Testing of a full-scale PTO based on a Switched Reluctance Linear Generator for Wave Energy Conversion

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Abstract

The paper presents a Switched Reluctance Linear Electric Generator developed and built to work as a direct drive PTO in a full scale wave energy converter.

The nominal characteristics of the electric generator, obtained in laboratory with dry tests, are 160 kN of nominal force and 1 m/s of nominal velocity, in good agreement with the design values. The proposed lab test schema does not use any hydraulic or pneumatic actuator but split the coils of the SRLG into two parts (two sub-machines, one acting as a motor and the other as generator), controlling them by means of two power electronic converters. Both static and dynamic tests (the latter, being representative of sea conditions) can be performed using the aforementioned test schema. Different strategies have been considered and implemented in the control system in order to assess their suitability and to achieve a better characterization of the machine's behavior. After the promising results obtained in the dry tests, Wedge Global Research and Development resources are now involved in a project focused in testing the linear generator's performance and reliability in real sea conditions.

Keywords: linear generator, switched reluctance, testing, wave energy.

1. Introduction

Seas and oceans represent a large potential source of renewable energy. The total worldwide net resource (that is the gross resource minus the areas with $P \leq 5$ kW/m and ice covered areas) is estimated at 3 TW [1]. It has been long (the first known patent dates from 1799 [2]) since the first invertors considered how to employ wave energy for human purposes.

Following the same spirit reflected in those initial challenges, the technological company Wedge Global S.L. has successfully developed a direct drive electrical PTO (*Power Take-Off*) system for harnessing the wave energy from the seas that is potentially suitable for different Wave Energy Converters (heaving point absorbers, pitching devices, OWC amongst others).

The existing PTO is the result of a R&D work that started in 2006 and involved its manufacturing in 2010. The PTO solution comprises three elements: not only an electrical machine but also the power electronics and the associated control system. It is based on an innovative Switched Reluctance Linear Generator, which has been internationally patented.

The original technological project was structured in three phases:

i. Manufacturing of the linear machine and of its control and drive systems.
ii. Lab tests: performance assessment (dry tests)
iii. Development of a test bench and marine performance assessment and functional tests.

The PTO has successfully completed phases *i* and *ii*. The current status of the project is the start of phase *iii*, which means developing a converter that serves as the PTO test bench for undergoing the sea trial stage. The targets of this stage are to verify the full functionality under open sea conditions, to analyze different control strategies in real applications and to confirm the excellent results achieved in the previous phases.

1.1 Main advantages of Wedge's PTO solution

Conventional WECs (*Wave Energy Converters*) incorporate hydraulics to convert slow linear movements (such as the heave of a float as a wave passes) into fast rotational movement. Then the high-speed mechanical energy is converted to electricity by means of a generator, typically a rotating one.

However, this configuration entails a loss in efficiency (as a consequence of the inclusion of an additional stage in the conversion of energy from wave to wire), higher maintenance requirements and the appearance of non-reversibility.

Thus, the option of a direct drive results as a possible alternative. Direct drive configurations avoid the need of intermediate mechanical systems between the primary moving element and the electrical machine, simplifying the power take-off.

Amongst direct drive electrical PTOs, the most noteworthy are the permanent magnet machine and the reluctance machine. The former, in spite of reaching higher power factors, shows the following drawbacks: complex mounting and maintenance, higher sensitivity to aggression by the water environment and high cost of magnets (increase of 7 times the Neodimium cost and 10 times the Cobalt cost in the last year). As a consequence, Wedge has opted for the latter, which is robust, reliable, scalable (appropriate in cases of long strokes), and does not demand any special maintenance.

2. Lab tests

2.1 Testing laboratory schema

Dry tests on Wedge's PTO were performed in the laboratory at CEDEX-CIEMAT facilities. The aforementioned tests allowed to determine the nominal characteristics of the linear generator.

In order to test the generator in the absence of any kind of mechanical driver or external actuator, the switched reluctance machine was divided into two sub-machines: one of them actuating as a motor and commanded by a power electronic converter (ASC, *actuator-side converter*), and the other one working in the generating mode and equipped with its own converter (GSC, *generator-side converter*) as well. Both converters are connected to the same DC link, as shown in Fig. 1.

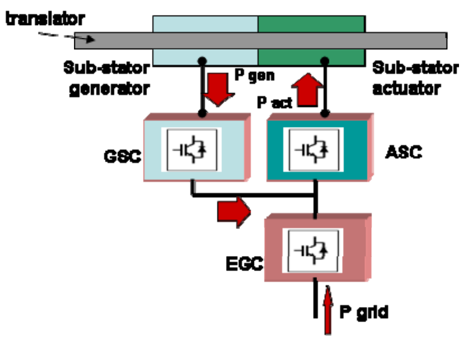


Figure 1: Laboratory testing lay-out.

The testing schema is completed with an *external grid-side converter* (EGC), which adapts the value of AC voltage at the connection point at the lab to the desired DC value in the common link.

This configuration showed to be adequate for testing not only the generator power and efficiency, but also the behaviour of the switched reluctance machine within different concepts and dimensions of point absorbers. Through an *"ad hoc"* designed control system it is possible to simulate different types of ocean waves or locations with known energy spectra. Moreover, since electric energy can be circled between both sub-machines, a better energetic efficiency can be calculated. Further information on the laboratory testing schema was presented in [3, 4].

As it has already been mentioned, in addition to the power electronic converters, a control system was designed to manage the power flow throughout the power electronics and the operation of the whole system. Control algorithms were developed under the platform dSPACE and integrated in a model in the MATLAB and LabView environments. The internal control for a switched reluctance machine is described in detail in [5].

2.2 Main experiments and results

The first phase of the experimental work comprised the characterization of the full machine. Windings resistance and friction forces were measured and the position encoder performance was checked (see Fig. 2). Results were coincident with the expectations.

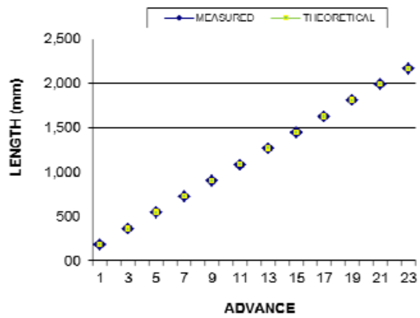


Figure 2: Results of the encoder calibration.

The second phase involved the execution of static tests. These tests were performed only in the generator sub-machine. They consisted in the measurement of the nominal features of the PTO by blocking the relative movement stator-translator and applying a force by the generator sub-machine. A load cell measures the real force exerted. Therefore, it is possible to characterize the force related with the current intensity at the linear electrical machine with regards to a constant current at fixed positions [6]. The values of the nominal characteristics and other parameters of the linear generator are shown in Table 1.

The third phase was the dynamic characterization. In order to accomplish the dynamic test, the actuator sub-machine was supplied with electricity from the grid through the ASC, causing the translator to move and, consequently, producing electric power in the generator side which is sent back to the grid through the GSC. Two operating modes were tested. Firstly, a constant force mode, which provided an almost squared shape of the speed function. Secondly, a sinusoidal mode, which meant a variable force in the generator so that the translator speed followed a sinusoidal curve. The maximum achievable force (and power) depends on the activation ON and OFF angles. Optimal switching angles were applied in other to achieve the optimal dynamic performance.

Finally, efficiency of the generator sub-machine was obtained as the ratio of the output electrical power (directly measured) over the input mechanical power (deduced from the static tests). According to previous definition, the efficiency of the machine has been measured for different speeds and extracted power levels, also modifying the activating angles. For the best cases and in a wide range of power, efficiencies up to almost 80% can be achieved.

Parameter	Value	Unit
Machine type	SR	-
Length	10.2	m
Stroke (1st generation)	2	m
Nominal voltage (DC bus)	1000	V
Nominal force	160	kN
Nominal speed	1	m/s

Table 1: Parameters of the Switched Reluctance Linear Generator.

It also has to be mentioned that results of force obtained from the static tests were validated against values calculated theoretically from a finite element model of the linear generator. Results showed excellent agreement with forecasts coming from the simulation programme (see Fig. 3).

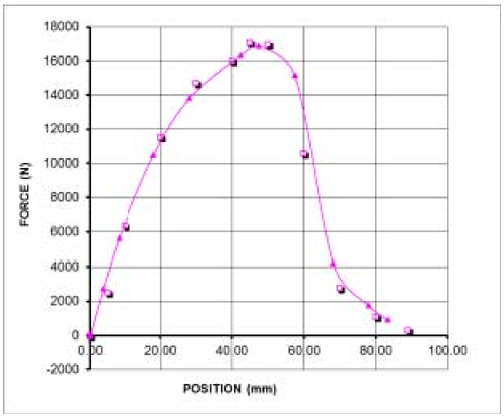


Figure 3: Validation of some force measurements (traingled dots in the continuous curve) against the FEM calculations (empty squares) at low current.

Further studies on the FEM model showed that slight modifications of the actual generator could bring its nominal rated force up to 200 kN.

3. Sea trials

The stage that follows the promising results obtained at the laboratory is the sea trail of Wedge's PTO. Testing at sea is an essential an indispensable step within the process of developing a commercial device for harnessing energy contained in waves.

The starting point of the sea trial is the design of the wave energy converter that will house the PTO in it and hence will serve as test bench. Apart from power production, considerations on relevant issues such as shape simplicity, reduction of loads on the structure (e. g. avoidance of slamming phenomena) and cost efficiency were present during the design process. The targets of the sea trials are checking the WEC performs as expected and achieving full marine functionality.

A necessary step prior to the WEC design is fixing the main boundary conditions: type of WEC, control strategy and location.

3.1 Typology of the WEC

First, the typology of the WEC has to be set. In this case, a heaving point absorber (small horizontal dimensions of the device relative to the wavelength of the incident wave) was chosen. It is a mature technology that has been used for navigation lights for years [7].

The device will consist of a two-body heaving system in which the wave absorption is obtained from the relative displacement between the two bodies. The two bodies will be a spar and a float moving up and down around the spar.

The wave, when passing over the device (rising and falling), creates a relative motion between the float, which moves up and down determined by the control applied over the PTO, and the spar (see Fig. 4). The displacement of the spar is not coupled with the movement of the float.

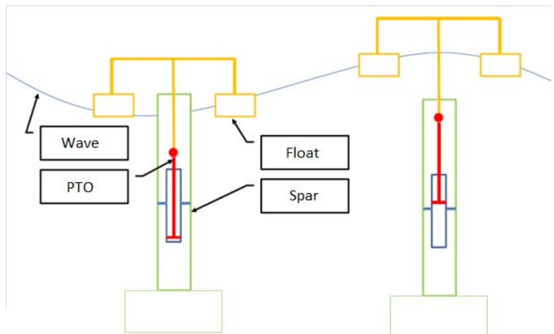


Figure 4: Hydrodynamic working principle of the WEC.

This resultant relative translation heave motion between the two bodies is transmitted to the PTO (hosted inside the spar) by means of a rod. The rod drives the translator of the electrical machine. The PTO will then convert this motion into electricity.

3.2 Control system

Several control strategies will be tested during the period of sea trials. Most representative ones are: damping control and optimum control (defined to maximize the power absorption).

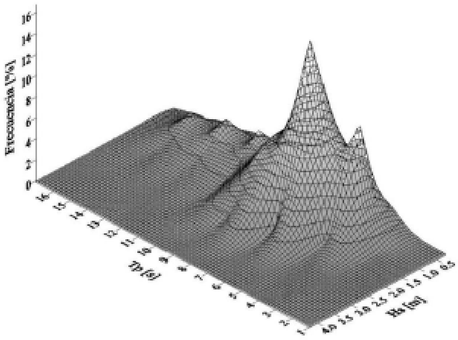
Constant damping implies a force in the PTO proportional to the relative velocity between the two bodies.

The optimal control theory implies to drive the WEC into mechanical resonant movement. It has long been understood that capturing the energy from waves is maximized by "tuning" the natural frequency of the excitation force [8]. The resonance can be well understood by modeling the whole system by means of an equivalent electrical circuit. This equivalent circuit replaces the mechanical and hydrodynamic variables in the equation of Cummins with electrical parameters, thus converting the mechanical problem into a basic electrical circuit analysis problem. Then, the optimal control theory is the same concept as the maximum power transfer theory.

Unlike other renewable technologies such as wind or PV, to get an optimal control it is necessary to tune the system to the site. Since the control system requires getting into resonance with the system, the point absorber design is completely related with the location.

3.3 Location

The definition of the WEC has to take into consideration the location of the trials. In this case, the test will take place at the PLOCAN facilities, in the Canary Islands (Spain). Scatter diagrams showing the sea states at the location considered (obtained from a coastal waverider buoy) can be seen in Fig. 5.



		Tp (s)											Total
		≤2,0	4,0	6,0	8,0	10,0	12,0	14,0	16,0	18,0	20,0	>20,0	
H_S(m)	≤0,5	0,000	0,371	0,716	1,484	1,903	1,829	1,046	0,516	0,033	0,004	0,000	7,902
	1,0	0,000	0,705	9,876	10,295	5,966	3,981	3,484	2,326	0,200	0,059	0,000	36,892
	1,5	0,000	0,000	6,099	17,137	6,151	2,026	1,373	1,046	0,093	0,004	0,004	33,936
	2,0	0,000	0,000	0,312	8,563	5,606	0,790	0,571	0,234	0,52	0,000	0,000	16,127
	2,5	0,000	0,000	0,019	0,820	2,690	0,256	0,152	0,089	0,041	0,000	0,000	4,066
	3,0	0,000	0,000	0,000	0,037	0,534	0,130	0,030	0,011	0,033	0,007	0,000	0,783
	3,5	0,000	0,000	0,000	0,000	0,093	0,108	0,011	0,000	0,000	0,000	0,000	0,211
	4,0	0,000	0,000	0,000	0,004	0,007	0,026	0,019	0,000	0,000	0,000	0,000	0,056
	4,5	0,000	0,000	0,000	0,000	0,000	0,007	0,015	0,004	0,000	0,000	0,000	0,026
	5,0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	>5,0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total		0,000	1,076	17,022	38,339	22,950	9,153	6,700	4,226	0,456	0,074	0,004	100

Figure 5: Annual average joint distribution H_s vs T_p for the coastal buoy.

As it can be deduced also form Fig. 5, power absorption in the range of T_p between 6 and 8 s (ω between 0.8 and 1.1 rad/s) comprises almost 53 % of the occurrence matrix. This fact reflects the main advantage of the PLOCAN site: this concentration and preponderance of lower periods makes possible to test scaled devices (1:3 or 1:4) to the detriment of full-scale devices. In case of testing full-scale devices, the advantage is that the survivability requirements will not be so demanding.

Finally, it is important to mention that the wave energy converter will operate standalone, burning the power in-site, as there will be no grid connection available.

3.4 Design of the WEC

The design of the geometry of the WEC will be based on the concept of resonance. The methodology applied in this design consists in an iterative search by modifying the geometry of each part of the device, as well as its inertia, in such way that the absorption pick is around 1 rad/s, as it is shown in Fig. 6, which represents the value of the dimensionless power absorption. Two resonance peaks appear: the spar resonance peak is the left one (lower frequencies), due to its relatively small hydrostatic restitution and large inertia. The second peak corresponds to the float resonance peak (lower mass and higher restitution mean higher resonance frequency).

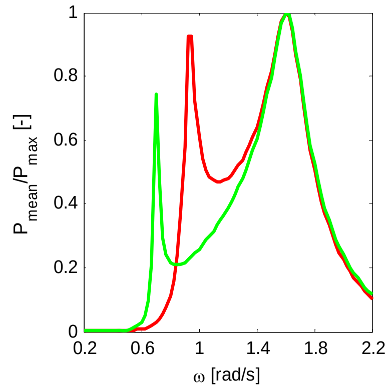


Figure 6: Dimensionless value of power absorption under optimal control for two different submerged body geometries considered (green line – bigger, red line – smaller).

Additionally, some further constraints were added to the hydrodynamic considerations. For instance, it was assumed that the internal diameter of the spar should be adequate to accommodate the linear generator with some tolerance to provide enough space for a maintenance operator. This becomes an advantageous key factor when analysing the O&M costs, as the device will not require to be towed to harbour for completing most of the maintenance tasks associated to the PTO. Other constraints to be regarded to at this stage could be for instance limits imposed in the excursion or the PTO load.

3.5 Equipment

Once the WEC has been defined and manufactured, the final task will be to carry out the marine tests, checking the whole system performs as expected.

The WEC will integrate some additional equipment and auxiliary systems so that the whole device can be controlled in a suitable way.

First, the device will incorporate ballast tanks in the two bodies for a long term adjustment of the natural frequency of the device to the optimum frequency of the sea condition at the site, so that the extracted power is maximized.

Second, it is worth mentioning the pneumatic braking and blocking systems, acting on the floater and against the spar. The existence of an inevitable geometrical constraint in the stroke of the linear machine makes them essential. They must, together with the end stops, ensure that the survivability is not at risk at any moment of the operation.

Third, as stated in section 3.3, the WEC will not be grid connected. Electricity generated by the PTO will be either dissipated in the form of heat using some resistances or stored in the batteries (only for auxiliary power demand) incorporated, according to the defined criteria. This implies the inclusion of two required systems: a dissipation system and a back-up system for supplying the control and operation systems.

Finally, the spar is anchored to the sea bed by means of a mooring system, comprising chains that link the device with the respective 'deadweights'.

Other relevant additional equipment which will be integrated with the WEC is: communication system (which will be redundant, and based on two technologies, radio-modem and Wimax), bilge pump, refrigeration system and cathodic protection.

3.6 Operation & Monitoring

The buoy will be working following stipulated modes of operation: start-up, stand-by, emergency, (normal) generation, controlled stop, storm, maintenance & inspection, …

The device will also include several sensors that will register both analogue and digital (alarms or states) signals. Examples of the magnitudes that will be measured are: temperature in the windings of the PTO, power produced by the PTO, voltage at the DC link, position of the translator of the PTO, accelerations on the WEC, strain/deformations on the structure, tension in the mooring line, … Some of the previous signals will become different inputs of the control system, and many of them will be sent to shore as part of the monitoring system.

The whole device will be controllable from a land-based control room, using an operation and monitoring environment similar to SCADA.

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