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Methodologies for testing PTOs under real conditions in the laboratory using actuators and hardware-in-the-loop scheme

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Abstract—[1]**This paper presents an analysis and further discussion of how some laboratory tests of power take-off (PTO) devices can improve the reliability of a wave energy conversion project, reducing the commissioning cost and reducing the failure risks in marine environment. Different alternatives of actuators are studied, presenting the pros and cons of each, and suggesting in what cases is more convenient to use one or another. Two big groups of actuators are considered: hydraulic and electric actuators. Among the later, a new classification is given into: direct-drives, rack&pinion, ballscrew and belt&pulley. Moreover, an additional option of back-to-back electric machines is possible when a multipole electric generator is used as PTO. Finally, a discussion of the convenience to allocate the system in vertical or horizontal orientation is also developed.**

A second part of the paper, and once decided the actuator type to be used during the experimental laboratory tests, presents a scheme of hardware-in-the-loop (HIL) scheme in order to validate the PTO electrical and mechanical performance, as well as the viability of the WEC control before its integration in the WEC. This testing scheme permits to evaluate the control strategy under different scenarios, obtaining the most convenient sites to implement the WEC, based on real PTO performance.

Keywords—**Wave energy conversion, power take-off (PTO), actuators, laboratory tests.**

I. Introduction: Improving reliability of wave energy converters

As stated in the SET-Plan Ocean Energy, ocean energy must reduce costs in order to be more competitive. Despite the current improvement in the technological development of different solutions, the harsh environment of the oceans is the main cause of uncertainties in the reliability of wave energy conversion systems, presenting the main barrier for the development of its massive energy potential [1]. The concept of reliability implies many issues, all of them related to minimize both the levelized cost of energy (LCOE) and the total expected life-cycle costs (operation, maintenance and failure costs). Since the wave energy conversion integrates many disciplines, the problem could be analysed from different perspectives. This paper focusses in the reliability analysis of the device in charge of the energy conversion from mechanical into electrical, what is usually named power take-off (PTO). The PTO comprises the electric generator, power electronic converters, control devices and sometimes additional mechanical devices for the conditioning of the mechanical power provided by the waves and got by the WEC.

Since the PTO system operation can be tested in a dry laboratory emulating the WEC operation conditions, preliminary commissioning of this important part of a WEC could be debugged and validated. An important reduction on the commissioning time could be achieved by this stage, saving important budget and reducing the potential failure risks involving the PTO equipment.

Although several analysis have been done previously in order to select the appropriate equipment, it would be convenient to test in laboratory the power response of the PTO system in order to solve potential difficulties and problems before the stage of sea commissioning.

Moreover, a previous evaluation of the performance of the PTO in terms of energy capture and control strategies could be useful to decide the most convenient location for the installation of the WEC.

Two different issues are considered in this paper related to the definition of the laboratory tests of a power take-off (PTO): a discussion about the selection of different solutions of actuator to emulate the wave performance, described in section II and the description of the hardware-in-the loop (HIL) scheme provided to operate the PTO under real electrical conditions, validating both the power response of the system as well as the control strategies used in the WEC from the point of view of the energy extraction, studied in section III.

Despite most of the considerations being applicable to any type of WEC, this work considers the particular case

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of point absorbers type and the study case of a PTO to be tested with the specifications given in table I.

The present work is part of the research accomplished during the project SEA TITAN (ID: 764014), corresponding to the H2020-LCE-2017-RES-RIA-TwoStage call, and being carried out between 2018 and 2020.

TABLE I

SPECIFICATIONS OF THE STUDY CASE FOR PTO TESTS

WEC Type	Point absorber
PTO type	Direct drive PTO
Stroke	6 m (± 3 m)
Maximum velocity	3 m/s
Maximum force	40 kN[a]
Moving mass	2500 Kg
Maximum acceleration	3 m/s²
Footprint available for tests	7 x 13 m
Maximum power supply	250 kVA

II. MECHANICAL ACTUATOR: EMULATING THE WAVES

The first element to be defined is the actuator. It is a device with the capability to provide an instantaneous mechanical force, equivalent to the one provided by the WEC in a certain sea location under certain sea conditions, all of them to be reproduced in the laboratory tests [2].

Different options can be selected as mechanical actuator, depending on the requirements of the PTO to be tested. Two big groups of solutions can be considered: hydraulic actuators and electric actuators. Among the electric actuators, a new classification is given: direct-drives, rack& pinion, ballscrew and belt & pulley. Moreover, an additional option of back-to-back electric machines is possible when a multipole electric generator is used as PTO. Finally, a discussion of the convenience to allocate the system in vertical or horizontal orientation is also developed.

The different options are discussed along this section.

A. Hydraulic Actuator

It is based on a pump driven by a motor that creates a flow of fluid at a certain pressure, controlled by means of valves [3]. The actuator converts the energy of a fluid into mechanical power. The most basic concept comprises a piston inside a cylindrical housing called barrel. On one end of the piston there is a rod. At the opposite end, there is a port for the entrance and exit of oil.

For this particular application, a double-acting cylinder with a piston rod on one side is required, since the force needs to be applied in both directions, as presented in figure 1. To extend the cylinder, the pump flow is sent to the blank-end port as in Fig. 1.a. The fluid from the rod-end port returns to the reservoir. To retract the cylinder, the pump flow is sent to the rod-end port and the fluid from the blank-end port returns to the tank as in Fig.1.b.

Some wave energy systems have been tested based on this solution [4].

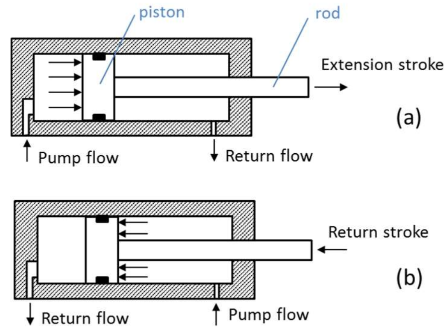

Fig. 1. Operation of a double-acting cylinder during extension (a) and return (b) stroke.

The maximum force of double-acting cylinders is given by equation (1).

$$F_{max} = p \cdot A_{rod} = p \cdot \frac{\pi d^2}{4} \quad (1)$$

where p is the pressure and A_{rod} is the area of cylinder rod, being d the diameter of the rod.

The rod velocity is given by expression (2):

$$v_{rod} = \frac{Q}{A_{rod}} \quad (2)$$

where Q is the flow rate of fluid entering the cylinder

Fluid flow is not the same during extension and retraction strokes due to the different areas at both sides of the piston. However, the power required in both operations is the same, according to the expression (3).

$$P = F_{rod} \cdot v_{rod} = p \cdot Q \quad (3)$$

Hydraulic actuators are appropriate for low velocity (lower than 0.2 m/s), low frequency (not continuous operation) and high forces (1000kN) with short stroke (0.5m). Increasing the velocity requirements implies that a higher fluid flow (Q) is required, according to (2), which increases very much the cost. On the other hand, increasing the force leads to use higher pressure. These effects requires an accumulation system to hold the pressurized volume of oil. The problem is even worse when facing long stroke applications; uncharged accumulators may starve the system of oil. In the end, deploying additional capacity in hydraulic accumulator systems allows them to achieve high speeds at high forces. The main disadvantage of this option is that it requires a high electric power supply due to the low efficiency (in the range of 40-55%) of the system. Moreover, these inefficiencies cause overheating, accelerating degradation of the oil and damaging seal components.

In order to improve the control performance, the force capability needs to be oversized.

Final implementation to be used for linear PTO tests is presented in Fig. 2, concluding that the required room is quite demanding in length.

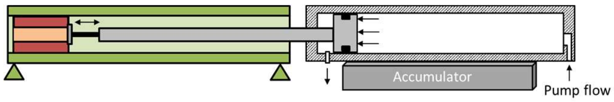

Fig. 2. Hydraulic actuator implementation for a linear PTO test.

B. Electric Actuator

Some options [5] can be stated, all of them driven by an electric motor and power electronic converter, with particular characteristics described as following:

1. Direct drive actuator: electric linear motor

In recent years, electric rod actuators have become more flexible, precise and reliable with increasingly larger force capacities.

That provides the maximum efficiency on the system, in the range of 75-80%. An additional factor in the electric cost is that electric actuators only demand electric consumption when it is required while hydraulics require permanently pressurized system, resulting in inefficient use of power.

The mechanical performance of an electric direct drive is completely dependent of the motor characteristics, being capable of providing at the same time high velocities and high forces. On the other hand, it is not usually a conventional equipment and most of the times it needs to design the machine specifically for this application.

Additional length is required for the system to accomplish the tests, equal to (4), as presented in Fig. 3.

$$L = 2 \cdot L_p - L_a + L_{dd} \quad (4)$$

where L_p is the PTO passive part length
L_a is the PTO active part length
L_{dd} is active part length of the electric direct drive actuator.

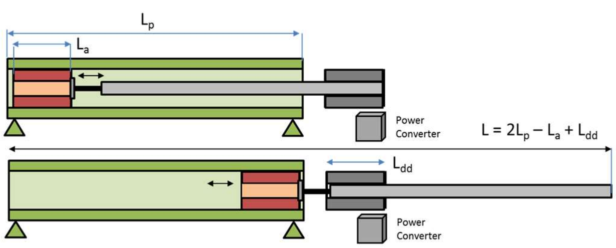

Fig. 3. Length requirements for the use of a direct drive electric actuator in PTO testing.

Commercial direct drive actuators have been found to accomplish the specifications of the study case. Requirements of force or velocity can be provided separately but not at the same time [6].

2. Rack & pinion actuator

The rack and pinion solution started being used in rail transport in the 1800s. Cogged railways were put in use in the USA and Europe steepest landscapes. The first cog railway in the world, still in operation, is the Mount Washington Railway in New Hampshire (USA), first operated in 1868.

Fig. 4. Rack and pinion interface for electric actuator (Source: Alpha-Wittenstein Inc.).

Today, the modern materials, treatments and optimized manufacturing make the rack-and-pinion solutions perform as well as electromechanical and other linear components. Fig. 4 presents a commercial solution from Alpha-Wittenstein supplier.

According to the product catalogues [7], it would be possible to fit the requirements with two units of pinion over one rack achieving a velocity up to 4 m/s.

Final implementation of this solution to test the study case of a linear PTO is presented in Fig. 5. Same considerations as the direct drive actuator related to the length required for the tests can be formulated, presenting an important limitation, as described in the figure.

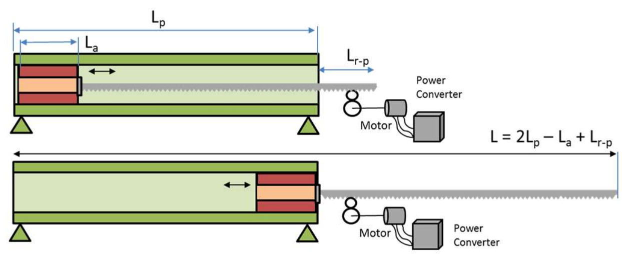

Fig. 5. Electric actuator implementation for a linear PTO test based on the interface of rack & pinion mechanical interface.

3. Ballscrew spindle actuator

The ballscrew used as mechanical interface for an electric actuator has many advantages compared to traditional hydraulic or pneumatic systems, i.e. fast response, no leakage, high accuracy, smooth movement, long life, high stiffness, low drive torque, energy savings and good repeatability.

The system is based on the concept that rolling motion of balls substitutes the sliding friction of conventional screws [8]. That implies that the efficiency is as high as 90% because of the rolling contact between the screw and the nut. Fig. 6 present an example of commercial solution.

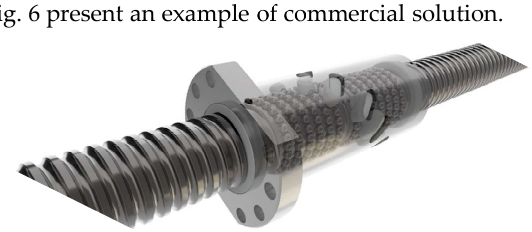

Fig. 6. Ballscrew solution for linear actuators (Source: Shuton).

Normally, the requested solution need to be specifically developed for the application but forces and velocities in the range of the study case are completely affordable. A

200 mm thread pitch screw can provide a linear movement of 3 m/s when spinning at 900 rpm.

As important advantage of this solution is that the available length for the tests is nearly the length of the PTO to be tested, as presented in Fig. 7.

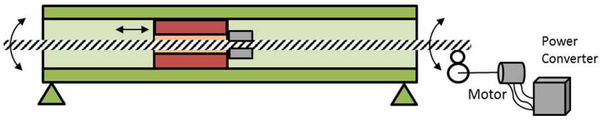

Fig. 7. Electric actuator implementation for a linear PTO test based on the interface of ballscrew mechanical interface.

However, an important drawback of this solution is that the PTO to be tested need to be crossed by the screw from one side to the other.

This technology is being tested as PTO for wave energy converters [9][10].

4. Belt and pulley actuator

This option consist on two pulleys at both sides of the PTO to be tested and a belt connected to the PTO moving part, as presented in Fig. 8. Generally speaking, this solution is more simple and does not also require extra lengths for the testing facility. However, there are some considerations to be taken into account. The longer the belt the higher the required tension force and the further the tensioning mechanism can move [11].

Additionally, as more tension force is induced on the belt, the external force it can transmit decreases.

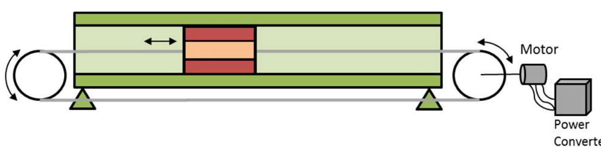

Fig. 8. Electric actuator implementation for a linear PTO test based on the interface of belt & pulley mechanical interface.

C. *Back-to-back Actuator*

There is a particular solution of actuator, appropriate and especially convenient in the case of linear direct drive PTOs, which consists of the following concept [12]. The electric generator is divided into 2 sub-machines, giving the possibility to drive both of them in a different way. That permits to impose an oscillatory movement in one of the machines, emulating the wave effect (named actuator) while the other machine is behaving as a generator (named generator), operating with an optimal control strategy to maximize the power. Fig. 9 presents this schema.

Two power electronic converters are used to drive each part. They will share a common DC link and connected to the grid through a grid-tie converter, which supplies only the system losses, recirculating the power during the test through the DC-link. Both converters have an internal control loop in charge of deciding about the switching pulses to control the current around the reference level. An external control loop is in charge of providing the force reference to the system depending on different parameters and operation variables.

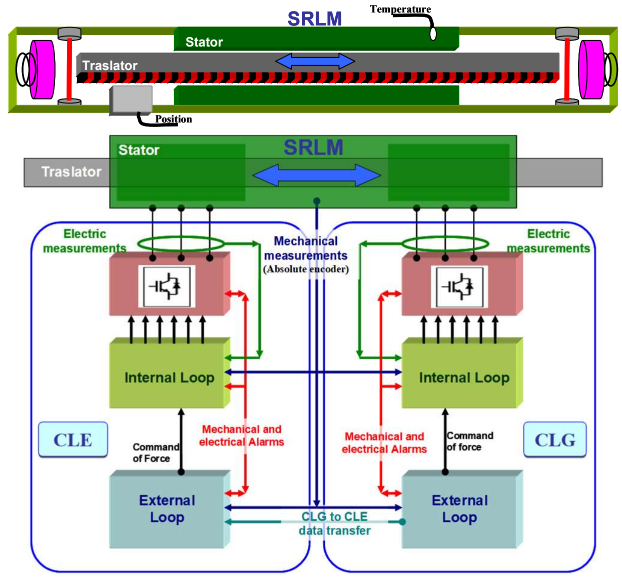

Fig. 9. Electric schema for testing the machine using half of the machine as actuator and the other as generator.

This option does not provide the possibility to test the linear PTO with full mechanical force, however it is fully electrically tested.

This implementation requires the minimum length for the tests, just the length of the linear generator. However, once the PTO tests are finished the laboratory remains no testing equipment for further projects.

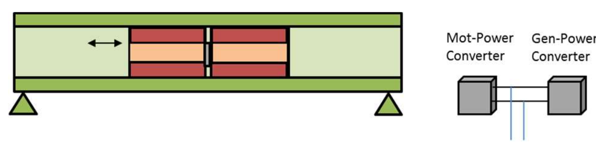

Fig. 10. Back-to-back scheme for a linear PTO test.

III. DISCUSSION ABOUT VERTICAL OR HORIZONTAL TESTS

Finally, and beyond the decision of the technology selected for the actuator, although not independent of that, a discussion of the convenience to allocate the system in vertical or horizontal orientation is now addressed, important in the case of a linear PTO. A vertical solution has the advantages of being closer to the final allocation of the PTO elements, since it reproduces the behaviour of the PTO moving parts in the same orientation than in the final WEC. The only difference, compared with the final implementation in the sea location inside the WEC, is the presence of the gravity, that in the sea location is compensated by the Archimedes force. In order to compensate gravity, a pulley and additional weight are required. The problem is that the required forces to achieve the dynamics of the system need to be calculated with double the mass (PTO moving mass plus additional weight to compensate gravity). Additionally, the mechanical structure required for the system is more complex and expensive, especially if the actuator option selected requires. This option would be only reliable for options B.3, B.4 and C.

The horizontal allocation of components simplifies considerably the experimental facility. On the other hand the mechanical behaviour of the components is much more demanding that the current operation conditions inside the WEC. Nevertheless, it is useful to test the system in extreme mechanical conditions. This option will be mostly preferred.

IV. HARDWARE-IN-THE-LOOP SCHEME FOR THE PTO TESTS

Once the type of actuator has been defined (according to the needs of the system to be tested), the next step is to provide a control (hardware and software) scheme for the PTO tests, described in the following section.

The scenarios to be tested are based on real sea locations, characterized by their sea states. After providing time profiles of position and velocities, obtained from previous simulations in a Wave to Wire (W2W) model with a certain wave energy converter and controlled by a certain control strategy, the system behaves mechanically as the real one in a hardware-in-the-loop (HIL) scheme [13]. This W2W model is analysed by means of a simulation environment in real time in the HIL platform. Fig. 11 presents the control scheme used for the PTO validation.

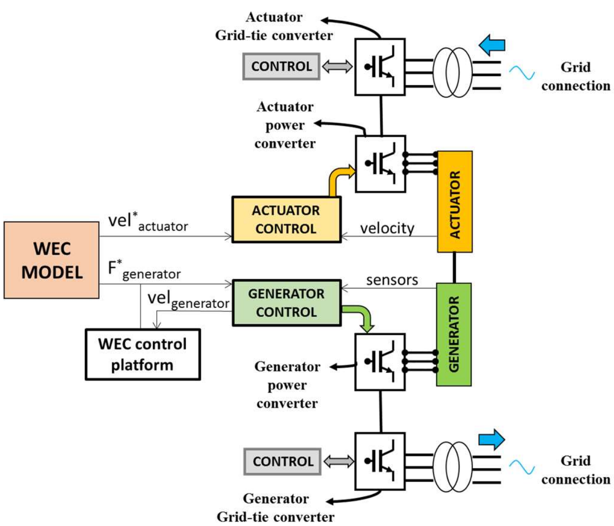

Fig. 11. HIL testing scheme used for PTO validation.

The testing facility and the HIL control scheme, described in detail below, is the experimental set up used as part of the European H2020 project SEA TITAN [14], started in 2018, with the objective of developing and testing in laboratory a new concept of PTO for wave energy converters.

The system comprises four different parts:

- Grid connection
- Linear PTO + power converter + control
- Actuator + power converter + control
- HIL Platform

The grid connection allows for injecting the generated energy to the network, as well as supplying power to feed the phases of the linear generator. It consists of the grid, a transformer and a grid-tie converter with its control. The control variable of this converter is the DC link voltage, which needs to be fixed at a constant value in order to have a proper behavior of the generator power converter.

The linear PTO, generates energy based on the combination of the actuator motion and a proper control from the generator control platform. The command control variable for the generator is the force to be developed by the PTO. In relation to this control variable, the WEC control platform is in charge of providing the force command, based on the measure of generator velocity and according to the control strategies already programmed. Moreover, this force command is used by the linear generator control to ensure that the generator force command is equal to the mechanical force developed by the linear PTO. In order to guarantee the usefulness of the HIL scheme, the generator control must be calibrated properly.

The experimental set comprised by the actuator and its control is responsible for sinusoidally pushing the linear PTO back and forth. The actuator control scheme is illustrated in Fig. 12. Based on the velocity error between the velocity reference calculated by the HIL Platform and the measured velocity, the actuator control generates a force reference. Then, this force is translated into currents so a PMW control can be performed.

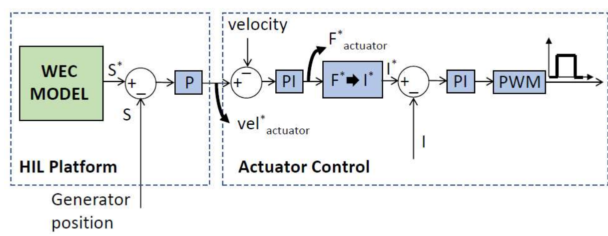

Fig. 12. Interaction between the HIL control and the actuator control.

In order to implement the HIL, a system that contains the software representation of the WEC is required, allowing for a plant control of both the actuator and the generator. A CompactRIO system from National Instrument, model cRIO-9049 [15], is selected as HIL Platform, as presented in Fig. 13. This device is a reconfigurable embedded system, containing a processor running on a real-time operating system (RTOS) and a reconfigurable field-programmable gate array (FPGA). The real-time mechanical W2W WEC model, which has a low integration step (0.05-0.001 s), is implemented in the HIL Platform through a state-space representation of 15th order. Besides, the incident wave profile, i.e., wave force distribution over time, is preloaded as a WEC model input, together with the rest of the site parameters. Therefore, based on the wave profile, site data, position and PTO force, the model outputs a position reference for the actuator. As shown in Fig. 12, the position error gives a velocity reference when passed through a proportional control. This new velocity reference is the control variable for the actuator.

Fig. 13. CompactRIO cRIO-9049 [12].

Communications between the HIL Platform and both the actuator control and the WEC control platform are performed via CAN. The HIL Platform sends the velocity reference to the actuator, and receives the position measurement from it, while WEC control platform sends the PTO force reference as an input for the WEC model. Additionally, instrumentation systems are used to obtain current waveforms and power measurements in different parts of the system. Thus, the performance of the linear PTO and the optimization of its control parameters can be obtained. In addition, the efficiency map of the system can be evaluated, considering different operation points and sea-states. A precision power scope from Yokogawa, model PX8000 [16], is selected for this task, which is connected to the CompactRIO via Ethernet (TCP-IP protocol). Besides, a commercial and calibrated electric energy meter is installed at the output of the AMSRM power electronic converter, in order to obtain a verified measurement of the electric energy generated by the AMSRM in each emulated sea-state.

This testing scheme permits to evaluate the control strategy under different scenarios, obtaining the most convenient sites to implement the WEC, based on real PTO performance.

V. Discussion and Conclusions

The discussion on the most appropriate solution for a certain application is based on factors such as: motion control provided by the HIL scheme, system components, space availability, force and velocity capabilities, temperature, number of life cycles, maintenance, cost, efficiency, environmental concerns and adaptability to different PTO types. A market survey and analysis of commercial solutions has been carried out, classifying the available options into three blocks, and which has led to the following conclusions:

Hydraulic solution

Although the pressure specification is not really a serious concern for hydraulic systems, the high velocity requirement of the present application (3m/s) is so, and that is translated into a very demanding fluid flow. That increases the cost significantly. Furthermore, in the case of SEA TITAN, a power supply installation rated at more than 300kVA would be needed, exceeding the available power in the lab, and also requiring a permanent power consumption to maintain the fluid pressure. Additionally, the space needed for the equipment is bigger than the available space at the lab. As a consequence, this option has been definitely rejected.

Electric solutions with mechanical interface (belt & pulley, rack & pinion and ballscrew)

These systems comprise a mechanical interface plus an electric drive, which is more efficient than the hydraulic option. In terms of cost, a high percentage is associated to the electric drive (close to 80%), with the mechanical interface representing a lower share of the cost.

The mechanical adaptation part shows different characteristics depending on the option considered. In the belt & pulley solution, it is based on two pulleys connected to the moving part of the linear generator through high resistance belts. The technology is similar to the one used in the lift industry, which is well known, although not very usual at this level of velocity (3m/s). That implies security levels need to be increased. The required space fits the available room at the lab. It is one of the most suitable options.

The ballscrew solution also fits the available room at the lab but presents a more expensive mechanical interface, although maintaining mostly the same cost for the electric drive. The main disadvantage of this option is that it is only suitable for PTOs with a moving part able to be crossed by a shaft.

Finally, the rack & pinion alternative, which can integrate an electric drive very similar to the two previous options, presents the least expensive mechanical part. On the other hand, the excessive required space makes this solution unreliable.

Direct drive back to back actuator

Among the electric actuators, direct drives have the best efficiency but are usually more expensive than the rest of the options. However, this option offers a huge potential of cost reduction since it only implies an extension of the already manufactured coils and magnetic materials used for the linear generator, thus saving the cost of new engineering and/or fabrication tools. On the other hand, it must be considered that an additional power converter would be required to drive the second part of the linear machine, which would now increase the cost. Additionally, as a difference to the rest of systems, this is a bespoke alternative that could not be used for testing other types of PTOs, since it is specifically developed for this one.

Table II, presented below, highlights a qualitative summary of the main characteristics of the different actuator technologies taken into consideration. Once the pros and cons of each option are identified, the final decision to be taken in the project will be based on the particular technical discussions and the matching between quotations from potential suppliers and the project budget.

TABLE II

COMPARISON BETWEEN THE DIFFERENT ACTUATOR ALTERNATIVES

	Hydraulic actuator	Electric actuator + mechanic interface			Direct drive back 2 back
		Belt&pulley	Rack&pinion	Ballscrew	
Required space	High	Low	High	Low	Low
Required power	High	Low	Low	Low	Low
Efficiency	Low	High	High	High	Very High
Operation cycles	High	Medium	High	Low	High
Maintenance	High	Medium	Low	Medium	Low
Vertical orientation possible	NO	YES	NO	YES	YES
Adaptability to other PTO types	High	High	High	Medium	Low
Cost	High	Low-Med	Low-Med	Medium	Medium

In the particular case of the SEA TITAN project, the decision among the three potentially viable options (belt&pulley, ballscrew and back to back) has not been taken yet by the time of writing this paper, but will be presented during the conference. After receiving several initial quotations, it has been concluded that the cost of a complete facility for testing linear generators would be in the order of 200k€.

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