Linear generator systems for wave energy conversion

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Abstract

The objective of this paper is to review linear generator systems for wave energy conversion and the research issues related to this. The paper starts with a short review of wave energy conversion, indicating that the different wave energy conversion systems that have been presented in literature have very different generator systems. Next, a few state-of-the-art linear generator systems are discussed, such as the linear generator of the Archimedes Wave Swing (AWS) and the linear generator developed in Uppsala. Subsequently, some remaining problems and possible solutions that need further research are listed. The paper concludes with some sensible directions for further research, such as investigating an increase of the speed of the linear motion of the wave energy converter, investigating other generator types with higher force densities and possibly better efficiencies (for example, transverse flux permanent magnet machines) and investigating generator constructions that result in cheaper generators.

Keywords: Linear generator systems, permanent magnet generators, ocean wave energy.

1 Introduction

The objective of this paper is to give a short review of linear generator systems for wave energy conversion and the research issues related to this. It starts with a review of linear generators and wave energy conversion. Next, state-of-the-art linear generator systems are discussed. Subsequently, some remaining problems and possible solutions that need further research are listed. The paper closes with a short summary of some issues that need further research.

2 Linear generators in wave energy

2.1 Wave energy conversion systems

There are different ways of classifying wave energy conversion systems. One possible way of classification is according to the operating principle. Four important types are the following [1].

- Oscillating water columns such as the Osprey.
- Overtopping devices such as the Wave Dragon.
- Hinged contour devices such as Pelamis.
- Buoyant moored devices such as the Archimedes Wave Swing (AWS) [2-7].

These different operating principles also require different power take off systems:

- Oscillating water columns mostly have air turbines that drive rotating generators.
- Overtopping devices mostly have hydro turbines that drive rotating generators.
- Hinged contour devices often use hydraulic power take off systems.
- Buoyant moored devices often have linear generator systems.

Linear generator systems are only useful in applications where the motion is linear; when there is rotating motion it does not make sense to convert this to linear motion.

In hinged contour devices such as Pelamis, there is also a linear power take off system. However, in this case the forces are extremely large, while the speed of the motion remains very low (in the order of 0.1 m/s). For these low speeds and high forces, hydraulic power take off systems are probably more suitable than linear generator systems.

In buoyant moored devices with a linear motion and speeds in the order of 1 m/s, there are different possible power-take-off systems, such as the following

- linear generators;
- gearboxes that convert the low-speed linear motion into rotating motion of a higher speed;
- hydraulic systems.

In this case linear generators are often preferred because they are expected to be more efficient and more robust than the alternatives.

2.2 Linear generators

Linear generators are rarely used. When converting a form of mechanical energy into electrical energy, mostly rotating motion is used. Generators in conventional power stations (coal, gas oil, nuclear), in hydro power stations, in wind turbines, in vehicles all use rotating generators.

Linear motors or actuators are used in for example transportation systems (including maglev trains), robotic systems, positioning stages, and so on. Mostly, these systems have a low power level. However, there are a few applications with power levels comparable to the power levels of wave energy converters, such as:

- maglev trains
- aircraft launching systems for future aircraft carriers [8,9], and
- roller coasters driven by a linear machine [10,11].

When these linear systems have to break, the machine is also operated in generator mode. However, in this case the objective is not to convert energy from a mechanical from to an electrical form in an efficient way, the objective is just to slow down the motion or to position the moving part.

Linear generators in wave energy converters are characterized by a high force (depending on the size of the wave energy converter) and a low speed. The main other application of generators with a high force and a low speed is in direct-drive wind turbines. There are many correlations between the problems in direct-drive wave energy conversion and direct-drive wind energy conversion. However, the irregular motion in wave energy conversion makes direct-drive wave energy conversion more difficult than direct-drive wind energy conversion.

2.3 Requirements and characteristics

The requirements for linear generators applied in wave energy conversion systems are

- high peak force,
- low speed,
- irregular motion, and
- low cost.

Other characteristics of linear generator systems in wave energy conversion systems are the following.

- There is a high attractive force between translator and stator. This again complicates the mechanical design and the bearing design.
- The air gap between stator and rotor is mostly relatively large. It is complicated to build a mechanical construction for a generator with a small air gap because of manufacturing tolerances, the limited stiffness of the complete construction, the large attractive forces between stator and translator, thermal expansion, and so on.
- Because of the irregular motion of continuously varying speed, the grid connection of the wave energy converter always has to be done using a power electronic converter that connects the voltage of the wave energy converter with a varying frequency and amplitude to the grid with a fixed frequency and amplitude.

3 State-of-the-art linear generators

There are different conventional generator types that could be used in wave energy conversion systems, such as

- linear induction machines
- linear synchronous machines with electrical excitation
- linear switched reluctance machines
- linear permanent-magnet synchronous machines.

In literature, these generator systems have been compared, mainly for direct-drive wind turbines, but also for wave energy conversion [3]. The conclusion is that permanent-magnet synchronous machines are the most suitable generator type for wave energy conversion.

The generator system for the AWS could be seen as a state-of-the-art generator for a wave energy converter. It is a permanent magnet generator with surface mounted magnets [2-7]. It has a three-phase full pitch winding with one slot per pole per phase. It is double-sided to balance the attractive forces and balance the bearing loads. It is illustrated in figures 1 and 2.

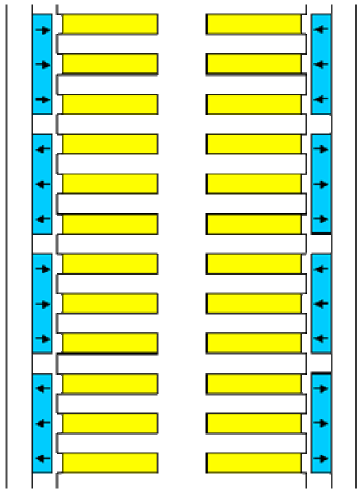

Figure 1: Sketch of a cross-section of the linear permanent-magnet generator of the AWS.

Figure 2: Photograph of the linear permanent-magnet generator in the AWS.

The linear permanent magnet generator developed in Uppsala is of a comparable type [12-16].

Some very rough numbers that could be used for first approximations of size, weight, cost and losses of generators of this type are given in table 1. It has to be stressed that these numbers are very rough, that these numbers only consider magnetically active material (copper, iron laminations, magnets and back-iron) and that the indication of the cost is not valid for prototypes, but could be a rough indication for series-production.

The maximum allowable force density or shear stress depends on the cooling of the machine. At an RMS value of the force density or shear stress of 40 kN/m^2 the losses are in the order of 6 kN/m^2. It is very hard to dissipate this with natural air cooling. With a water cooling system, higher force densities are possible.

In order to overcome the high attractive force produced by Maxwell stress, Mueller and Baker [17-21] have investigated air-cored machines, in which, the coils are suspended in a non-magnetic material. The electromagnetic performance is not as good as a conventional iron-cored machine similar to those used in the AWS or by Uppsala, but the mechanical and structural design is simpler. However, this generator type has not yet been applied in wave energy converters.

4 Problems and further research

The state-of-the-art linear generators for wave energy conversion have some disadvantages:

- their efficiency is physically limited
- they are huge and expensive
- the bearing load are large and the bearings are not maintenance-free

More research is necessary to solve these problems.

The next sections will discuss these problems and discuss further research to solve these problems.

4.1 Limited efficiency

For machines as depicted in figure 1, the voltage induced per unit of length of a conductor in a slot of a permanent magnet generator can be calculated as

$$\vec{E} = \vec{B} \times \vec{v} \qquad (1)$$

where

B is the air gap flux density and

v is the relative speed between stator and translator.

It is important to realize that this expression is not always valid, and can not be used in for example transverse flux machines. However, in most conventional machines (among which the permanent magnet machine of figure 1) it can be used. For air gap flux densities with an amplitude of 1 T and for a speed of 1 m/s, this results in an induced voltage in the conductor of 1 V/m. At the same time, there is also a resistive voltage drop in the conductor if the generator is loaded. This resistive voltage drop per unit of length of the conductor can be calculated as

$$\vec{E} = \rho_{Cu} \vec{J} \qquad (2)$$

where

ρ_{Cu} is the resistivity of the conductor material (mostly copper) and

J is the current density in the conductor.

For values of the current density in the order of 5 A/mm^2, this results in a resistive voltage drop in the order of 0.1 V/m. This resistive voltage drop is not only present in the slots, but also in the end windings and cable connections.

Maximum RMS value of the force density or shear stress (kN/m^2)	40
Loss density at an RMS value of the shear stress of 40 kN/m^2 (kW/m^2)	6
Weight of active material (kg/m^2)	1500
Cost of active material in series production (k€/m^2)	15

Table 1: Rough numbers characterising a linear generator for a wave energy converter

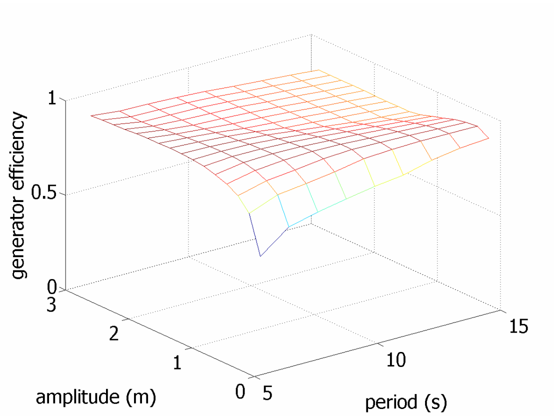

Figure 3: Average generator efficiency as a function of wave height and wave period.

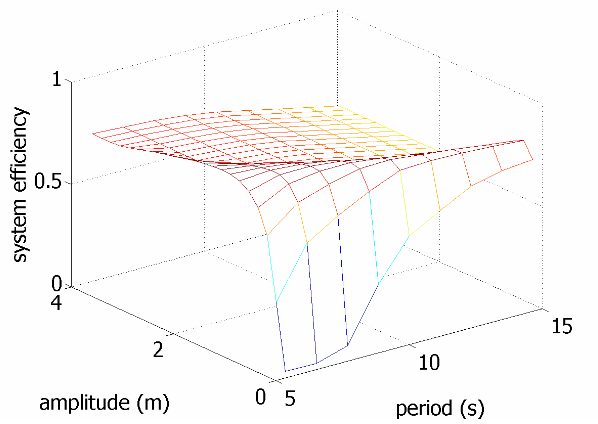

Figure 4: Average generator system efficiency (including cable and power electronic converter) as a function of wave height and wave period.

From these equations, a few conclusions can be drawn.

1. For low speeds, the efficiency is physically limited.
2. For speeds in the order of 0.1 m/s, the use of this type of linear generators is questionable.
3. By increasing the speed of the motion, the efficiency also increases. This is true as long as the speed is so low that iron losses are negligible. At high speeds iron losses may become dominant.
4. By decreasing the current density, the efficiency can be increased. However, decreasing the current density implies that the generator has to become larger and more expensive for the same force.

These two equations do not tell the complete story, mainly because iron losses are neglected. However, they give an important trend.

Sensible directions for further research are the following.

- It should be investigated if the speed of the linear motion of the wave energy converter can be increased.
- It could be investigated if there are materials with a lower resistivity than copper. However, copper already is a very good material compared to others. Only superconducting materials can do much better and it could be investigated if superconducting materials are a realistic option for wave energy conversion.
- It makes sense to investigate other generator types where this direct relation between speed and efficiency is eliminated, such as transverse flux permanent magnet machines [3,17,19,20].

4.2 Electromagnetic Forces

There are two main electromagnetic forces in an electrical machine as shown in Figure 4:

- The torque or thrust producing force, F_S, acting tangential to the rotor surface.
- The normal force, F_M, attracting the two iron surfaces.

These forces are given by equations

$$\sigma_S = \frac{\hat{B}\hat{K}}{2} \quad N/m^2 \tag{3}$$

$$\sigma_M = \frac{B_{gap}^2}{2\mu_0} \quad N/m^2 \tag{4}$$

where

B (T) represents the air gap flux density and

K (A/m) is the electric loading.

In linear machines as the machine of figure 1, the shear force density (3) is limited. The amplitude of the air gap flux density is limited to around 1 T because of saturation. The amplitude of the current loading is limited because current loading produces heat, and the heat dissipation is limited. For machines that produce a constant force and have air cooling, the resulting force density is limited to about 25-50 kN/m^2. With a good water cooling system, the force density can be increased further. The force of a linear generator in a wave energy converter is continuously varying. Therefore, higher peak force densities may be possible.

Figure 5 shows how these two force densities vary with flux density, for a typical electric loading of 50kA/m.

The fact that the force density is limited to a certain value implies that the active surface area of the generator is proportional to the force, which has serious implications in terms of the machine's physical size and mass. If the amplitude of the air gap flux density were 1T, then the normal stress is about 200 kN/m^2 while the shear stress is in the order of 40 kN/m^2. For a 100kW direct drive machine running at 1m/s, the tangential force required would be 100kN, which would require an air gap surface area in the region of 2.5 m^2. Hence the normal magnetic attraction force would be of the order of 500 kN, which the machine structure and bearing system would have to overcome in order to maintain the air gap. In the AWS, the maximum shear force is 1 MN, but to be able to produce this force, an active surface area in the order of 20 m^2 is necessary. If amplitude of the flux density is 1T, then the normal stress is 200kN/m^2 giving an attraction force of 4 MN, which the bearings and support structure would have to overcome.

All iron cored machines, that is those in which one iron surface moves with respect to another iron surface, will suffer from this large magnetic attraction force problem, which as can be seen from the simple example above becomes significant for low speed high force machines.

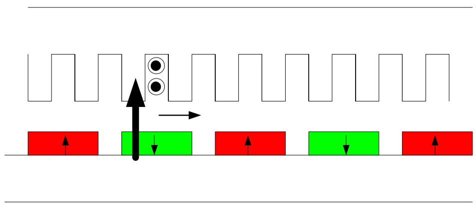

Figure 4: Electromagnetic forces in an electrical machine.

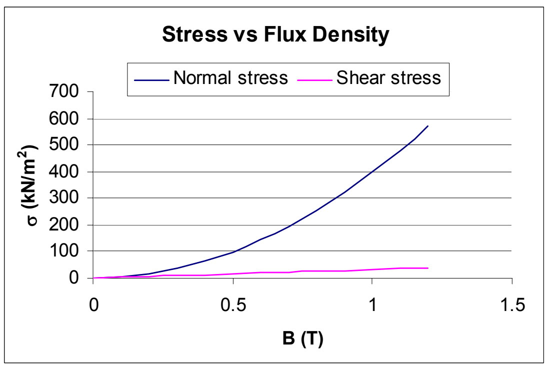

Figure 5: Variation in Normal and Shear stress.

4.3 Linear generators are expensive

The power available from linear motion is given by

$$P = Fv \quad (5)$$

where

F is the force, and

v is the speed.

The size of the generator is mainly determined by the force is has to make. In wave energy, the speeds are mostly rather low. If an amount of power has to be created at a low speed, the force has to be high. This generally leads to large and expensive machines.

There are a number of ways to deal with this problem.

1. If the power level would be kept the same while the speed could be increased, the force of the generator would decrease and therefore, the cost would also decrease. Again it appears to be interesting to investigate if the speed of the linear motion of the linear generator could be increased.
2. Another interesting research issue is the question if there are machine types where this limited force density does not play such a dominant role. Examples of these machines are variable reluctance generators, transverse flux permanent magnet machines and Vernier hybrid machines [3,17,19,20]. In literature, these machines are known for their high force densities, but they also have their drawbacks, such as a complicated construction, a low power factor and complicated iron losses. More research is necessary to find out if these machines are suitable or not.
3. Another interesting research issue is the question if it is possible to reduce the cost of the generator by using cheaper windings. In the machine of figure 1, distributed windings are used. In the machine of figure 6, concentrated coils are used instead [6]. These concentrated coils can be produced at a much lower cost, because a much larger part of the winding process can be done with machines instead of manually. Also the end windings can be much shorter. In machines with concentrated coils, different combinations of numbers of poles and numbers of slots are possible. The main drawback of machines with concentrated windings is the increase in eddy-current losses in the magnets and the back-iron. It needs to be investigated further if this increase is acceptable, and for which combination of numbers of poles and numbers of slots this is acceptable.
4. Clever ways of constructing the generator, for example by making it double-sided or cylindrical could help to reduce the cost.

4.4 Heavily loaded bearings and maintenance

There are three main types of bearings and each type may be assembled to allow either rotational or linear motion between two elements (all but one degrees of freedom are usually blocked):

1. Mechanical bearings (ball bearings, roller bearings, etc.) represent the most common solution in a large variety of applications, being rugged, reliable and cost effective. Much of bearings design is about failure analysis. Abrasion, fatigue and pressure-induced weldings limit the lifetime and the load capacity of the bearings. In more demanding applications, only maintenance can keep them operating properly. As the level of performance increases, in terms of precision, speed, lifetime and load capability, modern technology can offer alternatives such as fluid or magnetic bearings.
2. Fluid bearings rely on a thin layer of liquid or gas to support the load, separate and avoid direct contact between the moving parts. According to the operating principle and the fluid used, they may be broadly classifies as hydrodynamic (which require continuous motion), hydrostatic (require a pump) or gas bearings. If compared with common bearings, fluid bearings are highly versatile and almost maintenance-free. They can be used in applications in which requirements for load, speed or precision are too severe for ordinary bearings. Besides seals and -if present- pumps, a source of losses is fluid viscosity. Overall behaviour in terms of losses may be far better than mechanical bearings and, if the level of performance requested is significantly high, the cost can be lower.
3. Magnetic bearings are bearings which support a load using magnetic levitation. There is no contact between the moving parts and thus friction is absent. According to Earnshaw's theorem, permanent magnets alone cannot provide stable levitation. Electromagnets with continuous power input and active control system are required. Safety bearings should be added to avoid system damage in the case of either control or power supply failure.

In electromechanic applications, linear bearings are used primarily with linear motors, where some load has to be moved along a prescribed straight path with a certain accuracy. In other words, loads need to only translate in one direction, and possibly move back to starting position with high repeatability. The robotic uses of linear bearings have opened up a promising market for the devices operating with low thrust loads and high speed/precision. On the other hand, roller bearings for overhead cranes represent an example of an application in which accuracy is less important than loading capability. In all these applications, adopted bearings are mostly mechanical and thus require either ordinary maintenance or replacement.

In a conventional linear machine, the attractive magnetic forces between stator and translator are usually much higher than the propulsive force. Therefore, as the size and the power level of the machine increase, it may not be easy to design bearings that can deal with the resulting forces without regular maintenance.

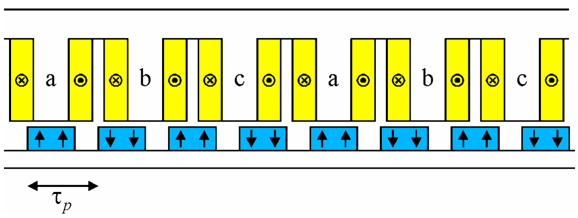

Figure 6: Linear permanent-magnet machine with concentrated coils.

When dealing with small off-shore wave energy devices implementing linear generators as power take-off system, such as floating power buoys rated up to a few tens of kW, maintenance is not expected to represent a critical issue. Things change considerably with a 2MW submerged power plant of the class of the AWS. The first full-size prototype had a weight of 7000 tons while the weight of the floater alone was about 400 tons. Most of the weight was due to the pontoon and ballasts, designed to transport and keep the device safe in place. Even assuming a future version of the AWS free of ballasts and pontoon, its huge dimensions and deployment in rough ocean sites would encourage neither frequent ashore recovery nor on-site long operations for ordinary maintenance.

The bearing design is crucial in maintaining a physical air gap between stationary an moving parts. The coefficients of friction for various plain bearings are listed in [22]:

- Plain bearing, Teflon 0.12 – 0.14
- Ball bearings $10^{-2} – 10^{-3}$
- Hydrodynamic bearings $10^{-2} – 10^{-3}$
- Hydrostatic bearings $10^{-3} – 10^{-6}$

The power lost due to friction is given by

$$P = vFf \qquad (6)$$

where,
v is the velocity,
F is the load force,
f is the friction coefficient.

For the same load force, F, hydrostatic bearings offer the best performance in terms of power lost. With such a bearing the working fluid could be in the air gap. Seawater would be the obvious fluid to use but there are then design issues to be overcome such as corrosion and the operation of windings in water. The issue of corrosion was discussed in [21] with respect to permanent magnets. Figures 7 and 8 show the effect of seawater on magnets using currently available magnet coatings.

The attractive magnetic forces between stator and rotor are rather high, typically 200 kN/m^2, resulting in high values of F in (6). As illustrated above there are challenges to overcome to design bearings that can deal with these forces without maintenance. However, there are a few ways of reducing bearing loads.

1. If the generator is constructed double-sided (as has been done in the AWS) this results in a significant reduction in bearing loads. However, because of manufacturing inaccuracies of the huge construction, the bearing loads remained considerable. Irregular bearing surface and heavy loads may quickly cause failure of roller bearings.
2. In a double-sided machine, by means of a back-to-back voltage source inverter, the phases of stator currents could be controlled in such a way that the attractive forces between stator and rotor are balanced with limited (below 5%) additional copper losses [5]. Because of the limited speed of the machine, attractive and propulsive force are practically independent which means that they can be controlled without additional sets of coils and without affecting the process of wave energy absorption [5]. It is however not clear how to evaluate exactly the attractive forces during operation, since they depend upon position and structure deformation due to stresses and temperature variations.
3. As a next step, the bearings could be made completely magnetic in all degrees of freedom. This would result in a bearing system that is in principle maintenance-free. However, the complexity of the system and its control (considering that air gap length is about 5 mm) would increase significantly. Instead of double-sided machines, multi-sided or even cylindrical machines could be considered, divided into a number of independent sub-machines to provide proper control. Extensive use of power electronics implies that the electrical losses in the system would increase significantly. Also copper losses may be higher. It could be investigated whether this is acceptable or not.
4. Elimination of the large attraction force will significantly reduce the bearing load due to electromagnetic forces. This can be achieved using air-cored permanent magnet machines as discussed in [21].

Using a single set of magnetic bearings for the generator and the floater does not seem realistic, because of the small air gap and the large hydrodynamic forces acting on the floater, unless superconductivity is considered. The floater may instead use hydrostatic bearings. (This alternative is also valid for the generator.) From the point of view of maintenance, the most critical element would be represented by the pump which is needed to operate this type of fluid bearings. (Hydrodynamic bearings are probably not viable because the moving parts stop twice per cycle and the overall speed is limited.) The pump may be a removable module located on the topmost part of the floater, a few meters underwater, and thus it could be easily replaced.

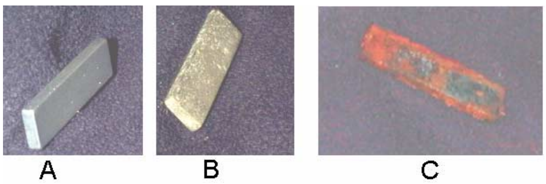

Figure 7: Standard coating for magnets (A) New, (B) after 6 weeks and (C) after 2 years submersion in seawater.

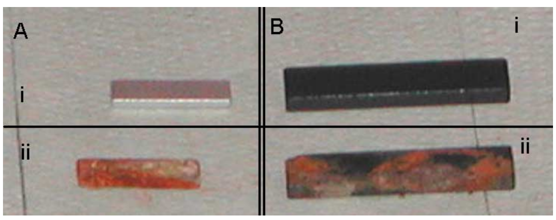

Figure 8: Alternative coatings for magnets (i) as new, (ii) after years submerged in sea water

5 Summary of interesting research work

Sensible directions for further work are the following.

- It makes sense to investigate if the speed of the linear motion of the wave energy converter be increased.
- It makes sense to investigate other generator types with higher force densities and possibly better efficiencies, such as transverse flux permanent magnet machines.
- As well as high force density machines it makes sense to further investigate air-cored machines in terms of their potential for a highly integrated electrical-mechanical-structural design solution.
- It makes sense to investigate generator constructions that result in a cheaper generator, for example using a cylindrical generator or a generator with concentrated coils instead of distributed coils.

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