Comparison of Linear Generators for Wave Energy Applications

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Linear generators are classified based on their topology and excitation methodology. These classifications affect efficiency, reliability, controller design, maintenance requirements, construction and materials requirements, and consequently the cost of implementation. Determining the best linear generator topology for wave energy extraction has yet to be achieved by wave energy researchers and designers. This paper investigates state-of-the-art research and commercial applications for linear electric machines in order to reach conclusions and recommendations for linear generator designs used in wave energy applications.

Nomenclature

B	=	Flux Density
LSM	=	Linear synchronous motor
LSRM	=	Linear synchronous reluctance machine
LSHM	=	linear synchronous homo-polar machine
PM	=	Permanent magnet
TFPM	=	Transverse flux permanent magnet
V	=	Voltage
VHM	=	Vernier hybrid machine

I. Introduction

THIS PAPER begins to address unanswered questions in wave energy conversion technologies, namely, whether linear generators (LG's) are a viable solution for wave energy converters, and if so, which one(s) should be used. LG's have inherent cost disadvantages when compared to their rotary counterparts, however their simplicity implies reliability and longevity which may make them advantageous in wave energy conversion. This paper is not directed at comparing linear with rotary designs, but rather determining the best linear generators for converting linear ocean wave motion into electricity. These optimal linear generators can then be compared against other system design choices such as linear to rotary machines with rotary generators.

There are numerous considerations in answering the proposed question. The ocean wave environment is the primary driver of the machine and its range of inputs to a wave energy system must be quantified in order to properly identify the LG's role in the application. The classifications of linear generators will be explored and defined to aid in comprehending their advantages and disadvantages in a wave energy application. For a given generator and system design, the control and excitation strategy may significantly affect the overall cost performance and should also be considered. Investigation into comparative techniques of similar technologies will provide insight into a proposed analysis approach. Current and relevant data on LG's will be used to make a preliminary assessment and comparison of the numerous LG options, identify additional research needs, and make recommendations on a system level selection methodology. After evaluating the existing LG options, it is apparent that several of the LG's evaluated are preferred.

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II. Wave climate and system considerations

The LG's being investigated will be subjected to the forces and velocities created by ocean waves. Wave climates vary seasonally and by location, thus generator inputs will vary substantially. For the purpose of evaluating LG's in direct drive wave energy converters, both the wave climate and prime mover (buoy, float, etc) will directly impact the force and velocity driving the LG. A buoy exposed to a wave front can be expected to encounter significant seasonal variations in wave power, in one practical example between 3.6 kW/m (T=6.5 s, Hs=0.75m) and 300 kW/m (T=12 s, Hs = 5m) [1]. These power levels are commonly computed using equation (1) [1], which is often arranged as shown in (2) to provide a measure of power per unit wave crest.

$$P = \frac{W \rho g^2 T H_s^2}{32\pi} \tag{1}$$

$$\frac{P}{W} = \frac{\rho g^2 T H_s^2}{32\pi} \tag{2}$$

P mean power (w)
g gravitational acceleration (9.81m/s^2)
H_s significant wave height (m)
ρ density of sea water (1025 kg/m^3)
W width of wave crest (m)

To optimize a generator to accommodate two orders of magnitude in power variation may be financially impractical. In the same way that wind turbines pitch their blades to reduce the power input to the system [2], wave energy devices may need to reduce the power input to the direct drive mechanism. In this study nominal values based on a survey of present wave energy technologies and research will be used.

A. Wave climate and system considerations

A high thrust wave energy converter that operates underwater, known as the Archimedes Wave Swing (AWS) operates at an assumed peak sinusoidal velocity of 2.2 m/s and a floater amplitude of 3.5m with a maximum required force of one MN [3]. Of the multiple studies surveyed, peak prime mover velocities of 0.5, 1.0, 2.1, and 2.2 m/s were used.

B. Direct drive wave power devices

The term direct drive means that the generator is directly coupled to the prime mover. In a wave energy application this implies that the generator motion will be reciprocating with sinusoidal or other characteristics. The key advantage to direct drive mechanisms is the removal of inefficient mechanical (e.g. hydraulic) or pneumatic conversion systems [1], [3], [4], and [5]. The methods studied in this research on determining LG performance in a direct drive wave energy converter are based on machine modeling that assumes a sinusoidal machine motion. In this study a peak velocity will be assumed with the understanding that some other velocity profile (such as trapezoidal) may be a preferred operational strategy.

C. Cost of system

Equalizing machine cost and efficiency between competing LG's must be implemented to allow for a comparative decision. It is proposed by Polindedr et al. that one such technique can be implemented by adjusting the total cost of each system by its power losses over a five year period [3]. A high efficiency machine will therefore have a lower cost penalty. This cost concept is represented in Eq. (3) below [3].

$$C = C_{gen} + P_5 E_d C_{kWh} \tag{3}$$

C total adjusted cost
C_{gen} active generator material cost
P_5 period of five years
E_d annual dissipation in the generator (from inefficiency)
C_{kWh} price of energy

Other considerations that may vary between competing LGs in a total cost model might include manufacturability, life expectancy, and maintenance costs. Additional factors directly impacting the cost of all LGs in this comparison is the time value of money, and the projected price of energy. Nevertheless, Eq. (3) is an excellent starting point, and should be considered when developing a more comprehensive comparison model. A more detailed cost model that incorporates all of the above factors is suggested for making a final system-wide design selection.

In the cost analysis of hybrid energy systems for remote islands [6], a comparison that explores many of these cost variables including time value of money, optimization of system tradeoffs, storage requirements, natural resources, and backup generation needs is made. The software tool that incorporates this technique is known as HomerPro, which is an NREL provided tool, that if properly applied may be useful in a more detailed cost analysis of a complete wave energy system [7].

III. Comparative techniques

Methods of comparison are analytical/experimental analysis followed by cost to performance estimates by selecting rotary or linear machines with known cost to performance measures and scaling those performance measures to the application. This is followed by relying on linear motion references (primarily linear motor texts) to provide generalized guidance based on the speed and torque requirements for the LG.

The methods studied in this research on determining LG performance in a direct drive wave energy converter are based on estimated materials requirements, prototypes, and associated materials cost estimates [1], [3]. This method encounters cost accuracy challenges because the potentially high costs of machining and assembly are not accounted for in the studies. Additionally, in some cases, raw material costs are used that do not account for the cost of turning those raw materials into wire or laminations.

Every rotary electric machine has an analogous linear counterpart [8]. Existing rotary generator technology may have a significant cost advantage over the LGs being proposed, but it may be reasonable to assume that LG's built in high volume would see similar cost advantages as rotary machines. For this reason, extracting rotary generator performance and cost data and applying it through proper scaling factors to a linear generator wave energy application will provide insight into the performance and cost of LG's.

Texts written on linear machines are primarily focused on motors used in trains and industry specific applications. The recommended applications have not considered the application of direct drive wave energy generation. Nevertheless, this source of information provides experience and balance to the study.

All three of these techniques should reveal the same answers to the question and can be used as a cross reference against the other methods. The machines in this study are scaled to the same operating conditions (speed, air gap, $/kW). Each of the comparison methodologies described may use any of the following suggested scaling factors.

A. Cost comparison

To compare the many machines in this survey, a base cost of magnetic materials will be the basis of comparison.

B. Control options

Similar to wind energy, wave energy systems might be characterized by the generator and control approach. For example, when comparing different wind energy schemes in wind energy research (circa 1975), wind energy systems were characterized as constant speed constant frequency (CSCF), and variable speed constant frequency (VSCF) [2]. This method of system classification in wind energy aided in the comparison of different system design strategies. Ultimately these design strategies affected comparisons based on criteria such as; generator type, control

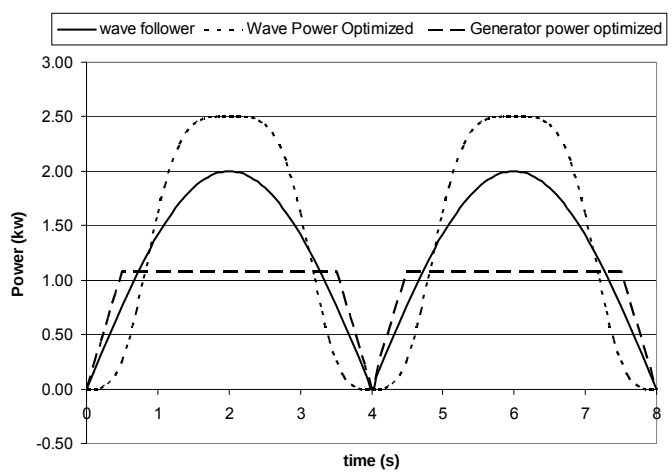

Figure 1. Wave energy buoy control modes.

methodology, blade pitch control, etc. [2]. Interestingly, the systems being compared in this study made no serious mention of the doubly fed induction generator, today's predominant generation method [2].

In a similar way it is apparent that the control methodology for the wave energy converter is important to the overall system analysis. Considering the control of the linear reciprocating speed and force in wave energy systems, several possible system control choices reveal themselves and are identified in Fig. 1; following the sinusoidal pattern of the wave (wave follower), optimizing the hydrodynamic and generator performance to extract maximum power from the wave (wave power optimized) [5], or controlling for a more constant speed-torque profile (generator power optimized) to optimize generator capital costs. It is not readily apparent from any reference that the different LGs being considered have a preferred control method.

C. Linear reciprocation

Linear reciprocation in a LG cannot be directly compared and translated from a rotary machine. As depicted in Fig. 2, the reciprocation requires that either the stator or rotor be longer than the other in order to keep the same surface area of active generating elements in operation. In the AWS LG study, this was accounted for by assigning an additional 12 m^2 of material to the translator [3]. This parameter of additional material is difficult to quantify without more rigid definitions on the LG application. For this study, it will be identified if there was no cost accounting for linear reciprocation.

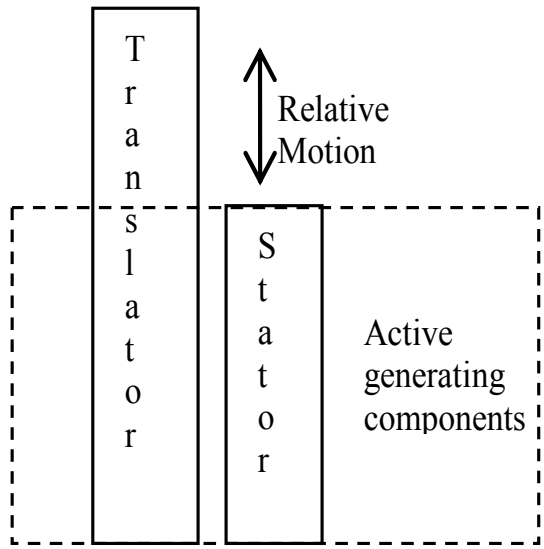

Figure 2. Materials required for reciprocation.

D. Linear performance conversions

In this study machines are equalized to the same operating conditions and parameters. As a first approximation, certain linear assumptions are made:

1. *Fixed stator current for a given machine design.*

This assumes that the conductor size, number of phases, and number of turns in each phase and slot is duplicated on the linear machine.

2. *Stator voltage is scaled linearly by speed (v)*

Given Faraday's law, Eq. (4), it is well known that the induced coil voltage (e) is the product of the number of turns (N) and the time rate of change of the magnetic flux (dΦ/dt) passing through the stator core. Assuming that all geometry is maintained equivalent such that the average flux density (B) is the same, and the time rate of change of area is the result of velocity (v) in the z direction times length (*l*), then Eq. (5) is also commonly applied. In Eq. (5) it is seen that the terminal voltage is a linear function with respect to speed. For this study, linear speeds of 1.0 m/s are evaluated.

$$e = \frac{d\phi}{dt} \tag{4}$$

$$e = \frac{dBA}{dt} = \frac{dBlz}{dt} = Bl\frac{dz}{dt} = Blv$$

$$where: A = lz, v = \frac{dz}{dt}(\text{linear speed})$$

$$then:$$

$$V = NBlv \tag{5}$$

3. Power is scaled linearly by speed (v)

Based on the above assumptions, and assuming that the generator is controlled such that constant current is maintained, then current density(J) and conductor area(A) are fixed with respect to speed; power (P) is also linear with respect to speed in a constant current case (6).

$$
\begin{aligned}
&P = VI\cos(\theta) \\
&P = VJA\cos(\theta) \\
&P = v\left[NB\ell JA\cos(\theta)\right] \\
&\text{where: } \cos(\theta) \text{ is the load angle } (\theta) \text{ power factor}
\end{aligned}
\tag{6}
$$

4. Air gap

For mechanical reasons, linear machines in wave energy converters will encounter mechanical air gap requirements of 5 mm or greater [3], [7], [8]. These air gaps are relatively large as compared to most rotary and other linear machines, thus when comparing machines with different air gaps, some scaling method for air gap must be applied. Based on the technical information reviewed, the machines will all encounter similar mechanical requirements, thus it would be appropriate to compare them using the same air gap. Most electrical machines are air gap dominant and operate in the linear region (iron not saturated), flux and voltage are assumed to change linearly with a change in air gap. For this study, an air gap of 5 mm is suggested for a common scaling parameter. As a first approximation, it is suggested that to equalize the comparison of machine rated power levels, that a scaling be applied to decrease power linearly with an increase in air gap length.

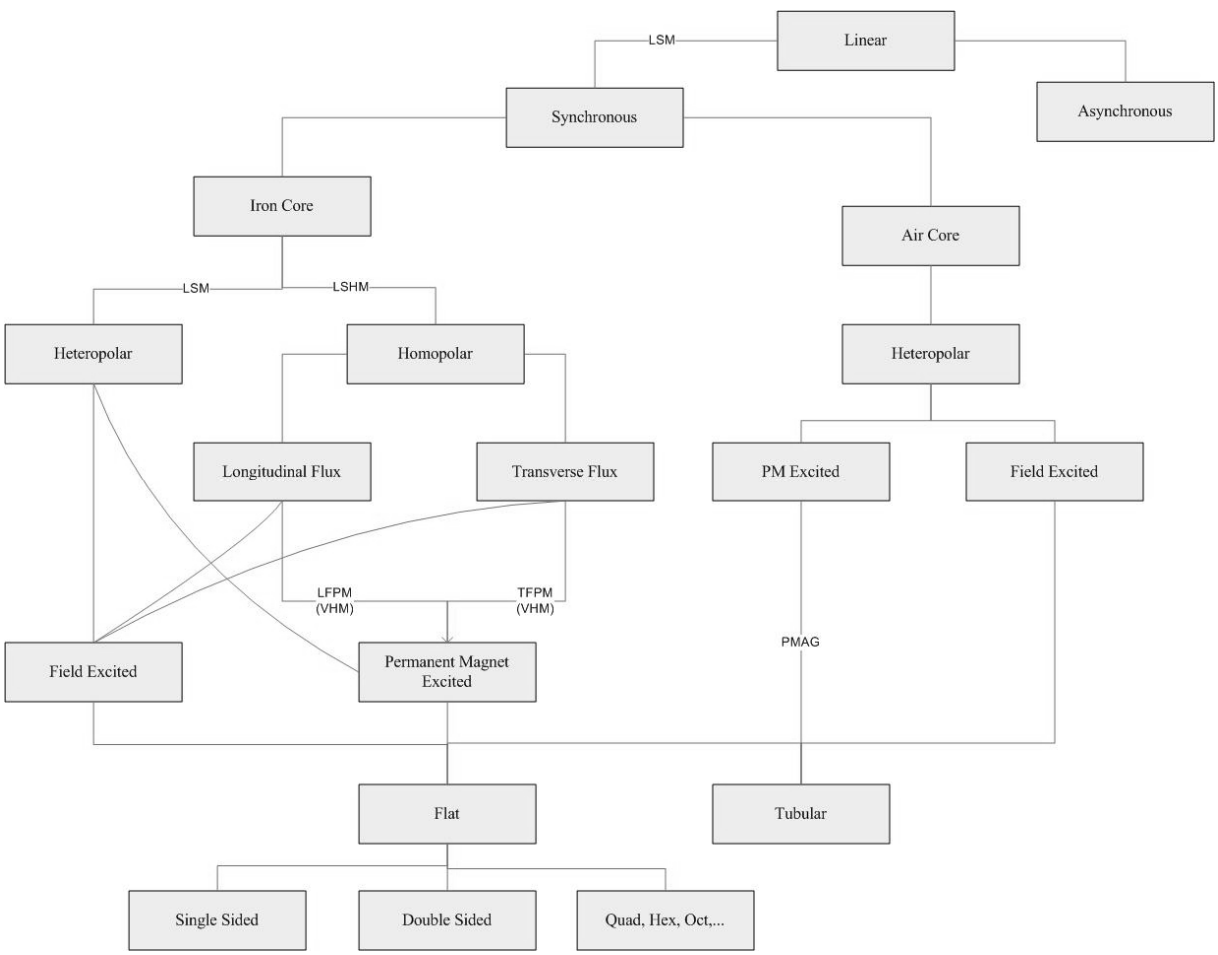

Figure 3. Linear synchronous topological classifications.

IV. Linear Generator Classifications

The LG configurations considered in this study are briefly described in this section. Figure 3 depicts the many possible variations in synchronous machine design. Due to the numerous configurations (over 100 possible [8]), it is impractical to discuss all possible configurations here. LGs like linear motors have rotary equivalents. The construction of linear machines are described by the deconstruction of a rotary machine into a linear machine as depicted in Figs. 4 and 5 [8]. In these figures it is observed that the direction of magnetic flux interaction with respect to the stator, rotor, and the direction of motion is maintained. Figure 4 (e) shows a flat single sided linear machine.

Figure 4 (d) shows a flat double sided linear machine. Figure 5 shows a tubular linear machine. In the sections that follow, the most common linear machine topologies are introduced and can be configured as either flat or tubular. It is left to the readers' creativity to realize the many possible methods for designing these machines.

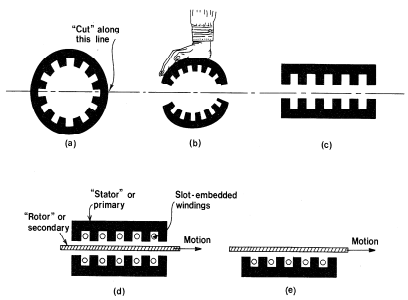

Figure 4. Rotary to flat equivalent [8]

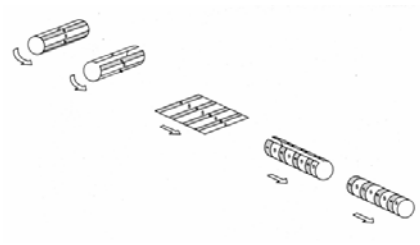

Figure 5. Rotary to tubular equivalent [8]

A. PM linear synchronous machine with stator iron (LSM)

The PM linear synchronous machine may be excited using a permanent magnet or with external electric field excitation. The magnetic fluxes of the field and armature windings are at the same speed (synchronous) [8]. Fig. 6 shows a typical cross section with a, b, c, a', b', c' stator windings. The arrows show permanent magnets with their magnetic orientation, and the regions marked with "Fe" contain the iron.

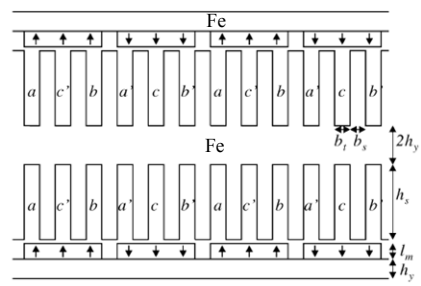

Figure 6. PM synchronous with stator iron. [3]

B. Externally excited synchronous with stator iron (LSM)

This machine operates on the same principles as in the PM version; however, field windings are used instead of permanent magnets to provide excitation. Fig. 7 shows one possible implementation of this topology using a flat single sided machine. This machine allows for adjustable excitation fields adding the possibility for another control parameter available to the system. This machine is classified as having a hetero-polar arrangement [8].

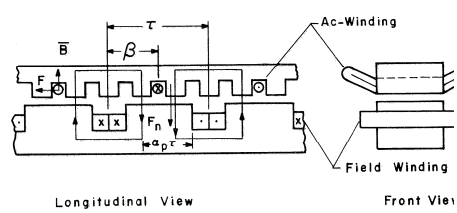

Figure 7. Synchronous, field excited with stator iron. [8]

C. Synchronous with variable reluctance iron core

The synchronous with variable reluctance machine can be implemented with permanent magnets or with dc field windings. Fig. 8. shows an implementation of a flat single sided machine using permanent magnets. This machine has the distinction of keeping all of the expensive elements on one side (the short side) of the machine and the less expensive laminations on the other side (translator or track). A permanent magnet version of this machine is also referred to as a Vernier hybrid machine (VHM) [1]. A field excited version of this machine is classified as a linear synchronous homo-polar machine (LSHM) [8].

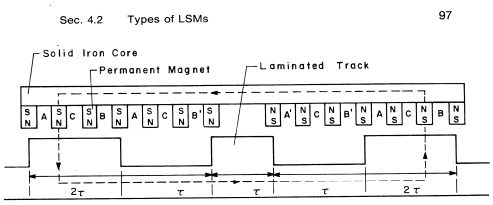

Figure 8. PM synchronous with iron modulation [8]

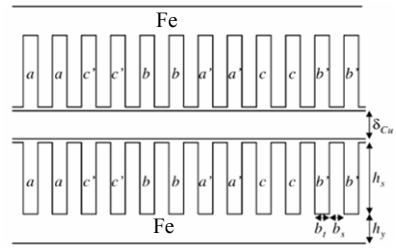

Figure 9. Induction with no secondary iron [3]

D. Induction with no iron in secondary

In the induction machine external excitation is provided by the stator terminal connection. Field excitation speed for the stator is exceeded by the speed of the copper secondary resulting in generator action. Fig. 9 shows the outer stator and a center copper conductor as the secondary. Implementation of induction machines in this application requires constant control of the synchronous stator field such that generator action is maintained. The copper is repelled from the stator and is therefore self centering when moving, requiring a simpler bearing system.

E. Induction with iron in secondary

The induction machine with iron is nearly identical in operation to the induction machine with no iron in the secondary. The iron improves flux density and thrust performance. The iron located in the center of the conductor is attracted to the stator. Thus bearing requirements may be more demanding on this machine. Fig 10 shows a typical induction machine with secondary iron.

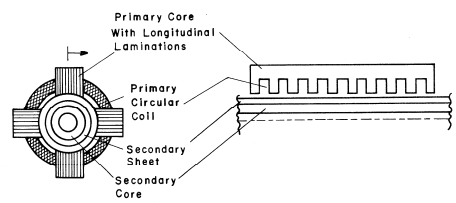

Figure 10. Tubular Induction with secondary iron [8]

F. Double sided moving iron TFPM machine

This double sided transverse flux permanent magnet (TFPM) machine is also a synchronous permanent magnet machine. The flux is transverse in direction, that is to say, the current inducing flux path is oriented transverse to the direction of the motion. In Fig. 11, flux travels transverse through the stator core. All of the previously mentioned machines are longitudinal in design (the flux path is in the same direction as the motion).

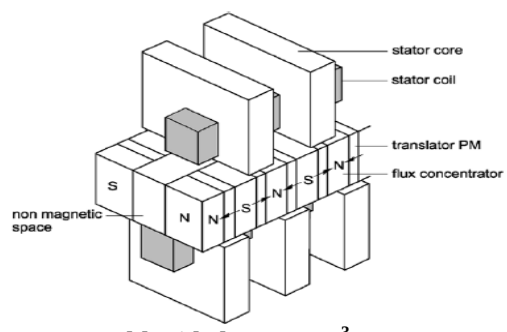

Figure 11. Double sided TFPM [3]

G. PM synchronous air gap wound with stator iron

The PM synchronous air gap machine was investigated by Oregon State University in 2003. It seeks a balance between the desirable low cogging forces in an air gap machine and the high shear stress capabilities of a stator with iron. Fig, 12 shows the cross section of a tubular version of the machine. The intent of the stator design is to provide a homogeneous distribution of iron in the stator such that the flux characteristics of the design are improved while the cogging forces due to reluctance variation are eliminated by the iron homogeneity.

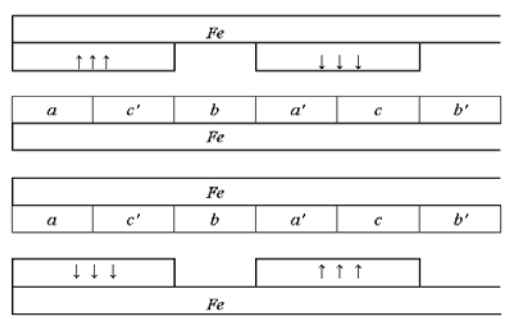

Figure 12. PM Air gap with iron

V. Air Gap Machines

This section begins a survey of existing research and technologies and provides needed background for the conclusions made in the survey.

A. Low-loss PM air gap machine with amorphous iron

An air gap wound, iron cored rotary motor was analyzed both analytically and experimentally using a small 375 Watt, 1800 rpm prototype [9]. The iron used was high cost amorphous iron also known as Metglass. Metglass is supplied as a very thin (0.001" or 0.025mm) insulated iron tape with very good efficiency characteristics. The machine is configured with flux directed in an axial direction, two permanent magnet outer rotors, and a central iron cored stator surrounded by toroidal wrapped coils. Analytical and experimental no load voltage performance was verified to be within five percent.

A technique to verify core loss vs. speed was utilized and is noteworthy for future application studies. In particular, the windage torque and speed was measured with no magnets in the motor, and then an additional set of data was taken with the magnets installed. The net torque-speed (power) difference in these measurements indicates losses directly caused by eddy currents in the system. Torque and power losses were initially assumed to be caused by the core loss; however, significant disagreement between measured core loss and manufacturer core material data was observed (2.2 Watt/kg iron measured versus 0.03 Watt/kg given in the material specifications). This error was later found to be caused by eddy current losses in the motor's outer aluminum casing. Additional errors in the analysis were due to unknown annealing methods used in the amorphous iron.

B. Flat dual sided air gap PM machine

A flat dual sided air gap PM linear generator was optimized for reduced torque ripple and reduced magnet volume [10]. The optimization method was implemented on each parameter individually and then simultaneously. The method involved a Genetic Algorithm (GA) approach to machine optimization based on user cost and priority parameter inputs. This study used the GA in order to weight the thrust, magnet volume, and thrust ripple for an optimized solution. Magnet volume and thrust were optimized to 526 cm^3 and 68N. This system is a flat linear machine; tubular machines may be more materially efficient [1]. The analytical techniques used to optimize performance may be useful for the air gap PM linear generator design.

C. Tubular air gap PM machine

A mid sized prototype rated at 10 kW average and 40 kW peak has been built and tested [11]. Strong arguments presented from experience include that iron cored machines are difficult to design and build due to the high attractive forces between the stator and translator. These forces require significant mechanical and bearing solutions to prevent stator and translator collision. Identifying useful assembly procedures for the large magnetic forces encountered, [11] is an excellent assembly reference for high energy magnets and large PM linear machines. The magnets are set and encapsulated with epoxy with a carbon fiber sleeve for protection. This machine has a mass of 2.3 metric tons [11].

Cost estimates are summarized in Table V. A significant point underlies this machine's parameters; it has a peak rating of 40 kW and a continuous rating of 10 kW. To equalize this machine to the others being evaluated, its 10 kW average power is upgraded by $\text{sqrt}(2)^2$ (or simply a factor of two) to allow it to be equally evaluated on a peak power basis. The factor of two is the result of a sine wave generator rms output (1/sqrt(2)) that is modulated by a sinusoidal ocean wave (1/sqrt(2)), thus to transform back to peak power a factor of two is required.

A 3kW PM air gap machine is designed for 0.5m/s peak operating speed and is built by M.A. Mueller and team [12]. This machine is the low power precursor to the machine in [11]. Some stated advantages for this machine are reducing reluctance forces due to the lack of armature iron, less structural demands in the design, and improved power factor [12]. This machine was observed to have good power factor ratings above 0.9 and very poor efficiency in the range of 50% due to the high current densities [1]. The 10 kW machine seems to have addressed these efficiency issues and is a more optimized approach to this machine configuration [11]. Significant justification for the use of a PM tubular air gap machine is made and although this machine appears higher in initial costs, the advantages of simplified machine construction and low bearing loads are substantial [1], [11], [12].

D. Tubular air gap PM machine with iron

A small 50 Watt prototype of this machine was developed at Oregon State University [13]. The basic material volumes provided in the paper provided sufficient information to make cost estimates similar to the other machines in this survey.

VI. PM Synchronous Machine With Iron Stator

A. PM synchronous and transverse flux linear generator

The cost and efficiency of multiple machines were analytically compared to allow for cost basis selection between the induction, permanent magnet with air gap winding, switched reluctance, PM synchronous, and PM transverse flux generators for use in the Archimedes Wave Swing (AWS) [3]. In this research it was concluded through analytical modeling that the synchronous LG with iron in the stator was the best choice based on total cost and efficiency [3]. This study introduced a new dual sided TFPM machine with only iron in the translator that costs significantly less than the other five options studied.

This study makes a strong case for the permanent magnet synchronous and TFPM machines with iron [3] and the analytical results for all machines evaluated in this study are listed in Table II and the two preferred machines are scaled and placed into Table III.

B. PM longitudinal flux linear generator

A lower power PM synchronous machine was modeled, prototyped, and evaluated for wave energy conversion [5]. This design is tubular in structure to improve the force to weight ratio [5], [14].

The proposed control strategy was optimized for a constant current reference with the controls targeted at maximizing the power extracted from the wave [5]. Experimental and modeled peak power levels achieved were in the range of fifty Watts.

The longitudinal flux permanent magnet generator also has the option of being made with buried or surface mounted magnets [15]. The longitudinal flux permanent magnet (LFPM) machine has structural advantages and power factor advantages (of 0.98 versus 0.31) over the TFPM machine [3], [15]. This topology was analyzed with four configurations composed of surface or buried magnet orientations (pole shoe or flux concentrating) with either iron (Fe) or neodymium-iron-boron (NdFeB) magnets [15]. The final conclusion reveals that the best selection was the NdFeB surface mounted orientation.

VII. Linear Induction Generator Survey

A tubular version of the linear induction machine with back iron was evaluated for performance in high speed reciprocating applications [16]. The machine is excited using either residual flux linkage or charge on the excitation capacitors. Best performance was observed at higher reciprocation frequencies of 60 Hz. These high rates of speed are likely unachievable in a wave energy converter, the paper provides another data point for induction machines. The device was modeled analytically, with FEA software, and experimentally validated. The air gap in this machine was 0.3 mm, which is considerably smaller than the 5mm proposed for wave energy applications. Inconsistent dimensions were provided and prevented estimation of material volumes and cost.

VIII. PM Synchronous With Vernier Translator

Evaluation of a PM synchronous machine with Vernier translator, described as a Vernier hybrid machine (VHM) suggests that each phase be independently wound such that the phase windings are not interspersed [1]. In such a configuration, each phase would be independently surrounded by a 'C' core as depicted in Fig. 13 [1]. Based on the geometry provided, estimates of materials used are summarized in Table V. This machine is identified to have favorable high thrust characteristics that are well suited for wave energy [1]. This machine has a very low power factor that was corrected with a frequency specific capacitance of 150 uF at 0.5m/s operating speeds for a corrected power factor of 0.81 [1]. Deviation from this speed caused significant power factor reductions. The cost and performance of this machine are favorable, but this advantage is slightly offset by the controls needed for power factor correction.

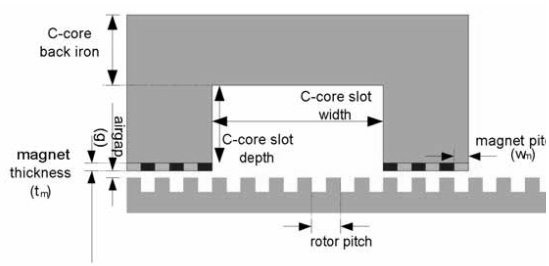

Figure 13. Vernier hybrid machine (VHM). [1]

IX. Summary of Comparisons

A. Comparison between air gap PM and VHM

A comprehensive evaluation comparing two 100 kW versions of the tubular air gap and VHM topologies was performed [1]. Table I below summarizes those findings. These costs clearly show the VHM as a lower cost alternative, but it has a higher mass and low power factor. At 0.77 euro per US dollar, these machines are estimated at $250/kW for the VHM and $650/kW for the tubular air gap machine.

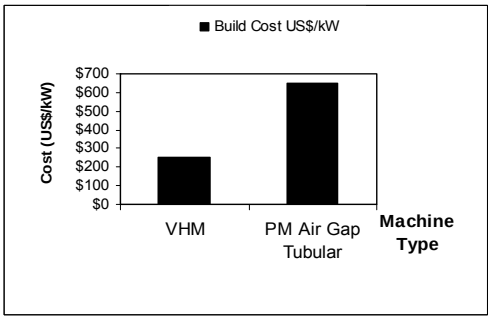

Table I. Comparison of VHM and Air gap tubular. [1]

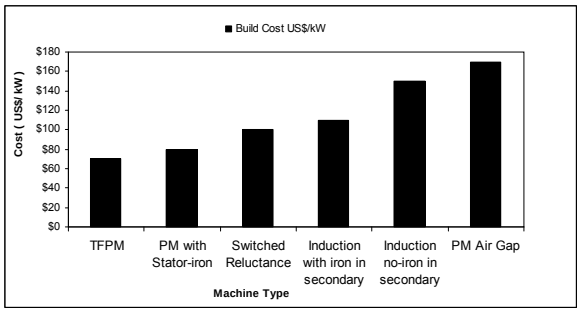

Table II. Comparison of direct drive LG's. [3]

B. Comparison of LG's for marine applications

Mentioned previously, several linear machines were compared for applicability in a direct drive wave energy converter. A summary of the findings is presented in Table II. This table also includes the cost of inefficiency and marks up the total system cost of each system by the cost of a 5 year energy loss due to inefficiency. This study indicates that the PM synchronous with iron and the new TFPM (similar to the VHM) machines have a cost advantage over the other machines analyzed [3].

C. Suggested linear machine applications

Linear motors have been utilized in trains and other industrial applications. This experience should apply closely to linear generator applications. The forces in wave energy application are high, while the velocities are relatively low, thus a high thrust to power ratio is desired. The low velocities place a high value on surface area optimization, thus a high thrust to area ratio is also desired. Also important are efficiency, reliability, and power to weight ratio. With this criteria established it is perhaps practical to reference existing texts on the topic for a suggested machine configuration. Tables IV and V summarize these suggested applications for linear motors and are evaluated with the above priorities [8].

Table IV shows seven possible configurations with the linear synchronous reluctance (LSRM), linear synchronous homo-polar (LSHM), permanent magnet or field excited linear synchronous (LSM), and DC homo-polar motors having the best force to square-root-power ratio. The DC homo-polar has a poor thrust to area ratio and is eliminated from the list of possibilities. The LSRM is a reluctance motor with no field excitation and will require a more complex controller to connect to the grid or an external power source.

Of the remaining options (LSM and LSHM) Table V gives no decisive advantage to one or the other. The LSM has a high thrust density, the LSHM has high efficiency and high power to weight ratio. The main advantage of the LSHM is that it has both the primary and field windings on the same side of the machine, thus minimizing magnet or copper investment in the translator and eliminating the need for brushes or moving cables on the translator.

Based on Tables III and IV, the LSM and LSHM are both good choices. The LSHM, also known as Vernier hybrid (VHM) has a cost and efficiency advantage and should be the preferred choice.

Motor type	Thrust/area, lb/in.^{2}	Thrust/$\sqrt{\text{input power}}$ lb/$\sqrt{\text{watt}}$
DC homopolar	0.15[a]	4.2
DC brushless	1.65[b]	0.75
LSM field-excited or PM	5.5[c]	4.8
Linear synchronous homopolar motor (LSHM)	2.4[d]	3.4
LSRM	2.5[e]	11.5[f]
DSLIM	6.8[g]	0.32
SLIM	3.4[h]	0.30

Table III. Quantitative linear motor comparison [8]

Motor type	Thrust density	Controllability	Efficiency	Power weight	Reliability
DC homopolar	Low	Good	Low	High	Low
DC brushless	Low	Cumbersome	High	Low	High
LSM	High	Good	Medium	Medium	Medium
LSHM	Medium	Good	High	High	Medium
LSRM	Medium	Good	Medium	Medium	High
DSLIM	High	Good	Medium	Medium	High
SLIM	Medium	Good	Medium	Medium	High

Table IV. Overall linear motor performance ratings [8]

D. Overall consensus on surveyed data

Table V represents a cost summary of the various machines reviewed in this research; they have been scaled to equivalent air gaps and speeds in order that the basis of comparison is equalized. The results have been sorted by cost per kW at 1m/s. The TFPM [3] was the overall materials cost choice at $160 US per kW. The TFPM is a transverse flux version of the VHM or LSHM, thus this cost conclusion agrees with the other comparison techniques in this survey.

The permanent magnet synchronous is the next likely candidate on a cost basis, but suffers a lower overall efficiency. The TFPM [3] and LSM [3] are followed by two more versions of the VHM [1] configuration. An air gap PM machine [12] eventually shows up at a cost of $600 US per kW.

The air gap PM machine suffers from a significant cost disadvantage when compared to the VHM and LSM configurations. However, as identified in the survey, the same qualities that make the VHM and LSM so cost effective also introduce significant cogging forces that must be mechanically compensated for with bearing and structural design. There was no quantitative data on the externally excited version of the VHM or LSM, thus further exploration on this topic is suggested.

In addition to the machine configurations, the decision between flat single sided, flat dual sided, and tubular should be made. Tubular machines are expected to have greater efficiency over flat or double sided designs [1]. Tubular machines, like dual sided machines, provide balanced reaction forces and reduce the overall bearing loads. Thus if practical to manufacture, tubular machines should be pursued.

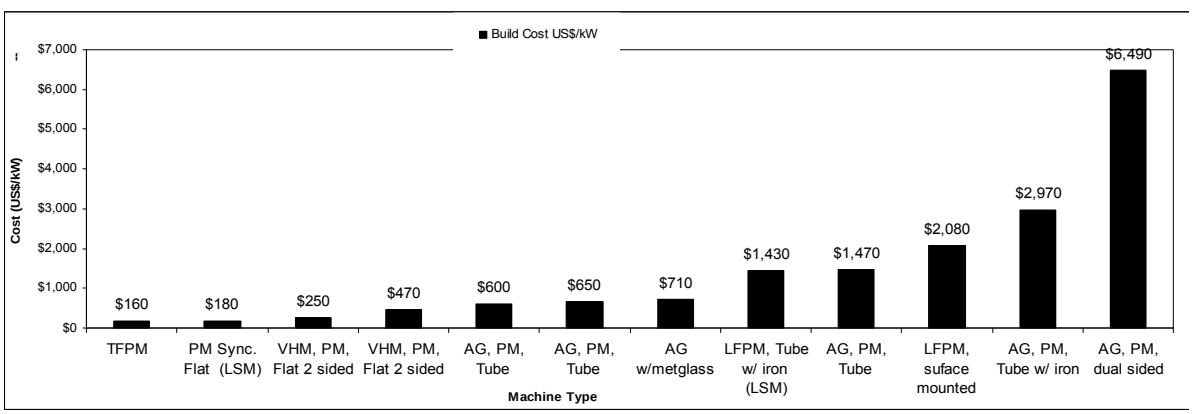

Table V. Summary of Surveyed data

X. Possible Alternatives

Throughout this research, it has become apparent that the low speed of wave energy devices puts linear generators at a cost disadvantage. As indicated in Table V, cost is a linear function with speed. While the estimated costs did serve for comparison between machines, the true costs of these machines are not fully realized.

If a highly efficient mechanism could reliably transform the high-thrust low-speed wave action from the buoy into a high-speed low-thrust rotary output, then a standard rotary generator with a much lower cost could be used for power generation.

XI. Conclusions and Recommendations

This paper is intended to help select the best linear generator for direct drive wave energy conversion. Ultimately it should help to prioritize the resources applied to the research on linear generators for direct drive wave energy

conversion. From this research, three topologies emerge as promising. The VHM (LSHM) appeared most favorable, followed by the LSM. However, the risks associated with the LSM and VHM are nearly identical, and if one fails due to cogging issues, so will the other. The air gap machine also showed a high probability of mechanical success. Two versions of the air gap PM machine should be investigated (those with and without iron in the stator).

In addition to the topology considerations, power factor correction and varying speed issues emphasize the need for external generator excitation. External field excitation can be used to both correct power factor and voltage output. The highest cost contributor to the linear generators evaluated in this survey are the permanent magnets; these costs are on the order of fifty to seventy five percent of the material costs of the machines. External field excitation would completely eliminate the magnet costs, but would require more copper and iron to generate the required field excitation. The viability of external excitation on both the VHM and air gap generators should be researched.

References

[1] N.J. Baker, "Linear *Generators for Direct Drive marine Renewable Energy Converters*", University of Durham, PhD. Thesis, 2003

[2] T. S. Jaya Devalah, R. T. Smith, "*Generation Schemes For Wind Energy Power Plants*", IEEE Trans. On Aerospace and Electronics Systems Vol. AES-11, NO. 4, pp. 543-550, July 1975

[3] 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, No.2, June 2005

[4] O. Danielsson, "*Wave Energy Conversion Linear Synchronous Permanent Magnet Generator*" , Uppsala University, Dissertation from the Faculty of Science and Technology 232, ISBN 91-554-6683-4, Nov 2006 d

[5] P. Cancelliere, F. Marignetti, V. Delli Colli, R. Di Stefano, M. Scarano, "*A Tubular Generator For Marine Energy Direct Drive Applications*", DAEIMI- Department of Automation, Faculty of Engineering ,University of Cassino, 2005

[6] C.C. Fung, W. Rattanongphisat, C. Nayar, "*A Simulation on the Economic Aspects of Hybrid Energy Systems for Remote Islands in Thailand*", proceedings of IEEE TENCON 2002

[7] National renewable Energy Laboratory (NREL), Hybrid Optimization Model for Electric renewables Program (homePro), www.nrel.gov

[8] S.A. Nasar, I. Boldea, "*Linear Electric Motors: Theory, Design, and Practical Applications"*, Prentice Hall, INC, Englewood Cliffs, N.J. 1987, ISBN 0-13-536863-4

[9] C. C. Jensen, F. Profumo, T. A. Lipo, "*A Low-Loss Permanent-Magnet Brushless dc Motor Utilizing Tape Wound Amorphous Iron*," IEEE Trans. Industry Applications, Vol. 28, No. 3, pp. 646-651, May 1992

[10] S. Vaex-Zadeh, A.H. Isfahani, "*Multiobjective Design Optimization of Air-Core Linear Permanent-Magnet Synchronous Motors for Improved Thrust and Low Magnet Consumption*" , IEEE Trans. On Magnetic, Vol. 42, No. 3, March 2006

[11] N. J. Baker, M.A. Mueller, P.J. Tavner, L. Ran, "*Prototype development of direct drive linear electrical machines for marine energy converters*" , Lancaster University, University of Edinburgh, University of Durham, UK, not published, 2005

[12] N.J. Baker, M.A. Mueller, E. Spooner, "*Permanent magnet air-cored tubular linear generator for marine energy converters*"' University of Durham, University of Edinburgh, IEE, 2004

[13] K. Rhinefrank, E.B. Agamloh, A. von Jouanne, A.K. Wallace, J. Prudell, K. Kimble, J. Aills, E. Schmidt, P. Chan, B. Sweeny, A. Schacher, "*Novel Ocean Energy Permanent Magnet Linear Generator Buoy*", School of Electrical Engineering and Computer Science, Oregon State University, Elsevier Renewable Energy journal, Volume 31, Issue 9, July 2006, pp 1279-1298

[14] A.W. Van Zyl, C.G. Jeans, R.J. Cruise, C.F. Landy, "*Comparison of force to weight ratios between a single-sided linear synchronous motor and a tubular linear synchronous motor*", International Conference on Electric Machines and Drives, 1999. IEMD '99 , 9-12 May 1999, pp 571 to 573

[15] O. Danielsson, K. Thorburn, M. Eriksson, M. Leijon , "*Permanent magnet fixation concepts for linear generator* ", Division for Electricity and Lightning Research , Department of Engineering Sciences, Uppsala University, Box 534, S-751 21 UPPSALA

[16] J. Faiz, B. Rezaeealam, S. Yamada, "*Reciprocating Flux-Concentrated Induction Generator for Free-Piston Generator*", IEEE Trans. On Magnetic, Vol. 42, No. 9, Sept. 2006