A novel proposal of PTO direct-drive linear generator, an Azimuthal Multi-translator Switched Reluctance Machine (AMSRM)

M. Lafoz, M. Blanco, J. Nájera, G. Navarro and L. García-Tabarés

Abstract: **Research and development on power take-off (PTO) in wave energy has been gaining relevance in recent years, appearing as a priority in various forums (JCR reports, SRIA in wave energy development, specific research funding program in WES, etc.). A new proposal of a linear electric generator to act as a PTO in wave energy extraction applications has been developed in the European project SEATITAN. In particular, the scalable and modular PTO has been designed to be adapted to four different wave energy converters of heaving point absorber type. The linear generator is based on a technology of multi-translator switched reluctance machine in which the magnetic flux is azimuthal. This topology allows reducing the amount of magnetized material needed and increasing the force density, besides having a cylindrical shape that allows adapting perfectly to the spar of point absorber type WECs. The Azimuthal Multi-translator Switched Reluctance Generator (AMSRG) has been completely developed and a prototype composed by two modules of 35 kN of force and 3 m/s of peak velocity has been manufactured. The manuscript details the design and manufacturing process as well as the characterization and validation tests. Those dry tests, delivered at the lab, comprise: the force characterization, the electric losses measurement, the dynamic characterization of frictional losses and a preliminary setting of control parameters.**

Keywords— **electric direct drive, heaving point absorber, linear generator, power take-off (PTO), switched reluctance machine.**

I. Introduction

Research and development on power take-off (PTO) in wave energy has been gaining relevance in recent years, appearing as a priority in various forums, such Join Research Centre (JCR) reports [1], the Strategic Research and Innovation Agenda (SRIA) in wave energy development [2] or specific research funding programs in Wave Energy of Scotland (WES). The continuous improvement of PTOs and demonstration of their performance is one of the main challenges identified as priority for wave energy devices [2]. Different types of PTO have been considered, depending on the wave energy converter technology under analysis. The most valuable requirements for a PTO are: high power density, wide power range of operation, reliability and survivability are some of the most valuable ones. Hydraulic, pneumatic, mechanic and electric direct-driven are roughly the technologies used for PTOs in wave energy conversion. Among them, direct-driven alternatives [3] have very attractive characteristics, since they increase: robustness, conversion efficiency, reliability and survivability, also avoiding intermediate conversion stages and eliminating sources of failure, with the corresponding reduction in LCOE associated to maintenance.

This paper presents the development, manufacturing and testing of an innovative concept of electric direct-driven PTO used in heaving point absorbers (HPA). The technology and the works presented have been carried out under the frame of the Horizon 2020 project SEA-TITAN H2020-.Nº 764014 [4]. The aim of this project was to develop one technology of PTO to be adaptable to four different devices of wave energy conversion. In fact, it is

Fig. 1. The four WEC technologies which define the PTO.

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the combination of the four WEC characteristics what determines the design parameters. Although the four selected WECs have different power, force, maximum velocity and stroke, a modular concept of PTO has been developed, in order to be adapted to the particular conditions of each WEC. Fig. 1 presents the different WEC technology develops considered.

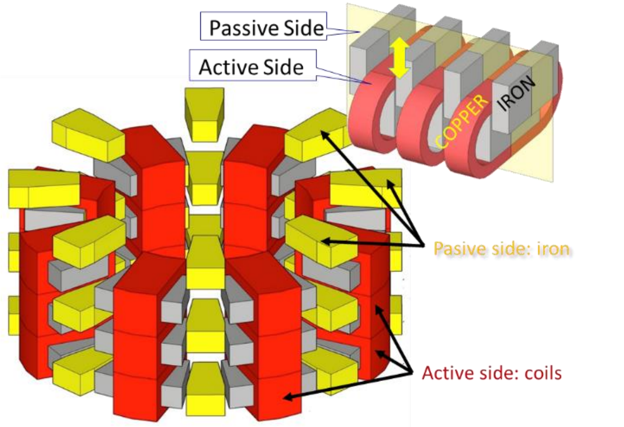

Fig. 2. Topology of azimuthal switched reluctance machine with three phases and 8 poles per phase

II. THE CONCEPT OF THE NEW LINEAR SWITCHED RELUCTANCE GENERATOR

The linear generator developed is based on an azimuthal flux multi-translator linear switched reluctance machine topology [5]. The azimuthal magnetic flux path allows eliminating part of the yoke, reducing the amount of magnetic material needed and therefore increasing the force density. Besides, the cylindrical shape allows adapting perfectly to the spar of HPA type of WECs. Fig. 2 presents the basic concept of the linear generator presenting the active part comprising the coils, in red with the yoke in grey, and the passive part depicted in yellow. A three-phase machine with 8 poles per phase is selected.

TABLE I
LIST OF PARAMETERS FOR ONE MODULE OF THE AMSRG PROTOTYPE

Parameter	Value	Definition
$F_{2D}\ [N]$	40 kN	Maximum force developed
$B_0\ [T]$	2.1 T	Flux density at the airgap
$v\ [m/s]$	3 m/s	Maximum velocity
$g\ [mm]$	2 mm	Airgap, distance between the active and passive poles
$J\ [A/mm^2]$	3.5 A/mm^2	Coil current density
$B-H\ curve$	M600-50A	Magnetic steel
$D\ [m]$	1.2 m	Maximum diameter
$L\ [m]$	8 m	Approximate length

The analysis of the four HPA characteristics provides a set of parameters for the basic module of PTO to be developed. Basically, some parameters related to the performance of the PTO, maximum force and velocity have been defined. Some other electromagnetic parameters have been also considered, taking into account rough dimensions of a PTO module. Finally, it is important to define the dimension related to the diameter of the WEC spar. These design specifications are compiled in Table 1.

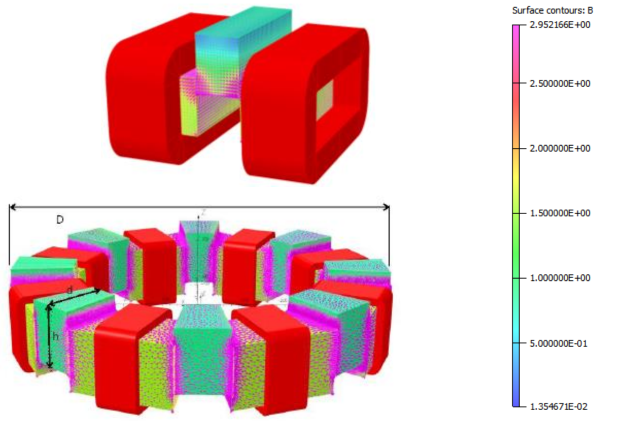

Fig. 3. Magnetic field distribution at the azimuthal switched. reluctance generator. Calculation with 3D-OPERA software.

A. Analysis based on finite element method

Based on the preliminary design, some electromagnetic analysis based on finite element methods (FEM), both in 2D and 3D, have been carried out [6], in order to confirm the required performance. From this analysis, the detail design is obtained, as well as the manufacturing drawings.

TABLE II
CONFIGURATIONS FOR THE LINEAR AMSRG

Configuration	*Advantages and drawbacks*
Long passive part moving	***Pros.:*** *Simplest configuration, does not require flexible electrical connections* ***Cons.:*** *Long and moving passive side which implies long stroke and excessive weight*
Short active part moving	***Pros.:*** *Small moving mass; the long passive side could be part of the machine structure* ***Cons.:*** *Moving active part; flexible electrical connections required*

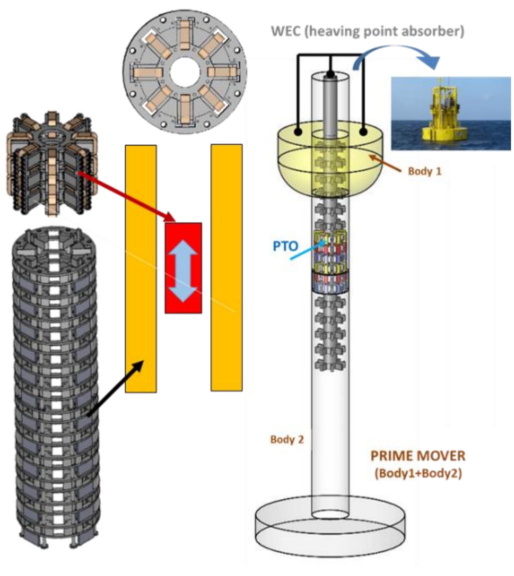

Fig. 4. Configuration of the active and passive parts of the PTO and adaptation to the HPA.

Fig. 3 includes an example of 3D-FEM analysis developed with the software OPERA. It presents the interaction of two single coils with the passive part pole and a complete model of one machine phase.

B. Configuration of the active and passive parts

An additional decision to be taken is whether the moving part is the active or the passive one.

After analyzing the pros and cons of several configurations, only two of them are reliable, as presented in Table II. The configuration of long passive part linked to the structure and a moving short active part is preferred, although it is required the use of a flexible cable carrier [7]. Fig. 4 presents a drawing of the final aspect of the design.

III. MANUFACTURING AND ASSEMBLY OF THE LINEAR PTO

A steel beam supports the structure as a basic frame for the linear generator, allowing its attachment to the ground by a concrete pad. It serves also as mounting reference for the assembly of the passive side, transportation and manipulation of specific safety elements, as it is the case of the end stops. Passive and active sides of the generator are described hereafter.

Fig. 5. Passive side of the AMSRG.

C. Generator passive side

The generator passive side comprises 8-pole magnetic steel laminated rings. The magnetic rings are mechanically attached and held together (via bolted unions) by equally-distributed connecting flanges, as displayed in Fig. 4. Some spacers are located-between consecutive rings, also responsible for supporting the rolling guides, along which the active side will slide in its reciprocating movement. Fig.5 depicts the passive part.

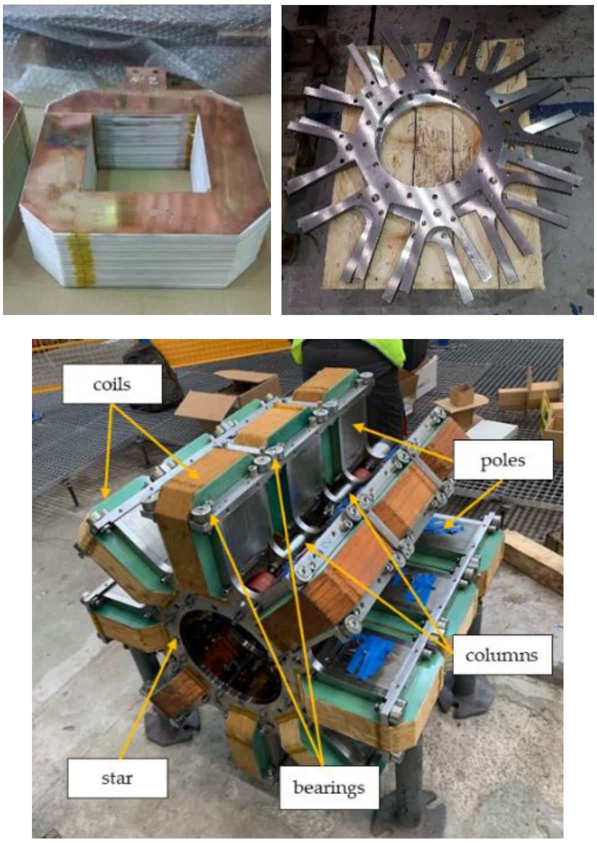

Fig. 6. Active side of the AMSRG. Coils and stars.

D. Generator active side

The active side hence slides along the passive one, inside of it thanks to sets or roller bearings mounted onto the former and which roll onto the rolling guides. The active side includes two complete 3-phase modules of the AMSR machine. Each phase integrates, as in the case of the passive side, 8 coils mounted onto steel structural poles.

Fig. 6 presents the final appearance of one of the active modules developed.

Fig. 7. Installation of the complete PTO (linear generator, power electronics and control) at the CIEMAT lab for the tests.

The final appearance of the system, including the linear generator, the power electronics used to exchange the electric power, and the control platform to be used to generate the current or velocity commands, which includes a hardware-in-the-loop scheme to emulate the WEC and the control strategy, are included in Fig. 7.

IV. Experimental Characterization and Validation of the Linear PTO

Once the fabrication has been finished, the linear PTO based on an AMSRG has been characterized, carrying out the following tests: electric losses calculation; force vs velocity characterization and friction loses measurement. The following section describes the procedures used respectively for the different tests accomplished.

A. *Measurement of electric losses*

The power losses at the generator have been measured for each current and velocity values in the range of operation. The consequences of the analysis are the following:

1) The losses produced by Joule effect drive the total losses, so the losses have a quadratic relationship with the current and with the force at high values of the current.

2) There is a strong dependence on the current and slight dependence on the velocity except at low velocities and high current values.

3) The losses of the power electronics (both switching and conduction losses) are one order of magnitude less than the Joule effect losses; therefore, they can be neglected.

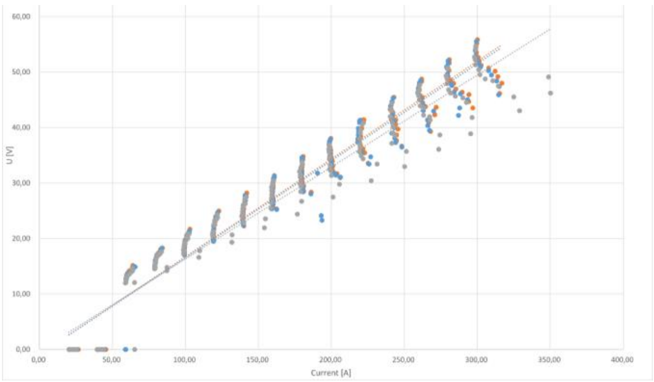

Fig. 8. Measurement of the ohmic resistance of the coils of one AMSRM phase by means of measuring current and voltage. Linear approach of 50V per 300A of current.

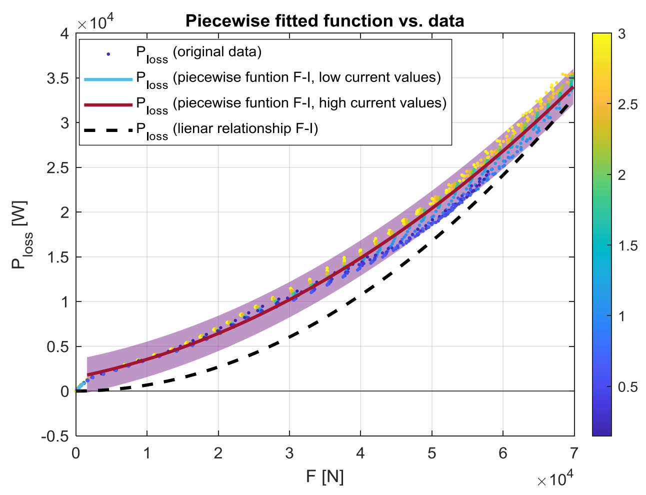

Fig. 9. PTO loss model fit (relationship power losses - force). Original data and loss model results.

The coil resistance value has been measured by means of the power-meter, which gets current and voltage for 14 values of current command and 12 relative positions between passive and active of the AMSRG. The results of whole set are shown in Fig.8 and the total resistance measured (including power cables) are ≈170 mΩ.

Based on the electric losses [8], the losses-force relationship has been implemented as a piecewise function where the influence of the velocity of displacement has been neglected. Looking at the relationship between force and current, and considering that the power losses are driven by the Joule effect losses; it can be derived that exist a quadratic relationship between force and losses at low force values (I_pto~k· 〖F_pto〗 ^2) and a linear behaviour at high force values (I_pto~k·F_pto). Fig. 9 shows the adjustment of these relations to the data.

B. *Force characterization*

This test aims at obtaining the force characteristic at the different positions of the phase-step and for different current values. The equipment required for this test is a load cell fixed to the structure of the linear generator and a blocking structure to modify the relative position between the active and passive part of the generator.

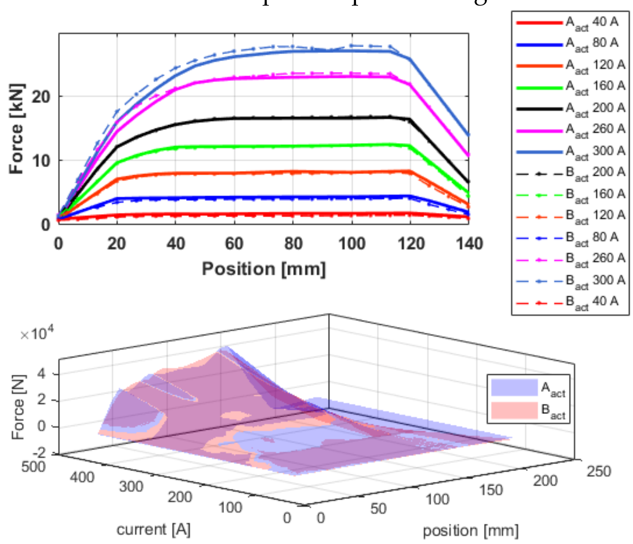

Fig. 10. Results from measuring the force for different current levels at different relative positions between PTO active and passive parts.

Fig. 10 shows the results obtained from the tests. Since the prototype includes two different modules for the active part, named A and B, the figure includes the results for both active parts in dashed and continues lines respectively in the upper figure. The lower part of the figure presents a surface plot of force vs position vs current for both active modules.

C. *Friction losses of the guidance*

The mechanical losses are due to the friction at the guidance system. In a linear machine, due to the non-possibility to maintain the velocity constant, a particular procedure must be defined to calculate the deceleration at different velocities produced by friction. A back and forth drift movement is proposed, reducing it sequentially from a certain maximum velocity during consecutive cycles, as presenting in central Fig. 11. The scheme included in the upper part of Fig 11 presents how this procedure applies force to accelerate the moving part, drifting the system after that, applying then a new force in the opposite sense to brake the system and to accelerate in the opposite direction. Every test acquires velocity data during the drift periods until the velocity reaches half of the initial value. 27 drift tests are accomplished to get enough number of data.

$$m \cdot a = \sum F = F_r$$
$$F_r = K_0 + K_0 \cdot v + K_0 \cdot v^2 = m \cdot \frac{dv}{dt} \quad (1)$$

Considering the decelerations areas compiled and taking into account dynamic equation (1), the friction force is calculated for each point analyzed multiplying the moving mass by the derivative of velocity (deceleration).

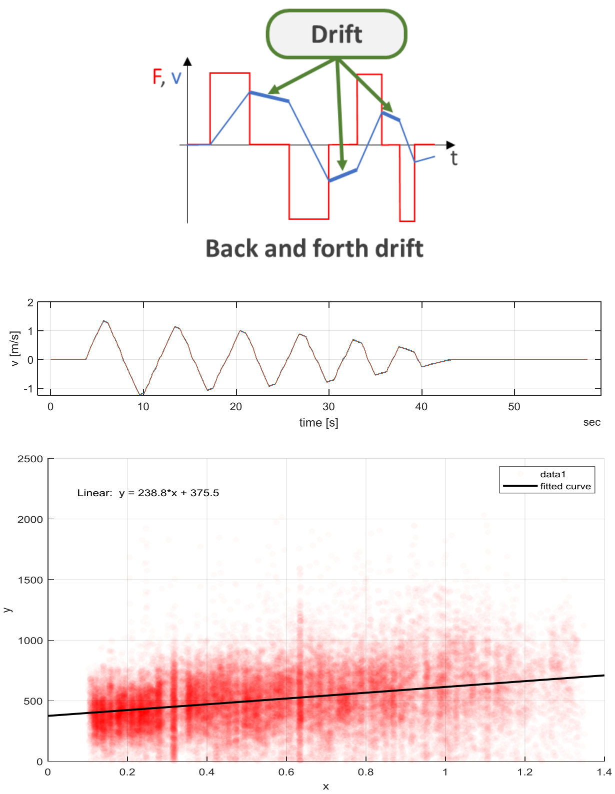

Fig. 11. PTO loss model fit (relationship force-losses). Original data and loss model results.

Lower part of Fig 11 presents the points obtained for the different tests. Vertical axis represents the product mass by deceleration and the horizontal is the velocity. The adjustment by root mean square error provides the result of 3.27kW of friction losses at maximum velocity of 3m/s, which means 15% of the rated power at that velocity.

It is important to notice that the tests have been carried out with the linear generation in horizontal position, where the load over the guidance is maximum. The natural orientation of the linear generator would be vertical, so the friction calculated is just an upper limit and indicative of the maximum value under the worse conditions. The real conditions could be much lower.

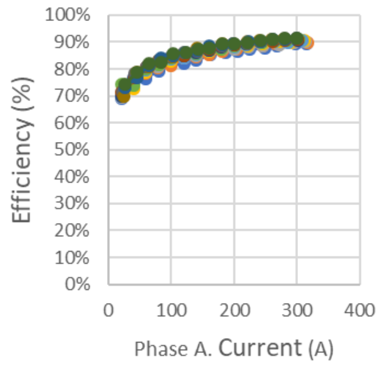

Fig. 12. Efficiency of the linear PTO.

D. *Total efficiency of the PTO*

Considering the electrical and mechanical losses calculated at different current levels, the efficiency of the linear generator is determined and depicted in Fig. 12 as a function of the current. The results presented are based on data obtained in phase A of the generator. The results from other phases are basically the same. The efficiency varies from 70 to 90% depending on the current or force produced by the PTO. Since the force applied oscillates along each cycle from zero to the maximum, an average efficiency must be considered in the range around 77%.

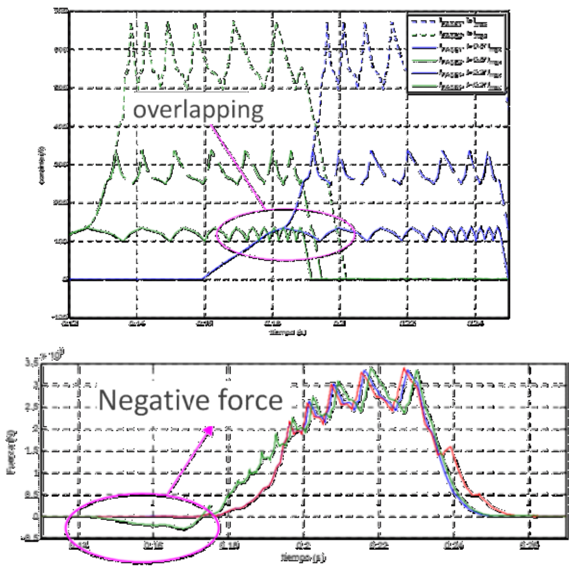

Fig. 13. Overlapping of machine phases and negative force: effects due to the non-appropriate selection of activation angles in AMSRG.

E. *Optimization of the activation angles*

The final adjustments of the linear generator have the objective to optimize the electric power delivery of the linear generator. In a switched reluctance machine the phase activation angles are critical to define the maximum electromagnetic torque and therefore the electric power supplied by the generator.

The phase-activation angles is the point where the current is activated in each phase of the generator, controlled to follow the current reference. The current derivative varies with the velocity and the current reference level, due to the inductance and the back-electromotive force effects. It is mandatory to define the activation and deactivation angles as a function of the current and the velocity in order to avoid two negative effects: the overlapping of generator phases and the negative force values, as presented in Figure 13.

The procedure to calculate the optimized angles is based on brute force, carrying out 100 experimental tests of back-and-forth moving of the linear generator, using 5 current levels, which means 5 oscillation amplitudes in terms of stroke, and different activation-deactivation angles. The time data compiled from the tests are subsequently treated calculating in each acceleration and deceleration the average power. This way, for each current and velocity is determined the activation-deactivation angles that lead to the maximum generated power.

V. Conclusions

The present work compiles a detailed procedure used to define, designing, manufacturing and testing and characterizing a novel linear generator used for wave energy conversion in heaving point absorbers that increase the performance and viability of linear PTOs over other technological solutions such as permanent magnet linear generators. The topology of an azimuthal multi-stator switched reluctance machine has been selected for this application since it is simpler, more robust, more cost effective, it is composed by flat coils that can be manufactured independently (reducing manufacturing costs), and can achieve the same controllability as any alternative machine with adequate power converters.

The azimuthal flux topology in this type of machine allows the perfect adaptation of the passive part to the spar of a point absorber. It provides the advantage of increasing the power density (in fact, a key performance indicator defined as *Stator Force Density –SFD-* provides an increase by a factor of 2 respect to a generator with similar characteristics in terms of current, voltage and amount of coils but no azimuthal flux). It also presents the added value to be utilised as structural reinforcement of the WEC, improving the dynamic stability during its operation.

The long passive part is made on replicable modules, being possible to increase the number of them depending on the stroke of the WEC designed.

The passive part selected is also composed by modules of 35kN (for the current design).

The characterization and fine adjustment of the linear generator, carried out by means of dry tests, are essential to define parameters of the system, used to design the control strategy as well as to analyse the potential energy to be obtained in a certain sea location using a control strategy.

Although an accurate methodology has been used to measure the mechanical friction losses, the horizontal position of the linear generator during the tests leads to an excessively pessimistic estimation of these losses.

The efficiency of the PTO varies from 70 to 90%, depending on the current level managed by the electric drive. The average efficiency will depend on the current profile used but considering a linear variation of the current, the average efficiency would be 77%.

The topology of modular active parts is versatile and allows to reconfigure the electrical connections to either enable both modules to work in generator mode or run in a *back-to-back* configuration for dry testing the PTO without need of an external actuator. Moreover, the rated power of the machine can be easily increased by just adding more modules.

VI. Acknowledgements

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