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An electrical approach to wave energy conversion

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Abstract

Motions in nature, for example ocean waves, can play a significant role in tomorrow's electricity production, but the constructions require adaptations to its media. Engineers planning hydropower plants have always taken natural conditions, such as fall height, speed of flow, and geometry, as basic design parameters and constraints in the design. The present paper describes a novel approach for electric power conversion of the vast ocean wave energy. The suggested *linear* electric energy converter is adapted to the natural wave motion using straightforward technology. Extensive simulations of the wave energy concept are presented, along with results from the experimental setup of a multisided permanent magnet linear generator. The prototype is designed through systematic electromagnetic field calculations. The experimental results are used for the verification of measurements in the design process of future full-scale direct wave energy converters. The present paper, describes the energy conversion concept from a system perspective, and also discusses the economical and some environmental considerations for the project.

Keywords: Wave energy; Conversion; Linear generator; Electric system; Simulation; Experiments

1. Introduction

Access to inexpensive energy in useful forms has been one of the most important issues for mankind throughout history. The fear of forthcoming energy shortages has even been

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the cause of wars. Today, oil and electricity are two of the world's largest trade goods between countries, proving their high relevance to society. Thus, any progress in these fields has a profound impact on society, in several aspects. Renewable electric energy conversion, that is economically competitive, is therefore a priority task for most of the world's countries today, adding also the dimensions of true sustainable growth.

The ideal renewable energy source has no fuel cost and provides a high power density that is available most of the hours during a year (allowing for a high utilization of the power plant at full load). The importance of a high availability is given by the fact that investment costs for all electricity producing units are set by the rated power P [kW], while incomes are governed by the produced energy W [kWh]. Thus, the basic economical considerations lay within the physics of the sustainable source[1]. One of the most promising sources, wave energy, demonstrates a relatively high power density. Furthermore, a high utilization can be obtained through engineering solutions that match generators to different ocean climates.

Even though ocean waves is a substantial energy source, with no fuel costs, a high power density and high utilization over the year, wave energy conversion is often neglected on technological grounds. However, humans can always rework and adapt technology, but not change the natural conditions of a source.

There are/has been numerous suggestions on how to convert wave energy into electricity in the literature, see for example Refs. [1–20]. Some of these are currently being tested in different parts of the world. The broad majority of these approaches use involved interfaces to match the low speed reciprocal wave motion to a conventional electrical generator, rotating at 1500 revolutions per minute. In general these interfaces consist of hydraulic systems and mechanical gearboxes. A linear generator enables a less complicated power take off (PTO) for wave energy conversion, since the translatory wave motion can be directly converted into electric energy. Over the last years, there have been an increasing number of reports on linear generators [1,4,13–20]. Two of the generators have been designed for existing power plants [1,4], while the remaining references describe the linear generator as a part of a novel wave energy converter design [13–20].

Several in-sea-trials have demonstrated the importance of coping with excessive wave power, for instance during a storm. Many installations have been destroyed by the harsh ocean weather. From an economical point of view, it can be noted that the large waves dictate the costs while the small and medium waves give the incomes. If a wave energy converter is to survive the peak powers in the ocean, it must have large safety margins. This usually raises the total costs of the system without giving a corresponding increase of the income. One way of reducing this problem is to place the converter underwater or at the seabed, thereby reducing the impact of large waves on the equipment.

The wave energy plant presented here, has been reported in different papers and conferences, and the principal ideas are more closely described in Ref. [16]. The suggested plant consists of a number of interconnected linear converters, as shown in Fig. 1. To ensure that wave power will benefit from the full potential of directly driven generator

[1] Presented at the European Science Open Forum, Stockholm August 2004 by M. Leijon.

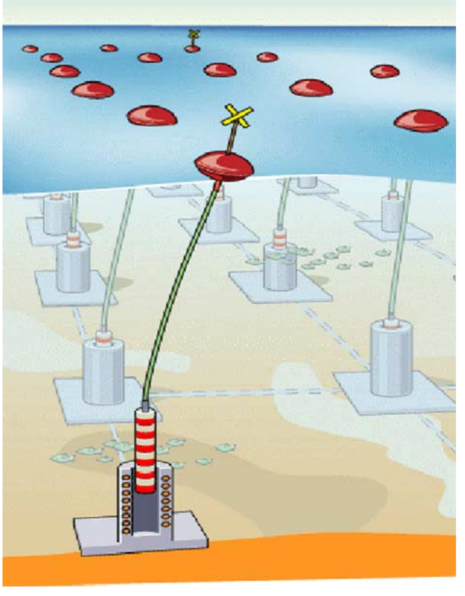

Fig. 1. Artist vision of a future wave power plant. By permission of Karl Åstrand.

technology, such as high efficiency and low maintenance costs, it is important to consider the full power plant; including absorber, converter, interconnections as well as the connection to the grid.

Each wave energy converter consists of a point absorbing floating buoy, connected to the linear generator at the seabed by a tether. The generator piston is driven by the motion of the buoy and counteracted by a spring, see Fig. 2. The whole generator is fixed at the seabed with the help of a massive fundament. During a storm, the buoy will/may at some stage be submerged, limiting the power transmitted to the energy converter. The remaining over power is handled electrically since, this is superior to a mechanical power control. These motives have been guidelines for the simulations as well as in the experimental work. The design of the linear generator is highly dependent on the local wave climate. Different design options, found through electromagnetic field simulations, have been reported for mild [13,15] to heavy [19] ocean climates. However, up to now, there has been no report on experimental results from a multisided permanent magnetized three-phase cable wounded linear generator. Each direct wave energy converter will produce a highly irregular altering current (AC), following from the reciprocal wave motion. From a system perspective, this current needs to be rectified into direct current (DC) before the plant is connected to the grid. [14,17]

There are different options for the electrical interconnection of an array of linear energy converters. Most of these deal with rectification and parallel connection on the DC-side. Rectification can be achieved by, e.g. diodes, thyristors or IGBT's (Insulated Gate Bipolar Transistors). The final choice depends on the actual generator topology. For example, a synchronous linear generator with permanent magnets designed for a low

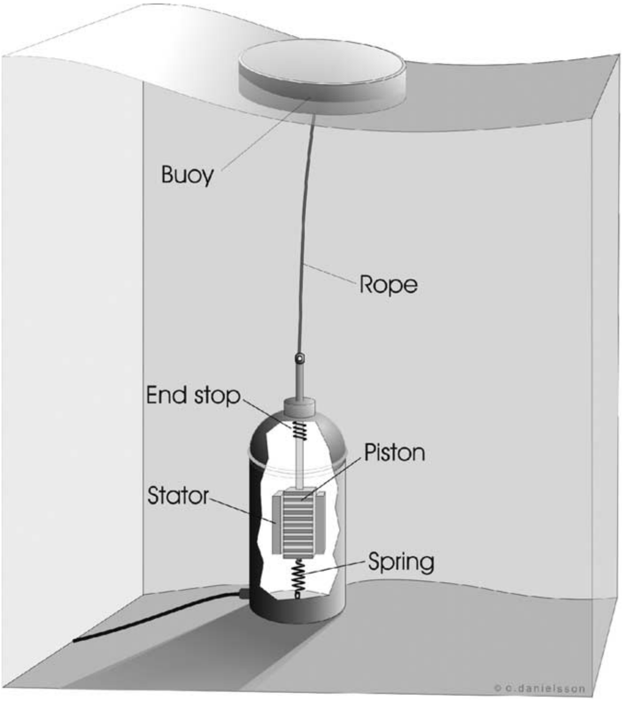

Fig. 2. Schematic figure of the wave energy converter, from Ref. [19].

load angle can operate with a diode rectifier, which is cheap, robust and have relatively low losses.

At the same time, the choice and the control of the interconnection scheme will directly affect the mechanical damping of the individual energy converter. Thus the array behaviour will depend not only on the linear generators, but also on the actual interconnection scheme and control algorithms governing the latter. Therefore, active control of the DC voltage has been investigated [20]. The approach so far has been to rectify the raw power into a DC voltage [14], as shown in Fig. 3. The same approach is used for other sources like under water kinetic energy conversion since it is a simple, low cost method with additional benefits regarding DC-transmission. At the grid connection

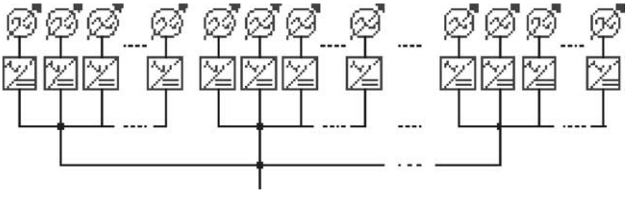

Fig. 3. An example of cluster configuration. Each circle represents a wave energy converter producing a highly irregular alternating current (AC). In this scheme, the converters are individually rectified, then connected into clusters. The grid connection is completed via a direct current (DC) cable. From Ref. [17].

a DC/AC converter suited for the correct voltage has to be implemented. Studies reveal that the DC voltage at different wave climates plays an important role in the optimisation of the whole electric production system.

The potential for generating energy out of waves is immense on a global scale but may, given the right technique, be feasible also in more sheltered seas.

Assessments of the technical wave energy resources in the ice-free zone of the Baltic sea are reported in Ref. [21]. These results point in the direction of an accessible gross potential of more than 20 TWh annually. A more detailed energy estimation using available wave data from a specific measuring position at 'Ölands södra grund' in the Baltic Sea [19]. The results are promising but should be viewed in the light of a strongly simplified algorithm for the energy absorption.

2. Theory and modelling

For designing novel types of generators for wave power utilization from first principles, a customized code has been developed[2]. Using this tool, both the design and simulation process can be performed using accurate (Finite Element) computation of the varying magnetic fields in the generator. The code can also handle nonlinear effects and thermal management. The basic starting point is Maxwell equations and the implication of Poynting's and Slepian's vectors.

Field simulations can either be carried out for a given moment in time, steady state regime, or as a function of time i.e. the transient regime. The stationary field solution provides a rapid estimation of fields and currents, while the transient solution is a more accurate portrayal of the magnetic fields in the generator. Calculation of machine-parameters, such as efficiency, load angle, losses and cogging as well as material cost and the behaviour of the generator at different loads and speeds is performed directly in the FE-simulation. The magnetic field in a cross-section of a linear generator is illustrated in Fig. 4, based on the solution of the vector potential according to equation:

$$\sigma \frac{\partial A_z}{\partial t} - \nabla \left(\frac{1}{\mu} \nabla A_z \right) = \sigma \nabla E$$

In the simulations the generator is represented by a unit cell, the size of which is dependent on the choice of winding ratio. A rational winding ratio requires a larger unit cell. For example, 5/6 winding slots per pole and phase is represented by a six times larger unit cell than winding with one slot per pole and phase.

The code has recently been further developed to enable simulation of a complete wave generator including buoy, spring and end stops when the buoy is exposed to a sinusoidal wave of given height and velocity.

The force on the buooy is calculated from [13]

$$m\ddot{x} = F_{es} + F_b + F_{em} + F_s + mg$$

[2] Primarily by Dr Arne Wolfbrandt and Dr Karl Erik Karlsson.

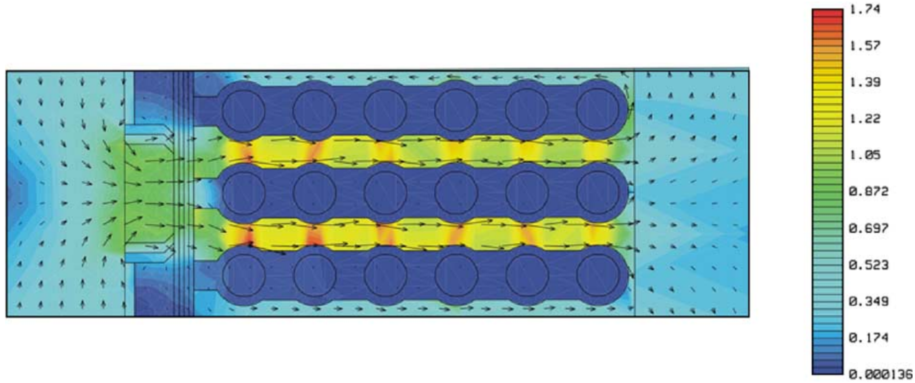

Fig. 4. Shows a PM (NdFeB surface mounted) linear generator (stator to the left and rotor on the right side). Piston or rotor movement is in *Y*-axis, inducing the flux in the stator according to Faraday's law. Arrows represent the magnetic flux vector.

where $\ddot{x}$ is the acceleration of the piston and m is the mass of moving parts. F_{es} is the force from the end-stops modelled as strong springs, which becomes active when the piston comes close to the ends. The buoy force, F_b, is proportional to the amount of displaced water by the buoy, Archimedes principle. No hydrodynamic forces and friction are taken into account in this version of the code. The buoy force is thus calculated as,

$$F_b = \rho g V = \rho g \int_{A_b} h dA$$

Where ρ is the water density, A_b is the bottom area of the buoy, and h is the vertical distance from the bottom of the buoy to the surface position of the wave. The electromagnetic force, F_{em}, is induced in the generator to counteract the piston motion; this force is obtained from the FE-calculation of the field in the generator. The last two forces are the gravity force, mg, and the spring force, F_s. The spring force, which pulls the piston downwards, is modelled by,

$$F_s = -F_{static} - k\Delta x$$

where F_{static} is static spring force which acts on the piston when the system is in equilibrium and no waves are present, k is the spring constant which give a force contribution when the piston is displaced, Δx, from its equilibrium.

Simulations under these constrain show the improvements, when using a spring in the return phase of the piston [16]. Basic simulations are made for both four-sided and eight-sided linear converters [13,15].

Even more realistic modelling would include real local wave data but also consider the effect of biofouling. Fouling occurs in most oceans, including arctic oceans. However, it is generally greater in subtropical and tropical waters. Apart from temperature, other factors affecting fouling includes light permeability, nutritional conditions and species composition. Fouling may negatively affect buoy buoyancy and dynamics but also include the upper parts of the rope. The extra weight in temperate waters, mainly caused

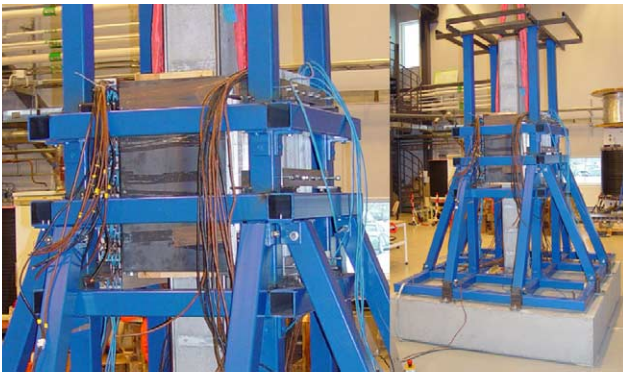

Fig. 5. Experimental set up of a multisided, three-phase synchronous, linear generator at the Ångström laboratory.

by mussels, e.g. Blue mussels (Bivalvia) and barnacles (Cirripedia) may be more than 10 kg/m^2 thus adding extra weight, whereas Algea more likely only will affect buoy dynamics and not its weight.

3. Experimental setup

For the purpose of verification computer simulations, and for gaining valuable practical experience, a 10 kW laboratory linear test generator has been constructed, see Fig. 5. This test generator is now operational and has been used for experimental tests throughout 2004. These tests include verification of simulation results and thorough investigation of the mechanical and electromagnetic properties of the prototype. The four-sided piston is equipped with NdFeB permanent magnets. The support system including stator and cable windings is shown in Fig. 5. The velocity of the piston is 6.75 cm/s. Voltage and current can be measured for each phase and are recorded with an oscilloscope (Tektronix TDS340).

Each side of the piston is 400 times 650 mm. The stator package is 700 mm long.

The experimental results from the four-sided Y-coupled three phase permanent magnetized linear generator are presented in the next section. The forces between piston and rotor have in this experimental set up determined using an air-gap of about 5 mm. A smaller air gap increases the power output of the generator.

4. Results

Until now, there has been no reported experimental result from a multisided permanent magnetized three-phase cable wound linear generator.

Fig. 6(a) shows measured three phase voltages from the stator winding over a resistive load of 5 Ohms and an air gap of 5 mm. The velocity of the piston in this

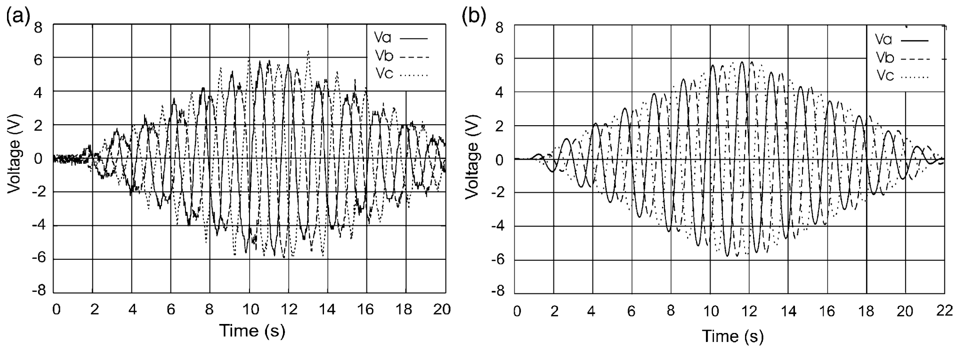

Fig. 6. Experimental voltages in (a), and one phase compared to the theoretical predictions in (b).

experiment was 6.75 cm/s, which is much lower than the speed at which the wave energy converter is intended to operate. Fig. 6(b) shows the excellent agreement found between measured data and simulations (using the FE code).

5. Conclusions

Today more than 80% of the world's electric power production comes from fossil fuelled plants. At the same time the CO_2 pollution needs to be diminished, and the public and many government are sceptical to the use of nuclear power. Further, the demand for electricity is forecasted to increase. Thus, the demand for economical renewable electric energy is very large. Today's focus has been in the areas of biomass, wind power and solar energy. Direct electrical conversion of energy from sources having a high utilisation degree and high power density, has been considered to be both difficult and uneconomical, however, recent studies shows the contrary [18]. The renewable sources to ultimately look for have no fuel cost, high power density (concentrated power) and high utilization (high number of full load hours per year). After addressing these sources described by physics, the key to future technological success lays in electromagnetism (Maxwell's equations) and converting low speed motions into electromagnetic energy as simple and cost efficient as possible—i.e. following the sources natural behaviour.

Well modelled hydrodynamic theory (Navier–Stoke's equations) is also of great importance for a future success. Already today, there is a focus on better analytical models for the interaction between buoy and waves. In this paper results using Archimedes simplified theory is used. Ecologically related issues, such as biofouling, have also to be considered already when the renewable energy conversion system is designed. Fouling, in terms of extra weight, may only affect the system slightly, and may to some extent be self-regulated in most exposed locations. Its effects should, however, also be seen in the light of cost of maintenance removing growth, or cost and environmental consideration of using anti-fouling substances. In many cases fouling may better be dealt with by slight over-dimensioning of crucial parts such as the buoy.

Efficiency and power quality of generator has to be taken into account when the system is designed so that the produced energy can balance the investment and installation costs. Low electromagnetic losses mean smaller forces and less heat development, thus less wear. Higher reliability means lower maintenance costs. Maintenance as well as installation is assumed to be costly when the power station is placed under water. These issues will affect the general design of the generator.

To address these issues for ocean wave energy conversion into electric energy requires robust and straightforward technologies with minimal investment and maintenance must be explored. Linear generators are ideally suited for direct conversion of the wave motion to electricity. The main reason that wave power are not yet commercial exploited deals with cumbersome installations with large associated investments thus rendering all present-day technologies nonpractical or not economically feasible. However, the amount of power available from wave power is substantial if it can be harnessed in an effective way.

After the initial extensive simulations the experiments conducted demonstrate that the computer calculations are within the accuracy, which can be anticipated. Several practical problems have been identified and corrected. The need for higher speed and implementation of the springs is a future task within the project.

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References

[1] Mueller MA. Electrical generators for direct drive wave energy converters. Gen Transm Distrib IEE Proc 2002;149(4):446–56.
[2] Carcas MC. The OPD pelamis WEC: current status and onward programme. Int J Ambient Energy 2003; 24(1):21–8 [UK].
[3] Duckers L.Wave energy, ch. 8 from, renewable energy,ed. Boyle G. Oxford University Press; ISBN 0-19-856451-1.
[4] Polinder H, Gardner F, Vriesema B. Linear PM generator for the wave energy conversion in the AWS. Proc ICEM 2000;309–13.
[5] Thorpe TW. A review of wave energy, volume 1, main report, December 1992.
[6] Falnes J, Lovseth L. Ocean wave energy. Energy Policy 1991;19(8):768–75.
[7] Clément A, McCullen P, Falcaõ A, Fiorentino A, Gardner F, Hammarlund K, et al. Wave energy in Europe: current status and perspectives. Renew Sust Energy Rev 2002;6(5):405–31.
[8] Korde Umesh A. Control system application in wave energy conversion. OCEANS 2000 MTS/IEEE conference and exhibition, Volume: 3, 11–14 September. vol. 3 2000 p. 1817–24.
[9] Salter SH. Progress on edinburgh duck, hydrodynamics of ocean-wave utilization. Berlin: Springer; 1985 p. 35–50.
[10] Budal K, Falnes J. In: Count BM, editor. Interacting point absorber with controlled motion, power from sea waves. London: Academic Press; 1980. p. 381–99.
[11] Korde UA. Time domain control if a single mode wave energy device Proceedings of the eleventh international offshore and 'polar engineering conference stavanger, Norway, June 2001 p. 17–22.
[12] Falnes J. Ocean waves and oscillating systems, Cambridge 20020 521 78211 2.
[13] Ivanova IA, Bernhoff H, Ågren O, Leijon M. Simulated generator for wave energy extraction in deep water. Ocean Engineering 2005;32(14/15):1664–78.
[14] Thorburn K, Karl-Erik Karlsson,Wolfbrandt A, Eriksson M, Leijon M. Time stepping finite element analysis of variable speed synchronous generator with rectifier, applied energy July 2004 – accepted for publication.
[15] Ivanova I, Ågren O, Bernhoff H, Leijon M. Simulation of a 100 kW permanent magnet octagonal linear generator for ocean wave conversion. Sci Tech Rev 2004;March [in Russian].
[16] Leijon M, Bernhoff H, Ågren O, Isberg J, Sundberg J, Berg M, et al. Multi-physics simulation of wave energy to electric energy conversion by permanent magnet linear generator. IEEE Energy Convers 2004; 19(4):1–6.

[17] Thorburn K, Bernhoff H, Leijon M. Wave energy transmission system concepts for linear generator arrays. Ocean Eng 2004;31(11–12):1339–49.

[18] Leijon M, Bernhoff H, Berg M, Ågren O. Economical considerations of renewable electric energy production especially development of wave energy. Renew Energy 2003;28:1201–9.

[19] Danielsson O, Sjöstedt ES,Thorburn T, Leijon M. Simulated response of a linear generator wave energy converter, ISOPE paper 2004 JSC-387 February; 2004.

[20] Eriksson M,Thorburn K, Bernhoff H, Leijon M. Dynamics of a linear generator for wave energy conversion, OMEA paper 51205, vancouver Canada; 2004. 20–25.

[21] Bernhoff H, Sjöstedt E, Leijon M. Wave energy resources in sheltered sea areas: a case study of the Baltic Sea, 5th European wave energy conference Cork Ireland; 2003.