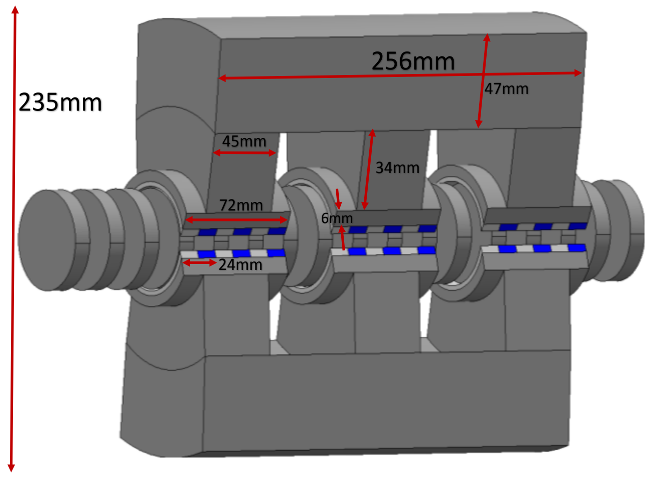

Fig. 7 Dimensions of a single 1.25 kW module

V. Consequent Pole VHM

A. Topology Development

The consequent pole machine possesses the same basic structure and operation principle as the baseline VHM, except that alternate PMs are replaced with tapered ferromagnetic poles, the *consequent poles*. All remaining magnets have the same polarity (south), while the ferromagnetic poles operate as north poles as shown in Fig.8. Hence, the number of PM pole pairs of the baseline VHM and consequent pole machines are equal. Fig.9 confirms that smaller pole to pole flux leakage is produced by the consequent pole machine compared to its counterpart. In other words, the flux linkage of the consequent pole machine is higher than that of the base-line machine. The effect of employing tapered consequent pole on the back EMF and cogging force characteristics has been investigated in [5].

By adopting consequent pole arrangement, the flinging flux can be reduced resulting in a noticeable increase in the main flux as shown in Fig.9. The rate of change of the flux linkage is enhanced and the induced no-load back EMF is proportionally increased as a result. In addition, with the use of the ferromagnetic poles, the active airgap is reduced and thus the corresponding magnetic reluctance is much lower than that of the baseline machine. Force and power density can be significantly improved [6]. Moreover, this machine is regarded as a doubly salient machine in which the salient poles are capable of transmitting high thrust force.

Since each stator tooth adopts three PMs and three ferromagnetic poles, the magnet mass is reduced by 50%, potentially leading to a reduction in the original cost of PM material.

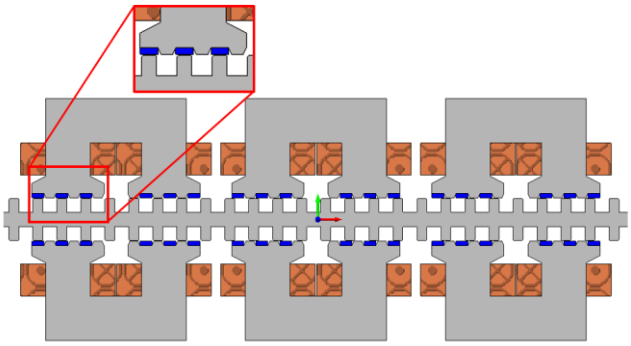

Fig. 8 The consequent pole machine

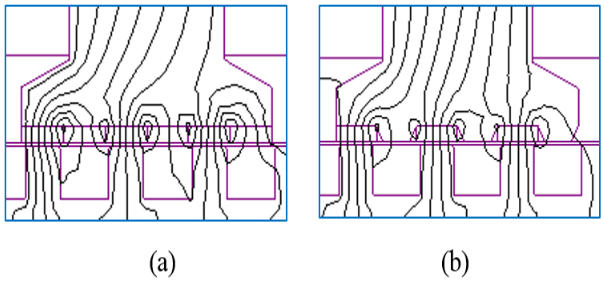

Fig. 9 Flux path of the VHM (a) and consequent pole (b) machine

B. 25kW Design (minimum magnet mass)

A 25kW consequent pole design comprises of ten equal 2.5kW units. Each unit has six C-cores facing each other, while the iron translator is sandwiched in between. Based on the aforementioned analysis, the consequent pole machine is capable of generating high thrust force with an acceptable value of force ripple, 4%, while it requires half of the magnet mass of that of the baseline VHM. Another key feature of this machine is that the cogging force is about 4.8 % of the average force making the machine operate smoothly. However, as expected with this family of machines and discussed above, the power factor of the consequent pole machine when designed for minimum magnet mass is low (0.36) caused by the stronger armature reaction.

C. 25kW Design (improved power factor)

In order to investigate the effect of changing the machine parameters on its power factor different methods have been individually carried out using FEA. The influence of varying PM thickness on PF has been analysed and Table III shows the impact of increasing PM thickness. As the magnet thickness increases the power factor is slightly improved due to the additional flux linkage produced by the extra amount of magnet material. However, as the magnet thickness rises the leakage flux is increased which contributes to a minor improvement of the power factor. Moreover, by increasing the PM thickness beyond 6mm, saturation starts to affect the thrust performance. In addition, increasing magnet thickness up to 6mm is not an effective method of power factor improvement, where 50% extra magnet martial improved the power factor by only 12.6%. Therefore, the magnet thickness of 4mm is kept the same as the baseline.

TABLE IV: INFLUENCE OF PM THICKNESS ON THE PF

PM thickness [mm]	**4**	**4.5**	**5**	**5.5**	**6**
PF	0.36	0.362	0.367	0.376	0.385
Back EMF (RMS)	87	91.2	92.8	94.8	96.8

As for the E-core design, varying axial length has been investigated separately to improve the PF. Table V illustrates the effect of increasing the machine axial length on the PF. It can be found that by increasing the axial length the PF can be improved almost linearly. In addition, since the armature current is reduced the machine losses are reduced. By adopting this method the magnet mass and machine mass is linearly increased with the axial length.

TABLE V: INFLUENCE OF AXIAL LENGTH ON THE PF

Axial Length (mm)	**81**	**160**	**200**	**220**	**260**	**300**
PM thickness (mm)	**4**	**4**	**4**	**4**	**4**	**4**
PF	0.2	0.36	0.42	0.44	0.48	0.52
Back EMF (Peak)	44	87	108.9	119.5	134.4	143.5
PM mass (kg)	10.4	20.7	25.87	28.6	33.6	38.8

VI. FLUX SWITCHING AND TRANSVERSE FLUX MACHINES

A. Topology Development

The Transverse Flux Machine (TFM) is often proposed for torque dense applications such as that required for electric vehicles [7,8]. In a linear form it has been studied for wave energy [9] and the free piston engine [10,11]. The flux path is three dimensional, precluding the use of a simple laminated structure. Rotary topologies have been presented which use soft magnetic composites [11], laminations [12], or a combination [13]. The advantage of having no competition between space requirements of flux carrying teeth and space occupied by windings is well documented in the literature [14]. Fig 10 shows the basic layout of a cylindrical TFM.

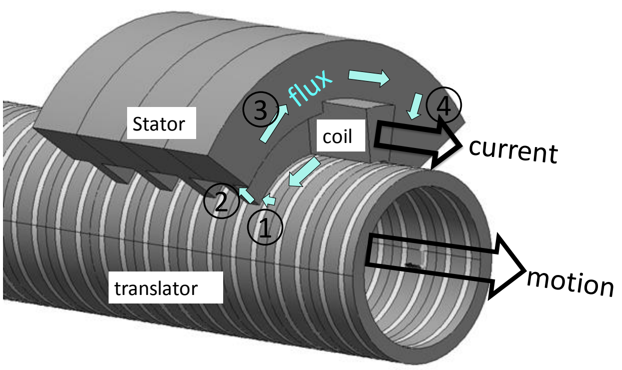

Fig. 10. The linear transverse flux machine

In wave energy, the amplitude of oscillation is likely to be large compared to the length of the stator. In this case study, for an active length of 6m and movement of 2.8m, at any one time less than 70% of the magnets are being utilized, with the other 30% being outside the stator. In order to improve magnet utilization, the TFM advantages are combined with a flux switching type machine to allow the magnets to be mounted on the stator, as with the previous topologies.

A Linear Flux Switching Machine (FSM) has the magnets located within the same toothed structure as the coil. Interaction with a moving iron translator manipulates the flux to oscillate around the coil in order to induce an emf– Fig 11.

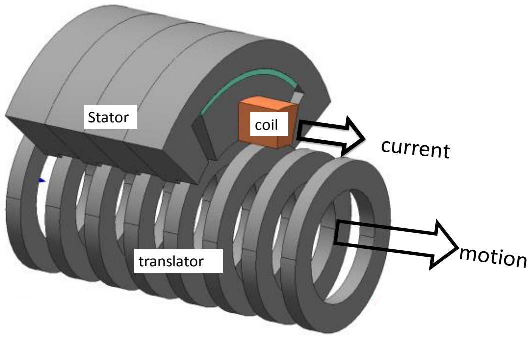

Fig. 11 Tubular flux switching machine

Linear FSMs have been proposed in Super conducting form for wave energy [15] and linear transportation [16,17]. They are particularly attractive in applications where the stroke is long, as the moving translator consists of a pure iron structure [18]. Other authors have considered topologies where the current moves perpendicular to the physical motion, in both flat [19] and tubular configurations [20].

In all reported configurations, the coil slot width and magnet height share the same orientation and together make up the stator pole pitch. There is hence a play off between the magnetic and electric loading. The topology proposed here has the current flowing parallel to the direction of motion and hence imitates the three dimensional flux path of the transverse flux machine. The stator mounted magnets are radially magnetized and the flux path is modulated by the interaction of a set of offset translator teeth and straight stator teeth.

The two flux paths, corresponding to the translator teeth aligning with alternate stator teeth, are shown in Fig 12. The flux is gathered circumferentially on the upper and lower surfaces of the magnet, before being channeled radially down stator teeth. There is an inherent leakage path circumferentially across adjacent teeth - also shown in Fig 12. The topology was first previously introduced by the authors [21] and is effectively a linear version of the Flux Switching Modulated Pole Machine which was shown in [22] to offer a lower component count and simplified rotor at the expense of an 18% reduction in rated torque per unit magnet mass.

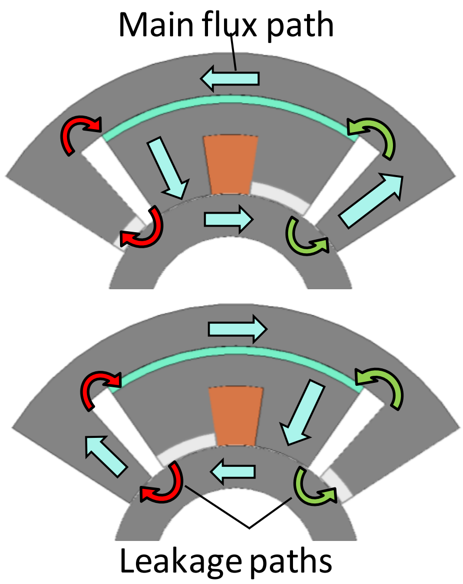

Fig. 12. Flux paths in the FSM

B. 25kW Design optimisation for minimum electric load and minimum magnet mass

For linear flux switching machines and the TFM, output force is generally related to the magnetic loading, electric loading and translator surface active area [23]. Since there is no inherent limit on the translator mass in wave energy then there are two optimisation strategies to trade-off: minimising electric loading (stator MMF) or minimising magnetic loading (minimise magnet mass).

This design has been optimised in commercialised software MagNet, where all topology dimensions are set as variables with a single design objective and force requirement. An internal algorithm will converge the result to optimal condition within all variables' limits. The variables of this design are shown in Fig. 13 below. Here, the authors have used both the minimising electric loading and minimising magnet mass goals to investigate better machine efficiency and power factor [21]. Single electrical poles of the resulting machine designs are shown in Fig 14 and results are listed in section VII.

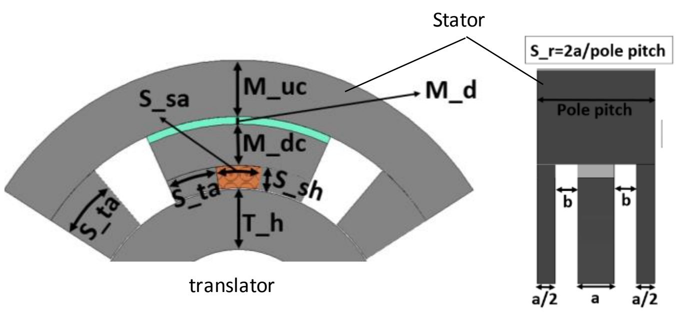

Fig. 13. Design variables for FS

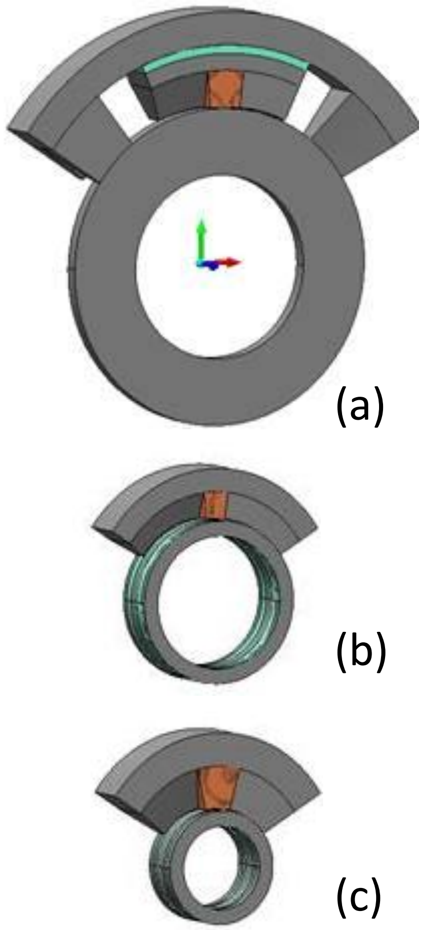

Fig. 14. *Final designs (a) flux switching (b) transverse flux high power factor (c) transverse flux low magnet mass*

VII. Machine Comparisons and Discussion

A. General comparison

Machine design is a compromise between alternative parameters. The Carbon Trust argued that for wave energy converters, it is Cost of Energy (CoE) that is most important, based on Present Values (PV) [24]. Using this metric, the cost of energy of the electrical drive will be of the form

$$
\begin{aligned}
\text{CoE} &= \frac{\pounds}{\text{kWh}} \\
&= \frac{\text{capital cost} + \text{PV (operation \& maintenance cost)}}{\text{PV (energy produced over device life time)}} \\
&= \frac{\text{Capex} + \text{Opex}}{P_{\text{wave}}\eta} \times \text{constant}
\end{aligned} \tag{6}
$$

For a fixed wave field (P_{wave}) and assuming operational expenditure (opex) for the generator is minimal and magnet mass is the dominant cost differentiator between these designs, (6) can be simplified to :

$$\mathrm{CoE} = \frac{A \times \text{magnet mass} + B \times {}^{1}\!/_{\text{power factor}}}{\eta} \tag{7}$$

Where A is the supply and processing cost of magnet material used in the electrical machine (£/kg) and B is the market value of a power converter based on its rating (£/kVA). Power factor is the ratio of real and reactive power for the generator. A machine with a lower power factor hence requires a larger converter to deliver the same real power.

If the magnet mass between designs is fixed, this can be further summarised as

$$\text{cost of energy} = f(\eta.\text{powerfactor}) \tag{8}$$

Efficiency and power factor are hence provided in the following sections to evaluate alternative machine types.

B. *VHM machines*

Fig 15 shows the relationship between magnet mass and power factor for the two VHMs. It clearly shows that magnet mass can be used to improve power factor. At all values, the E-core machine has a higher power factor. Other comparison criteria are shown in Table VI for three fixed magnet masses. Here, and throughout this paper, the computed efficiencies are based on mechanical output power and copper, iron and magnet losses.

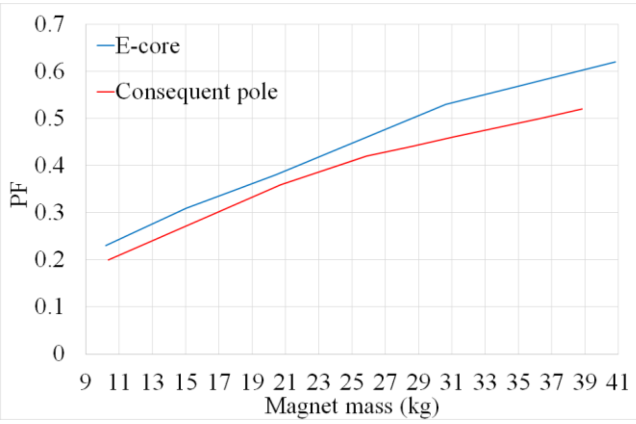

Fig. 15 variation of PF with respect to the magnet mass for E-core and consequent pole machines

TABLE VI: COMPARISON OF VHMS

	E-Core			Cons. pole		
Magnet mass (kg)	10.2	20.4	40.8	10.4	20.7	38.8
Power factor	0.23	0.38	0.62	0.2	0.36	0.52
Stator mass (kg)	560	890	1460	560	890	1320
Force ripple (kN)	1.8	3.7	7.2	1.2	2.4	3.6
Efficiency at rated current	89	94	95	94	97	98
Overload force capability (kN)	60	79	77	56	79	87
Translator mass (kg)	87	174	348	87	174	348

In this example, these results suggest that the E-core can deliver an improved power factor, whereas the consequent pole will operate at a higher efficiency.

C. *Transverse machines*

A comparison of the transverse flux machines is shown in Table VII. The flux switching machine has the largest magnet mass of all, despite only having magnet in the active part of the machine. It has proved difficult to curtail the leakage paths shown in Fig 12 and the flux switching machine is hence discounted from further consideration.

The TFM optimised for low electric loading has a power factor of 0.8, but at the expense of double the base line machine in terms of magnet mass. For the TFM optimised for low magnet mass, its performance is comparable to the equivalent VHMs i.e. a magnet mass of ~20kg for a power factor ~0.35 – despite many of the translator mounted magnets being inactive.

TABLE VII: COMPARISON OF VHMS

	Flux switching	**Transverse flux (minimising MMF)**	**Transverse flux (minimising magnet usage)**
Magnet mass (kg)	76.6	65.3	23.5
Translator diameter (mm)	60	32	22
Total mass stator (kg)	1535	471	648.7
Total mass translator (kg)	404	167	110
Active length (mm)	6000	6000	6000
Cogging force (kN)	2.0	6.4	3.0
Efficiency at rated current (%)	94	97	94.8
Power factor at rated current	0.30	0.80	0.34
Overload force (kN)	56.3	78	52

VIII. CONCLUSION

A generic 25kW specification has been developed for a wave energy converter. It is shown how this can be used to relate peak and average values of force and current within an all electric power take off. Several machine topologies have been presented. Force dense permeant magnet machines are known for their poor power factor and it is shown that this can be improved, but at the expense of increased magnet mass. A brief discussion of the cost of energy of the electric drive is presented.

Two variations of a linear Vernier Hybrid Machine are investigated, where the magnets are mounted on the stator. It appears that the E-core Vernier Hybrid Machine can give the greatest power factor, whereas the Consequent pole can achieve a higher efficiency.

Two transverse flux machines topologies were presented, optimised for power factor and minimal magnet mass respectively. In a classic transverse flux machine, magnets must be mounted on the translator and so a flux switching variant was considered. In this application, the flux switching performance was curtailed by pole leakage and the transverse flux machine could not offer an overall performance improvement in terms of magnet mass and power factor compared to the Vernier Hybrid Machines.

IX. Reference

[1] M.A. Mueller, N.J. Baker, "Modelling the Performance of the Vernier Hybrid Machine" , IEE Part B Proc. Elec. Power Appl., Vol 150, no. 6, November 2003, pp647-653.

[2] M.A.H. Raihan, N.J. Baker, K.J. Smith, A.A. Almoraya "An E-core Linear Vernier Hybrid Permanent Magnet Machine with Segmented Translator for Direct Drive Wave Energy Converter" IEEE, IEMDC, Miami 2017 2017. In Press.

[3] T. W. Ching, K. T. Chau, and W. Li, "Power factor improvement of a linear Vernier permanent-magnet machine using auxiliary DC field excitation," IEEE Transactions on Magnetics, vol. 52, pp. 1-4, 2016.

[4] E. Spooner, L. Haydock, "Vernier hybrid machines", IEE Proceedings - Electric Power Applications 2003, Volume: 150, Issue: 6 Pages: 655 - 662,

[5] A.A. Almoraya, N.J. Baker, K.J. Smith, M.A.H. Raihan, "Development of a Double-Sided Consequent Pole Linear Vernier Hybrid Permanent-Magnet Machine for Wave Energy Converters". IEEE, IEMDC 2017, Miami 2017 2017. In Press.

[6] X. Liu, C. Zou, Y. Du, and F. Xiao, "A linear consequent pole stator permanent magnet vernier machine," in Electrical Machines and Systems (ICEMS), 2014 17th International Conference on, 2014, pp. 1753-1756.

[7] H. Yu-Sheng, T Mi-Ching, "Development of a Novel Transverse Flux Wheel Motor" *IEEE Trans on Magn*, 2011, Vol 47, Issue: 10 pp 3677-3680

[8] N.J. Baker, G.J. Atkinson, J.G. Washington, B.C. Mecrow, G. Nord, L. Sjoberg, "Design of high torque traction motors for automotive applications using modulated pole SMC machines", *Proceedings of IET Power Electronics, Machines and Drives* (PEMD 2012),

[9] H. Polinder, B.C. Mecrow, A.G. Jack, P.G. Dickinson, M.A. Mueller, "Conventional and TFPM linear generators for direct-drive wave energy conversion", *IEEE Trans on Energy Conversion*, vol 20 pp260-267 2005

[10] P. Zheng, C. Tong, G. Chen, R. Liu, Y. Sui, W. Shi. S. Cheng. "Research on the Magnetic Characteristic of a Novel Transverse-Flux PM Linear Machine Used for Free-Piston Energy Converter", *IEEE Trans on Magn*, pp 1082 - 1085 Vol 47, Issue: 5, 2011

[11] G. Lei, C. Liu, Y. Guo, J. Zhu, "Multidisciplinary Design Analysis and Optimization of a PM Transverse Flux Machine with Soft Magnetic Composite Core", *IEEE Trans on Magn*, 2015, Issue: 99

[12] K. Lu; W. Wu , "High Torque Density Transverse Flux Machine Without the Need to Use SMC Material for 3-D Flux Paths", *IEEE Trans Magn*, 2015, Vol51 issue 3

[13] J.G. Washington, G.J. Atkinson, N.J. Baker, A.G. Jack, B.C. Mecrow, B.B. Jensen, L. Pennander, G.L. Nord, L. Sjöberg, "Three-Phase Modulated Pole Machine Topologies Utilizing Mutual Flux Paths", *IEEE Trans on Energy Conversion*, Vol 2 pp507-515 2012

[14] H.M. Hasanien, A.S. Abd-Rabou, S.M. akr, "Design Optimization of Transverse Flux Linear Motor for Weight Reduction and Performance Improvement Using Response Surface Methodology and Genetic Algorithms", *IEEE Trans on Energy Conv*, 2010, pp598-605, vol 25

[15] L. Huang, J Liu, H, Yu, R. Qu, H, Chen, H, Fang, "Winding Configuration and Performance Investigations of a Tubular Superconducting Flux-Switching Linear Generator", *IEEE Trans on Applied Superconductivity*, 2015, Vol 25,

[16] S.E. Abdollahi, S. Vaez-ZAdeh, "Back EMF Analysis of a Novel Linear Flux Switching Motor With Segmented Secondary", *IEEE Trans on Magn*, 2014, Vol 50

[17] R. Cao; M. Cheng; Mi, C.; W. Hua; W. Zhao, "Comparison of Complementary and Modular Linear Flux-Switching Motors With Different Mover and Stator Pole Pitch", *IEEE Trans on Magn*, 2013, Vol 49, pp 1493 - 1504

[18] W. Min, J.T. Chen, Z.Q. Zhu, Y. Zhu, M. Zhang, G.H. Duan, "Optimization and Comparison of Novel E-Core and C-Core Linear Switched Flux PM Machines", *IEEE Trans on Magn*, 2011, Vol 47 pp 2134-2141

[19] L. Huang, H. Yu, M. Hu, J. Zhao, Z. Cheng, "A Novel Flux-Switching Permanent-Magnet Linear Generator for Wave Energy Extraction", *IEEE Trans on Magn*, 2011, Vol 47, Issue: 5

[20] J. Wang, W. Wang, K. Atallah, D. Howe, "Design Considerations for Tubular Flux-Switching Permanent Magnet Machines", *IEEE Trans on Magn*, 2008, vol 44, pp4026-4032

[21] J. Wang, N.J. Baker, "Comparison of flux switching and modulated pole linear machines for use with a free piston", 2015 *IEEE Electric Machines & Drives Conference* (IEMDC 2015),

[22] N. Ahmed, G.J. Atkinson, N.J. Baker, L. Sjoberg, N. Stannard, "Flux Switching Modulated Pole Machine topologies which offer greater mechanical simplicity", *2013 IEEE Electric Machines & Drives Conference* (IEMDC 2013)

[23] N.J. Baker, J. Wang, G.J. Atkinson, "Optimization and comparison of linear transverse flux and flux switching machines" Electrical Machines (ICEM), 2016 XXII International Conference on. IEEE, 2016: 2471-2477

[24] J.Callaghan, R. Boud,, Carbon Trust, Future Marine Energy, Results of the Marine Energy Challenge, Cost competitiveness and growth of wave and tidal stream energy January 2006, see https://www.carbontrust.com/resources/reports/technology/marine-energy/ (accessed July 2017)