Methodology and results of the sea trials for a second generation tidal converter

A. López, L.R. Núñez & J.A. Somolinos / E. Novoa & A. Carneros Lozano

ABSTRACT: Based on the main characteristics of second generation tidal power converters (TEC), a review of the present state of the art for this technology is presented herein. The main steps involved in the process of a TEC development (starting from the initial idea up to production) are described. Also, the applications of these devices are described through some significant tests, required according to the readiness level procedures of the technology. Later, the GESMEY second generation TEC and the PROCODAC project are described; whose main objective has been the design, construction and sea trials of a 10 kW prototype. Finally, the objective and design for these tests are explained and the main results from the sea trials of power and operational procedures are shown.

1 INTRODUCTION

1.1 Tidal & currents energy

The sea, with an extension of more than the 70% of the Earth's surface, is a huge collector, accumulator and transformer of energy; nonetheless and only until a few years ago, its energy was only extracted by means of oil and gas wells, mainly due to difficulties in the installation and operation of Marine Renewable Energy (MRE) plants (Hardisty 2009). Together with wind and waves, marine currents are one of the most promising sources of MRE. These mainly originate from: tides, winds, density differences in the water and Coriolis forces.

Although the most important source is tidal energy, only in those areas where the average velocity of the streams reaches a minimum value, is it possible to obtain enough kinetic energy to be considered as a useful source of renewable energy. By extension, the devices harnessing the sea current energy are known, in Europe, as Tidal Energy Converters (TECs).

In America, the common name is hydrokinetic converters. The quantification of the energy that could be extracted from sea, ocean and tidal currents is estimated at more than 800 TWh/year (Brito & Huckerby 2013). From this huge potential and as shown in Figure 1, most of it is concentrated in locations with depths of over 40 m.

1.2 TEC types and evolution

These devices are usually classified based on four significant parameters (Myers et al 2010):

Figure 1. Potential energy distribution of marine currents.

- The fitting system (moored, fitted with piles, gravitational...).
- The movement type of the energy conversion element (rotary, alternative or linear).
- The orientation of the conversion element related to the stream (parallel, vertical or horizontal axes).
- The existence (or not) of flow acceleration elements.

The development of TECs, like any other offshore devices, is classified in different steps or generations according to sea depth and stream speed (King & Tryfonas 2009). Currently, the industry effort is focused on the so-called first generation devices (fixed to the bottom of the sea, and suitable for sites

with depths below 40 m). The most common types of first generation TECs are (see Figure 2):

- Devices with open rotors and axes parallel to the water stream.
- Turbine devices with acceleration conduits.
- Devices with blades rotating around an axis perpendicular to the current.
- Devices with oscillating or linear speed blades.

Also, as can be seen in Figure 3, there are an increasing number of second-generation prototypes which can be moored to the sea bottom and are suitable for depths of over 40 m. To date, there is only one proposal (Roos 2011) for a third generation TEC which can harness the energy of low velocity currents.

Figure 2. First generation TECs.

Figure 3. Proposals for second and third generation TECs.

2 TEC DEVELOPING PROCESS

2.1 TRL & TPL levels

The Technology Readiness Level (TRL) was introduced by NASA in order to model the technology development process of complex new systems.

Today, the TRL is a standard model in research, development and innovation programs such as Horizon 2020. As shown in Figure 4 (Fitzgerald & Bolund 2012), the TRL model can be a guide for the development process of the ocean’s renewable energy harnessing devices that need an extended program of simulations, model testing and prototypes of different scales.

For a deeper analysis and in order to minimize the technological and economical risks of the development process, the TRL model can be completed with the Technology Performance Levels model (TPL) which measures the economic aspects of the technology being developed (Weber 2012).

2.2 TRL for second-generation TECs

In the practical development of TEC designs, the TRL model is usually simplified down to the five stages presented in Table 1. In this process, the main objective is to monitor the power efficiency of the device.

Second-generation TECs include mooring systems with specific and complex installation and maintenance procedures. With this, the development process needs numerical simulations that must be validated through physical model tests. Another requirement is to check the feasibility of the oceanic operation procedures and the sea keeping abilities of the device in operational, transportation and maintenance states.

Due to the need of actuation elements for motion control (such as flaps or ballast tanks), the tests checking the positioning system must be made with models over one meter in size. For most

Figure 4. TRL levels for the development of MRE devices.

Table 1. Main TEC development stages.

Stage	Development level	Main tasks
1	Conceptual Design	Explain concepts for the subsystems. List the major components. Identify R&D needs for next stages
2	Construction Design	Detailed structure and machinery design. Conduct physical tests at an intermediate scale and/or carry out CFD or other numerical simulation
3	Operation Design	Conduct physical tests at a large scale, possibly with a degree of integration between some of the subsystems
4	Technical Demonstration Prototype	Full-scale prototype testing at sea
5	Commercial Demonstration Prototype	Full-scale commercial demonstrator testing

TEC devices, this is equivalent to a 1/10 scale and, usually, the stage three tests that check the operational procedures should be made in a controlled sea environment.

3 FIRST PROTOTYPE TESTS

3.1 Objectives

The main objective of the procedure model described in section 2 is to surround the creative process, necessary when developing new complex systems, with an engineering methodology which reduces costs and risks. In order to achieve this, the product design must include procedures for the device fabrication, installation, maintenance and decommissioning along with a test program and specific procedures for the different TRL steps.

The main objective of stage 3 in the TECs development procedure is to check the operational design which must include the verification, if feasible, of all the main subsystems present in an integrated prototype. It is equivalent to a complete technological demonstration of the steps included in TRL-5 and TRL-6.

For an oceanic device, these tests must be made, at least partially, in an open, non-controlled environment. With this, the development process must progress from a scaled model, tested in experimentation tanks, to a scaled prototype tested at sea in similar conditions. Thus, designers are forced to consider various logistical and operational aspects whilst minimizing extra costs and risks.

For a TEC with a nominal power of around 1MW, the scaled prototype must have a nominal power between 5 and 10 kW and a rotor diameter between 1–2 m. As showed in Figure 5, this small size limits the nacelle diameter and the number of power and auxiliary systems that can be installed in the prototype.

Therefore, it is usually not feasible to integrate all the TEC subsystems (rotor, power train, electronic converters, power exportation, positioning system, structure, mooring, ancillary systems and control) in a prototype of this size and only the most important must be selected.

3.2 Power and manoeuvres testing procedures

With the main subsystem obviously being the hydro-electro-mechanical power train, it is unnecessary to exactly reproduce in this stage the other parts of the power system, such as power converters and power control.

For a second-generation TEC, it is also very important to test the mooring and positioning systems, including its control. For this, a complete instrumentation is required in order to validate the models and simulations of the device.

Generally, due to cost, privacy and logistical constraints, stage 3 tests are not carried out in oceanic test sites like EMEC (Sankaran 2013), that are designed for device prototypes of over 100 kW.

As showed in Figures 6 & 7, the developing teams usually search for an estuary or a river

Figure 5. Internal equipment 10 kW PROCODAC prototype.

Figure 6. Triton prototype positioning test preparation.

Figure 7. Schottel solution for power tests.

mouth with a sea-like environment located close to the manufacturing facilities. A calm water environment is sought due to the fact that the scale effect makes even the smallest of waves greatly disturb the tests (Starzmann 2013).

If a natural water current of at least 2 m/s is not present on the test site, the power performance tests should be carried out through pushing or towing of the device while connecting the electrical power exit to a passive load. The most important aspect of these tests is to check the efficiency, torque, forces and other hydrodynamic parameters of the rotor.

For mooring and manoeuvring tests, a specific protocol, emulating as closely as possible the procedures designed for the full size TEC installation and maintenance operations, should be designed.

4 THE GESMEY TEC

4.1 Objectives

The goal of the GESMEY TEC (Generador Eléctrico Submarino con Estructura en Y or Submarine Electrical Generator with Y Structure), that started with an idea of Prof. López and which has been patented by the UPM (López 2011a), is to develop a second-generation device with a low-cost life cycle.

Initially designed for the Strait of Gibraltar and other World locations with water depths of over 40 m, the objectives of the GESMEY design can be summarize as:

- Simplified installation
- Minimum environmental impact
- No surface elements in operation
- Robust and simple construction
- Scalable (depth, stream speed, power)
- Extended use of COTS technologies (Commercial Off The Shelf).

4.2 GESMEY conceptual design

The first stage of GESMEY was developed by a joint multidisciplinary research team comprised of professors from the E.T.S.I. Navales of the UPM and engineers from the Fundación C.T. SOERMAR. As a result of a study of alternatives, the design shown in Figure 8 was chosen. It can be seen that the GESMEY TEC is comprised of the following elements:

- Rotor: With fixed pitch blades to improve reliability
- Central nacelle: Power Take Off components (PTO) and auxiliary systems
- Columns: Main structural components and auxiliary ballast tanks
- End torpedoes: Main ballast tanks. They provide stability during operation (asymmetric loads) and afloat (like a semi-submersible platform).

An important portion of the inner volume of the columns and torpedoes is used as water ballast tanks. Changes in their ballast volume allows for the control of the floatability, position and orientation of the device, as can be seen in Figure 9 (Núñez 2011a).

4.3 Adaptation for tidal currents

The first GESMEY design was optimized for uni-directional currents, but this is usually not the case in sites with tidal currents that follow an elliptical path. In order to adapt to these conditions, the GESMEY mooring system was redesigned and an underwater rotating buoy (BOSCEM patent) was included with the mooring layout, shown in Figure 10. For a 1MW device that operates with

Figure 8. GESMEY basic design.

Figure 9. GESMEY emersion manoeuvre simulation.

Figure 10. GESMEY & BOSCEM operation simulation.

water speeds of around 2.5 m/s (model GSY-M1M), their main characteristics are:

- Rotor diameter: 23 m
- Torpedoes: 2 · 11 m
- Nacelle: 4 · 11 m
- Columns length: 12 m
- GESMEY deadweight: 120 t
- BOSCEM dimensions: 10 · 4 · 6 m
- BOSCEM deadweight: 50 t

5 THE PROCODAC PROJECT

5.1 PROCODAC aims

During the first stage, the GESMEY conceptual design included some model tests in a hydrodynamic towing tank (see Figure 11) and an extensive simulation program that concluded with very promising results (Núñez 2011b).

Thanks to these results, grants could be secured for the 2nd and 3rd development stages which included the structural design (beyond the scope of this work by its industrial and confidential nature)

Figure 11. GESMEY scale model.

along with the design and realization of the first operational sea trials.

All this was made within the PROCODAC R&D project with the participation of Balenciaga Shipyards, the F.C.T. SOERMAR and the UPM research group GITERM. The main aim of the project was the design, construction, systems integration and sea trials of a 1/10 scale prototype. The PROCODAC prototype development has had diverse technical and management objectives such as:

- Checking the rotor design, the feasibility of the PTO compact concept and the electrical power exit.
- Developing a methodology for the operational procedures design and checking the more significant manoeuvres.
- Developing a first level instrumentation and control system.
- Incorporating an industrial partner to the project.
- Validation the adaptation of naval construction procedures in the marine renewable energy field.

5.2 Prototypes characteristics

In order to make an adequately sized prototype, it was necessary to limit the electric power to 10 kW and locate the main parts of the auxiliary systems outside of the nacelle. Also, due to logistical constraints, the tests were carried out in the Bay of Biscay close to the shipyard. In this chosen area, no locations with significant water currents could be found, forcing the power tests to be undertaken with a towing procedure, such as the one depicted in Figure 6. With this, a design with a central nacelle was chosen; the power train, a complete measurement system (see Figure 5) and a ballast control system with mem-

brane tanks were located in the torpedoes. The prototype, called GSY-ME10, was made in stainless steel (see Figure 12). Its main characteristics are (Núñez 2013):

- Nominal power (at 3 m/s): 10 kW
- Rotor diameter: 1.6 m
- Total length: 2.0 m
- Envelope diameter: 2.9 m
- Central nacelle: 459 · 2937 mm
- Total volume 0.70 m³
- Deadweight 330 kg

Furthermore, a scale model of the BOSCEM buoy was constructed (Figure 13), based on a NACA profile with dimensions of 1.0 · 0.4 · 0.8 m with a displacement of 0.22 m³ and a deadweight of 80 kg (without ballast). Due to its reduced size, it was not feasible to properly reproduce its inner equipment.

Figure 12. The PROCODAC prototype.

Figure 13. BOSCEM buoy prototype deployment.

6 POWER SEA TESTS

6.1 Test elements and configuration

As explained in section 5.2, no site with appreciable marine currents could be found near the shipyard. The design of a towing system that took into consideration the buoy, the generation device and the cable and ropes between them was therefore required. The solution adopted is shown in Figure 14. Behind the towing vessel, a small pneumatic boat was located from which the buoy was attached. The aim was for the previously mentioned pneumatic boat to simulate a “reversed mobile seabed”. Due to this change, it was necessary to adapt its buoyancy force downwards by means of solid and water ballasts.

Also, as can be seen in Figure 14, the real mooring system had to be replaced by one that comprised of: two main towing cables (near horizontal cables linking the device, buoy and vessel), the supporting cables (linking the buoy and the boat), the safety ropes (non tension rope from the buoy to the device and from it to the blue safety buoy) and the umbilical cable for power and control (green cable linking the device, buoy, boat and vessel).

The power system located in the nacelle was comprised of a three blade rotor (yellow in Figure 12) a power meter with integrated thrust bearing, an epicycloidal gear, a 10 kW alternator and the electrical protection systems.

From the device to the vessel there, a multifunction umbilical cable was installed with the following elements:

- Power exit (×3) electrical cable
- Excitation (×2) electrical cable
- Auxiliary power feed (×2) electrical and data cable
- Nylon tubes for pneumatic control.

The resistors load bank and the instrumentation system including the excitation and the load controls, were located aboard the towing vessel.

Figure 14. PROCODAC power test simulation.

6.2 Sea test results

The final tests were carried out in the outer part of the Bilbao port (Figures 15 & 16) where the prototype was towed at different speeds with two towing cable lengths in order to obtain the power speed curve and to correct for the wake effect of the ship's hull and propeller (Winter 2011). Due to prototype size and constraints of the instrumentation it was not possible to study the effects of turbulence on the power performance, as predicted with numerical modelling studies (López 2014).

Also, due to the complexity of the elements and cables involved, a specific procedure for the

Figure 15. Bilbao port power sea tests.

Figure 16. Power test control screen.

Figure 17. Prototype power test results.

deployment of the whole system was designed. In order to minimize the effect of the tidal current on the results, trials were conducted up and down the selected area. Unfortunately, for the days licensed to use the port area, a gale prevented the completion of the scheduled testing program.

The tests results validate the power take off and the rotor designs and serve as a base for a future improved power control design. Figure 17 shows a good agreement between the rotor model power prediction and the test results (with the wake effect correction).

7 DEPLOYING SEA TESTS

7.1 Objectives and configuration

The objective of these tests was to check the emersion and immersion procedures for the buoy and the device. Unfortunately, the small size of the prototype and other constraints, forced the selection of only the most important ones, namely, the device movements.

Because of this limitation, most of the deploying operations were simulated with OrcaFlex (López 2011b). With this, some of the important test results could be used in order to validate the simulation models.

Due to these constraints, only the emergency emersion procedure was tested for the buoy. To check the device manoeuvres, a gravity base placed in shallow water was used with a scale arrangement of the mooring and connection cables (Figures 18 & 19). For the ballast control, an air membrane tank system with pneumatic bags was used in every torpedo. Due to the lack of space, it was necessary to locate the air control system in the vessel, along with reducing the number of ballast units to one per torpedo.

7.2 Instrumentation and results

The device was instrumented with depth, pitch and roll sensors whilst, for the ballast control, an open loop control was used in order to obtain high flexibility in the tests (Somolinos 2010; López 2013). The operations manoeuvre control screen is showed in Figure 20.

These sea trials were made in the Zumaia port, adjacent to the Balenciaga Shipyard facilities. With the final ballast system installed, there were no problems when making “one dimensional” immersions and emersions operations. It was nonetheless expected that the turning phase of these manoeuvres would be very difficult to carry out with a fine control. The initial symmetrical pneumatic bags were therefore modified in such a way that

Figure 18. Buoy emersion test.

Figure 19. Device emersion simulation.

Figure 20. Deploying operations control screen.

Figure 21. Immersion turning sequence.

Figure 22. Turning operation simulation validation.

when the pressure decreased, one side collapsed before the other. The final results were successful immersion and emersion operations, as can be seen in Figure 21.

After the tests, the turning phase with a simplified model of the bag volumes and centroid changes were simulated with the results shown in Figure 22.

8 CONCLUSIONS

The main conclusion of the PROCODAC project sea trials was that the GESMEY device and the BOSCEM buoy have proven their design functionality and that it is feasible to start with stage 4 of the project in order to construct and test a prototype with a nominal power in the order of hundreds of kW.

Also, it was shown that for second-generation TECs, it is feasible to carry out tests that validate the TRL levels 5 & 6 with limited facilities, although the design of specific procedures and the development of a tailored instrumentation system are still needed.

For the GSY-ME10 prototype, the PTO design, including the rotor, has been proven and has a power output in accordance with numerical simulations. It was also proven that it is possible to realise the underwater movement operations by means of a ballast control system.

In the next stages, it will be convenient to improve or change the tank membrane ballast system and design the mooring system in order to simplify the deployment of towing ropes for different sea conditions. With this and in order to incorporate the actuator movements identical to the final ones, the next device and buoy prototypes must have an increased size.

ACKNOWLEDGEMENTS

The works described in this paper have been supported by the following grants of the Spanish Administration: Proyecto de Investigación Aplicada Industrial IAP-590000-2008-6; Actuaciones de I+D Sector Naval. C.N.4.02.5605/I+D-01; Proyecto de Investigación Fundamental DPI2011-24113.

The experimental work of PROCODAC project has involved many people, among which the authors should highlight the excellent work made by M.A. Orrico, I. Jimenez, F. Rodriguez, F. Garcia and M. Santamaría.

REFERENCES

- Brito, A., Huckerby, J. (eds) 2013. *Ocean Energy Systems. Annual Report-2012*. OES-IEA. www.iea-oceans.org.
- Fitzgerald, J & Bolund, B. 2012. *Technology Readiness for Wave Energy Projects; ESB and Vattenfall classification system*. 4th International Conference on Ocean Energy. Dublin. ICOE'12.
- Hardisty, Jack, 2009. *The Analysis of Tidal Stream Power*. Chichester. Wiley-Blackwel.
- King, J., Tryfonas, T. 2009 Tidal Stream Power Technology. State of the Art. Bremen. IEEE Oceans Conference.
- López, A. et al, 2011a. *Dynamic Behaviour of a Second Generation Hydrokinetic Converter*. Santander. IEEE Oceans Conference.
- López, A. et al, 2011b. Simulation of GESMEY Generator Manoeuvres. The European Modelling & Simulation Symposium. Roma. EMSS'1.
- López P., Amable et al, 2013. *Inertial Behavior of Off-shore Devices*. 5th International Workshop on Marine Technology. Gerona.
- López P., Amable et al, 2014. *Modelado Energético de Convertidores Primarios para el Aprovechamiento de las Energías Renovables Marinas*. Revista Iberoamericana de Automática e Informática industrial Vol.2–2014 pg. 224–235. www.elsevier.es/RIAI.
- Myers, L.E. et al. 2010. *Equimar Deliverable D5.2: Device classification template*. Equitable Testing and Evaluation of Marine Energy Extraction Devices. www.equimar.org.
- Núñez, L.R. et al, 2011a. *Conceptual Design of an Ocean Current Turbine for Deep Waters*. 1st International Conference on Maritime Technology and Engineering Lisboa. MARTECH'11.
- Núñez, L.R. et al, 2011b. The GESMEY Project. Design & Development of a Second Generation TEC. 9th European Wave and Tidal Energy Conference. Southampton. EWTEC'11.
- Núñez, L.R. et al, 2013. *New steps in the development of the second generation TEC GESMEY*. 10th European Wave and Tidal Energy Conference Aalborg. EWTEC'13.
- Roos, I. 2011. The electricity of the future—underwater? *Future by Semcom*, vol.3 (24–29).
- Sankaran, A. et al. 2013. *Assessing long term Tidal site characterisation using Acoustic Doppler Current Profilers*. 10th European Wave and Tidal Energy Conference Aalborg. EWTEC'13.
- Somolinos, J.A. et al, 2010. *Automatic System for Underwater Ocean Current Turbines. Application to GESMEY*. International Conference on Oceanic Energies. Bilbao ICOE'10.
- Starzmann, R. et al. 2013. *Full-Scale Testing of a Tidal Energy Converter Using a Tug Boat*. 10th European Wave and Tidal Energy Conference Aalborg. EWTEC'13.
- Weber, J. 2012. *WEC Technology Readiness and Performance Matrix—finding the best research technology development trajectory*. 4th International Conference on Ocean Energy. Dublin. ICOE'12 Huckerby, J. et al, 2011. *An International Vision for Ocean Energy*. OES-IEA. www.iea-oceans.org.
- Winter, A. 2011. *Speed Regulated Operation for Tidal Turbines with Fixed Pitch Rotors*. Kona. IEEE Oceans Conference.