Multiphysics Simulation of Wave Energy to Electric Energy Conversion by Permanent Magnet Linear Generator

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***Abstract*—The possibility to use three-phase permanent magnet linear generators to convert sea wave energy into electric energy is investigated by multiphysics simulations. The results show a possibility, which needs to be further verified by experimental tests, for a future step toward a sustainable electric power production from ocean waves by using direct conversion. The results suggest that wave energy can have an impact on tomorrow's new sustainable electricity production, not only for large units, but also for units ranging down to 10 kW. This gives wave power a larger economical potential than previously estimated. The study demonstrates the feasibility of computer simulations to give a broad, and in several aspects a detailed, understanding of the energy conversion. The simulation results also give a useful starting point for future experimental work.**

***Index Terms*—Linear generator, permanent magnet generators, power conversion, power generation, technological innovations, underwater electronic equipment.**

I. INTRODUCTION

A. Background

AS AN introduction to this paper, the authors like to acknowledge the pioneers over the last 30 years in the world-wide wave power research, i.e., Thorpe, Falnes, Salter, and others for their extensive and important work. Thorpe [1] and recently Clement *et al.* [2] have overviewed wave energy technologies and their present status. Falnes gives a thorough account of the theory for wave energy and its extraction [3]. Buoys of various shapes have been studied for absorption of the potential energy of the waves. A theoretical limit for the absorption efficiency of a linear array of symmetrically radiating point absorbers is 50% [3]. However, the efficiency can be higher with finite dimensions. The Salter's Duck has achieved 90% absorption efficiency by optimizing the shape and operation of the buoy [4]. The mechanical energy of the absorber needs to be converted into electricity. Mueller and co-workers [5]–[7] have an interesting approach to the design of wave energy conversion.

An ongoing project to convert sea wave energy is the Archimedes Wave Swing (AWS). A pilot plant has been designed for 4-MW peak power [8]. The AWS is a submerged air filled chamber, where a floater (lid) is moved up and down by pressure variations produced by passing waves. A three-phase linear permanent magnet generator is designed to extract electric energy from the motion of the floater [8].

Today, several countries have activities within wave energy, but Sweden has not. In the mid-1980's, the area was considered to be difficult and uneconomical. Moreover, the Swedish waters were estimated to contain too little wave energy and the general opinion was that it could not be motivated to do research on small 5–50 kW conversion devices. Despite this, one of the more tested technologies has been developed in Sweden, the so-called IPS OWEC Buoy with a power of 100 kW or more. It is now manufactured in the U.S. The device pumps water up and down, thereby driving a traditional generator [12].

The waves in the ocean and their behavior have been the objectives for many investigations [1], [2]. However, apart from some tests, mechanical solutions with a traditional rotating machine have been predominant for the conversion.

The dominating countries in the development of wave power have so far been Denmark, India, Ireland, Japan, Norway, Portugal, The Netherlands, Australia, the U.K., and the U.S. [13], [14]. Most of the projects remain in the research stage, but a substantial number of plants have been deployed in the sea as demonstration schemes. Several ways of classifying wave energy devices have been proposed, based on the energy-extraction method, the size of the device, etc.

B. Potential

It is a challenging task to convert the vast energies in the ocean waves into electric energy. When approaching sustainable electric power production for the future, attention must be paid to the economical constraints. The social, ecological, and environmental impacts are not the scope of the present paper, although it is necessary to pinpoint the needs for research and investigations regarding these items.

Renewable electric energy supply is today one of the highest priorities in many parts of the world. The Kyoto declaration 1997 and the last agreement at Marrakech 2002 are significant proof of this. Both the EU and the U.S. have set their targets on future greenhouse emissions.

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TABLE I

EUROPEAN WAVE ENERGY POTENTIAL IN SOME EU COUNTRIES [9], USING EARLIER PRESENTED TECHNOLOGIES. DIRECT CONVERSION CAN HAVE A POSITIVE IMPACT ON THE ESTIMATED POTENTIAL

Country	**Technical potential**	**(TWh/year)**
	Near shore	*Offshore*
Denmark	2 – 3	5 – 8
France	3 – 5	12 – 18
Germany	0.3 – 0.5	0.9 – 1.4
Greece	1 – 2	4 – 7
Ireland	7 – 11	21 – 32
Italy	3 – 5	9 – 16
Portugal	4 – 6	12 – 18
Spain	3 – 5	10 – 16
UK	14 – 21	43 – 64

Today, more than 80% of the world's electric power production comes from fossil-fuelled plants. As the demand for electricity is forecasted to increase, the need to find methods to extract electric energy from renewable sources like sea waves is urgent. Estimations of wave power are given in Table I for some EU countries. The wave energy potential in the EU has been estimated conservatively as 120–190 TWh/year offshore and an additional 34–46 TWh/year at near-shore locations [1], [9], [10].

C. Economy

The economic impact of the utility factor, which is of crucial importance to any scheme of renewable electric energy production, is analyzed in [11]. The utility factor is defined as

$$\alpha = \frac{P_{\text{ave}}}{P_r} = \frac{W}{P_r \cdot 8760}$$

where P_r is the rated power and P_{ave} is the average produced power of the installed equipment. P_r and transient conditions determine designs of devices and systems, while investment payback is determined by the annually produced energy W. As emphasized in [11], wave power will probably achieve a higher utility factor over a year than both solar and wind. The majority of wave energy is by nature *converted* wind energy with longer duration and higher mass and thereby energy density.

The energy flux of sea waves attenuates on a slower timescale than wind, i.e., waves will persist even when the wind has ceased. The utility factor for sea wave energy can thereby be higher, although in practice, it has to be considered in the design of wave energy converters and systems. As the utility factor is a key parameter in the economics of renewable energy production, wave energy is expected to be competitive with other sources of renewable electric energy. Calculated values for investment, with parameters relevant for wave power, are shown in Fig. 1.

D. Opportunity

Linear generators as direct converters were earlier regarded as impossible, since low velocities were believed to give too slow flux changes and thereby large and expensive electromagnetic converters.

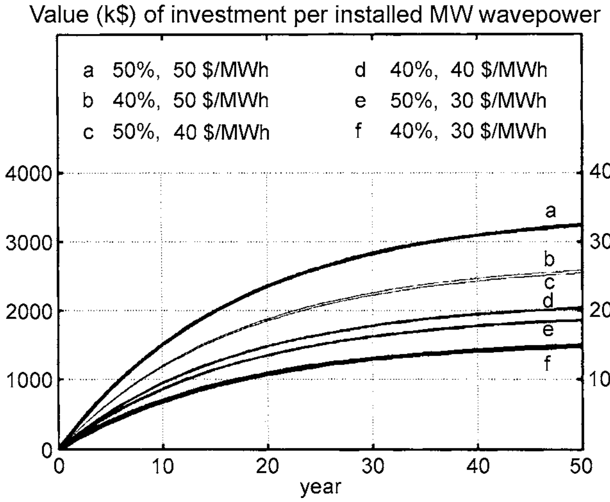

Fig. 1. Value of investment per installed MW wave power for different values of the utility factor and price for the electricity. The computation corresponds to an interest rate of 6% and a maintenance cost of $3/MWh [11].

Reports from activities in England [4]–[7] and The Netherlands [8], as well as results from electromagnetic simulations of a permanent magnet linear generator at bottom of the sea connected to a floating buoy presented, show a neglected opportunity. In particular, detailed modeling and simulations, as opposed to the traditional rule of thumb estimates, need to be carried out in order to improve technology.

II. THEORY AND SIMULATIONS

A. Theory

The theory of wave energy is well described in a book by Falnes [3]. For a propagating harmonic wave on deep water, half of the energy in the wave is potential energy and the other half is kinetic. The transported time averaged wave power per unit width L of the wave front is

$$\frac{dP}{dL} = cTH^2, \quad c \approx 976\ \mathrm{Wm}^{-3}\mathrm{s}^{-1}$$

where $1/T$ is the frequency and the height H of the wave is twice the amplitude, $H = 2\ \mathrm{A}$.

The potential energy gives a lift force on a buoy, as illustrated in Fig. 2. For simplicity, the buoy is modeled as a point source with respect to its influence on the surrounding water.

The buoy drives a piston in the generator with a force corresponding to the Archimedes lift force, and is from this point of view considered to be finite, with the diameter much smaller than the wavelength. The motion of the piston is modeled by

$$m\frac{d^2x}{dt^2} = F_{\text{buoy}} + F_{em} + F_{\text{spring}}$$

where the force is a sum of the Archimedes lift force on the buoy [3], the inductive force from the generator, $F_{em} \approx -k_{em}dx/dt$, and the mechanical spring forces $F_{\text{spring}} \approx -F_0 - k_{sp}x$. The electromagnetic inductive force is determined by a detailed computation of the retarding effect on the piston associated with the induced stator currents and the applied load.

The multiphysics problem of a new permanent magnet linear generator adopted for wave energy conversion has been simulated. For the electromagnetic design, the finite-element method

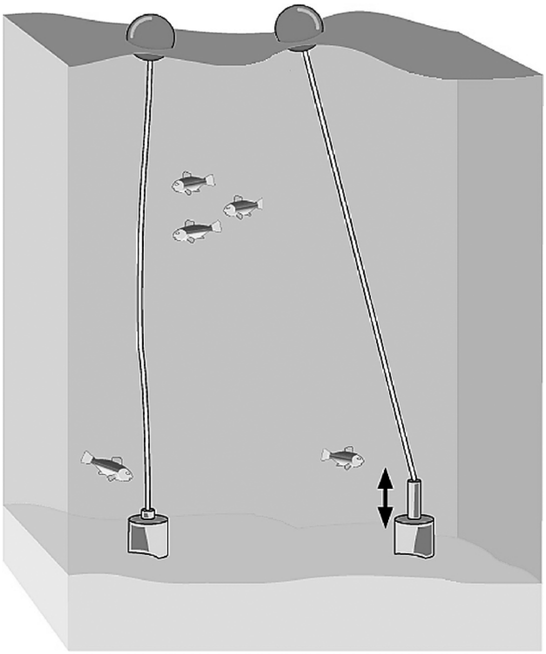

Fig. 2. Outline of buoy, rope, and linear generator for direct conversion of wave energy to electricity.

(FEM) has been used to solve Maxwell's equations at a low frequency, as follows:

$$\nabla\cdot\mathbf{D}=\rho_f,\quad \nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$$
$$\nabla\cdot\mathbf{B}=0,\quad \nabla\times\mathbf{H}=\mathrm{j}_{\mathrm{f}}+\frac{\partial\mathbf{D}}{\partial t}.$$

Simultaneously, the thermal behavior of the design has been simulated for different loading situations and geometries. The basic thermal equations are Fourier's law for heat conduction and the continuity equation for heat

$$\mathbf{j}_{\text{heat}}=-\lambda\nabla T,\quad \frac{\partial T}{\partial t}+\frac{\kappa}{\lambda}\nabla\cdot\mathbf{j}_{\text{heat}}=h$$

where the heat source h consists of iron losses and ohmic losses in the copper coils.

B. Computer Simulations

The FEM is of significant practical use in modern engineering. Today's computer capacity transforms yesterday's almost impossible problems into possibilities that can be simulated and demonstrated before the construction phase. Several different options, new ideas and optimizations can be tested in the computer laboratory environment. Some calibrations are always necessary, so the need for experimental verification still remains after a simulation phase and should not be neglected. However, simulations of the linear generator improve the starting point for the forthcoming experimental work and significantly improve the speed of the development.

In the case of electromagnetic energy converters, simulations have previously been used during the extensive development of the so-called Powerformer, the worlds highest voltage generator, both in hydro versions (155 kV/75 MVA), turbo versions (130 kV/42 MVA), and several other prototypes. It was also used for the development of high-voltage motors called motorformers and high-voltage permanent magnet machines. The construction phase was in all cases preceded by simulations of the devices [15]–[18].

In this project, two of the authors (Dr. Karlsson and Dr. Wolfbrandt) have further developed the simulations to model an arbitrarily chosen wave function as input to the multiphysics solver for a linear generator. The time variations are general and thus not limited to a single frequency. Several aspects of multiphysics effects of mechanics, thermodynamics, and electromagnetics can be modeled within the simulations.

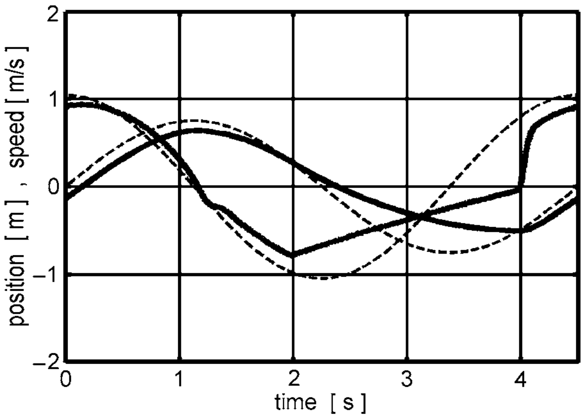

Fig. 3. Speed and position of piston and wave. Solid lines refer to the piston and dashed lines to the wave. The wave speed has a maximum close to $\mathrm{t}=0$.

TABLE II
PARAMETERS FOR THE SIMULATION

Wave:		
Wave height:	1.5	m
Time period of wave:	4.5	s
Wave length	30	m
Buoy, piston, and spring data:		
Area of buoy: buoy	20	m^2
Volume of buoy:	10	m^3
Weight of buoy:	260	kg
Static spring force:	10	kN
Spring constant:	20	kN/m

III. RESULTS

A. Motion

The time evolutions of the speed and position of the piston and the wave in a simulation of a 10-kW linear generator is shown in Fig. 3. The solid lines refer to the piston and the dashed lines to the wave. The computations are done over one wave period. Table II also contains wave conditions and other parameters for the simulation.

In Fig. 4, the forces on the buoy and piston are presented. A rope is connected between the buoy and the piston. At $\mathrm{t}=0\,\mathrm{s}$, the buoy lifts the piston and gives extra tension to the spring. At $\mathrm{t}=2\,\mathrm{s}$, the lifting force from the buoy ceases and at $\mathrm{t}=4\,\mathrm{s}$ the spring force ceases. The electromagnetic force acts to decrease the speed.

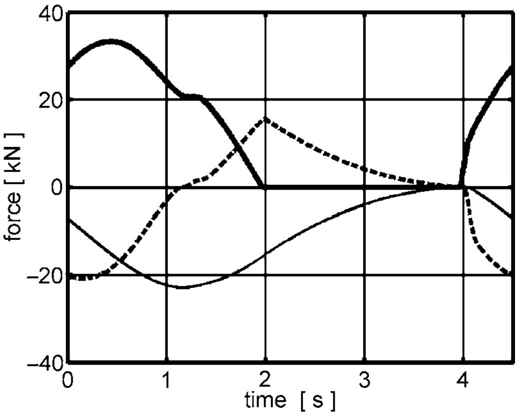

Fig. 4. The forces from buoy (thick solid line), spring (thin solid), and the electromagnetic force (dashed).

TABLE III
PHYSICAL QUANTITIES FOR THE SIMULATED 10-kW LINEAR GENERATOR

Rated power	10	kW	
Armature voltage	578	V	(rated)
Armature current	10	A	(rated)
Electric efficiency	0.83		
Average frequency	13.4	Hz	
Load angle	12.1	°	
No of poles	660		
Air gap width:	2	mm	
Air gap field :	0.59	T	
Number of sides (in stator)	4		
Stator width:	300	mm	
Pole width:	25	mm	
Stator length:	3 925	mm	
Piston length:	5 425	mm	

The direction of the electromagnetic force changes sign at the upper $t = 1.2$ s and lower $t = 4$ s turning points of the piston motion, and the generated power becomes zero at these events.

B. Linear Generator

Data from the simulation are summarized in Table III, where physical quantities for a simulated 10-kW three-phase linear generator with surface mounted permanent magnet NdFeB are given. Already a small 10-kW generator may be of economic interest. Linear generators of larger scale (100 kW or more) will have a beneficial impact on cost and economy.

Several different designs for a small three-phase 10-kW permanent linear generator for wave power (or wave energy conversion) have been simulated. Fig. 5 illustrates one pole of the simulated generator with $q = 1$ (the number of slots per pole and phase) and its corresponding flux. The maximum magnetic field appears near the innermost stator coils. For simplicity, only one pole and one of four stator sides of the total electromagnetic converter is shown in Figs. 5–8. However, the computation is carried out for a complete device and end effects are included.

An essential part in the design is to avoid mechanical solutions that are not robust. By using a large number of poles, the physical dimensions of the generator can be reduced, and the rate of magnetic flux change can be increased. An ultimate choice for the conversion may differ from the one given here, but the present design is already sufficient to be of interest.

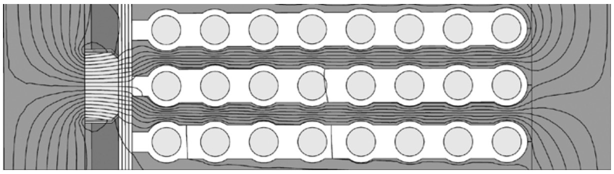

Fig. 5. Magnetic flux plot in one pole in the rotor and one side of the stator.

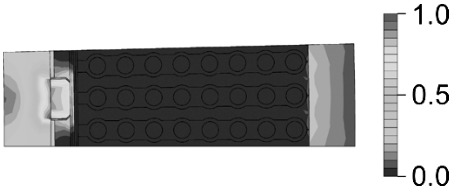

Fig. 6. Minimum magnetic B field in a permanent magnet of the piston [unit: T].

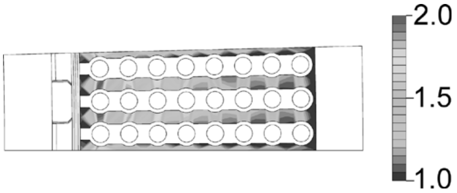

Fig. 7. Maximum real and effective magnetic B field [unit: T].

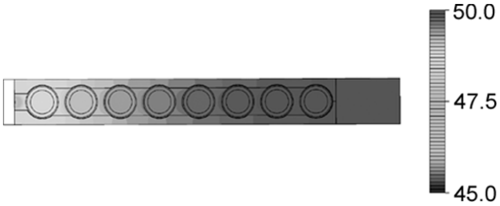

Fig. 8. Temperature in one stator slot [unit: °C].

In Figs. 6 and 7, the minimum and maximum B-field during the whole 4.5-s simulation cycle are presented.

One example of the thermal simulations is presented in Fig. 8, where the temperature in one stator slot is shown. The surrounding temperature is set to 40 °C, which is conservative considering a submerged location of the generator. The computed stator temperature is sufficiently low for long-term operation of the polymer-insulated cables.

C. External Circuit

The FEM simulations also handle external circuits. The voltage in one phase of the stator is shown Fig. 9. As the load is resistive, the phase current is proportional to the phase voltage. The peak current is 19 A.

For the sake of visibility, the moving average smoothens rapid oscillations in the power, having a mean frequency of 13.4 Hz. This comparatively high-frequency results from the large number of poles and that $q = 1$ in this particular simulation.

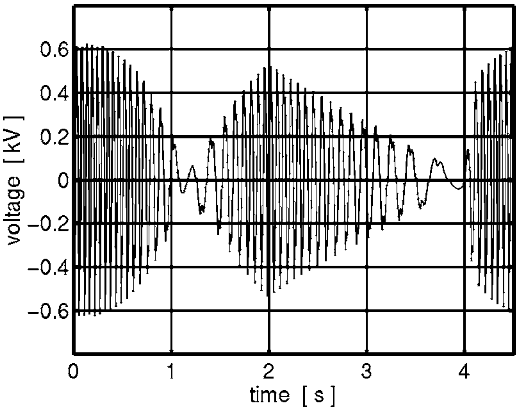

Fig. 9. Voltage in one phase of the linear generator.

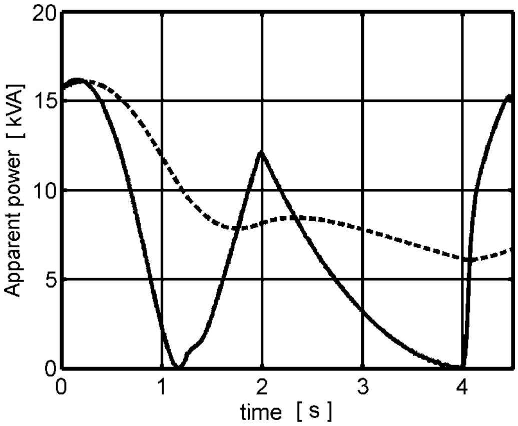

Fig. 10. Generated ac apparent power. The time integrated apparent power (dashed line) is 7.2 kVA, with the simulated wave.

It can be observed that if a linear generator with a low load angle can be designed, the need for complicated external devices can be reduced, and thereby, the need for extra investments and maintenance.

IV. DISCUSSIONS

The air gap width needs to be small in order to reach high electric efficiency. Mechanical vibrations, originating from the piston motion in particular, have to be suppressed to avoid wear and maintain a well-defined air gap width over the lifetime of the generator. The mechanical and electrical design for the stability of the piston motion is thus crucially important. A key result is that a linear generator has to be designed with at least 4 stator sides to balance the forces. In the present simulation, the number of slots per pole and phase q is equal to one. To suppress the fluctuating torque on the piston (cogging), a rational number should be chosen for q. This will be analyzed in more detail in a forthcoming paper.

There is quite a good possibility that three-phase permanent magnet linear generators are an unrecognized option, one for which technical solutions have not been deeply investigated for sustainable electric power production. The simulations presented indicate a possibility that it can be an economical complement for electric power production at several places, even with comparatively small wave heights as in the Baltic Sea. The simulations will necessarily have to be validated by extensive experimental testing and measurements.

Future work will be focused on both experimental setups and further simulations of the many parameters involved in the design and physical behavior. Although these presented simulations of a wave energy converter looks very promising, this work is only expected to serve as a starting point toward a future real device.

V. CONCLUSIONS

In order to get an overall picture and reduce the cost for the design of new kinds of generators, multiphysics simulations are suggested as a first step in the development. The FEM has demonstrated to be a feasible tool for multiparameter simulations, especially in the field of energy conversion. Previously, the simulation tool has been used for large high-voltage hydro and turbo generators. It has also been used for the development of high-voltage motors and high-voltage permanent magnet machines. The simulations were in all these cases verified in real operating constructions [19]. In this paper, the tool has been used to simulate conversion of wave power into electric power (Fig. 10) by three —phase permanent magnet linear generators. By using a large number of poles, 660 in the simulation presented in this paper, the geometrical dimensions of the generator can be reduced, and the rate of magnetic flux change can be increased. Among several results from the simulation, the most important one indicates a possibility to economically access the vast energy of the waves by direct conversion into electric energy. The results from the simulations remain to be verified by experimental work.

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